E-MEEG: Methods for de-coupling eye-movement artifacts from event-related potentials and fields

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Specific Aims

Although there are several decades of studies on reading, we still don't know what is happening neurally when we read naturally. Language research has made significant progress in visual word recognition by focusing on two powerful techniques: eye-tracking and neurophysiology recording. These two techniques work on different domains: eye-movement behavior and neurophysiological brain response, in hopes of describing underlying cognitive processes related to word recognition. The eye-movement literature has been informative providing detailed models to the behaviors evoked when reading: skipping, regressions, fixation durations, but it hasn't been able to a solid linking hypothesis between the behavior and its cognitive underpinnings. There is contention over whether the linking assumption is that we don't move the eyes until we have finished processing (E-Z Reading serial model: Reichle et al., 1998) or that we have distributed parallel processing (SWIFT parallel model: Engbert et al., 2002). Neurophysiology models have provided insight to regions that may be implicated in lexical access (Lau et al., 2008) but the time seems to lag behavioral results. Due to potential artifacts in the data, reading task in neurophysiological experiments take a non-natural task of rapid serial visual presentation (RSVP), which can have imposing processing constraints (Rayner, 1998).

There is no strong evidence showing that the eye-movement behaviors we see in reading and are correspondent to the ERPs we see in RSVP reading tasks. There have only been a few studies have tried to couple the two techniques together (Kretzschmar et al., 2009), (Kliegl et al., 2012). Combining these two methodologies will help tighten the cognitive processing linking hypothesis to reading by providing on-line measure of both eye-movement and brain response. Here, we seek to mend the gap between the eye-movement and neurophysiology literature by developing a method for combining eye-movement methodologies with neurophysiological recordings. We will use both EEG and MEG (MEEG) for neurophysiological recording. Simultaneous recording of both serves two purposes: EEG recording ties brain responses with prior literature while MEG provides more accurate spatial resolution to sources generating observed language effects. The overall objective is to understand how language is processed on-line by aligning the neural correlates from neurophysiology with the eye-movement behaviors seen in reading. We will compare different eye-movement removal algorithms in a non-linguistic, contingent-display saccade movement paradigm. In this task, we will derive methods for distinguishing basic oculomotor movements from perception. This will provide the necessary foundation to look at linguistic stimuli (Aim 1). Using a robust cloze-probability language task, we will seek to replicate the neurophysiological effects after accounting for eye movements (Aim 2).

Aim 1: To reliably remove eye-movement artifacts in a contingent-display paradigm. Two general classes of eye-movement removal algorithm will be compared: extended independent component analysis (Jung et al., 2001) and multiple source eye correction (Berg & Scherg, 1994). Using a contingent display saccade movement paradigm, a visual salient cue (e.g. checkerboard) will be presented at various locations while the brain responses are recorded.

Aim 2: To reliably replicate cloze probability findings seen in both eye-tracking and electrophysiological studies. Meyer & Schvaneveldt (1971) demonstrated that there is a speed up effect in word recognition when the semantic association between two words increases. Ehrlich & Rayner (1981) and Kutas & Hillyard (1984) have both found effects due to cloze probability in eye-tracking and EEG, respectively. Two sub-experiments will be conducted aside from simultaneous recording for direct comparison: eye-tracking only, MEEG using RSVP only. This helps enriches the model of on-line language comprehension by bridging the gap between behavior and electrophysiology.

Research Strategy

Aim 1: To reliably remove eye-movement artifacts in a contingent-display paradigm.

Overview: The goal of Aim 1 is to evaluate two different classes of eye artifact removal: independent component analysis and multiple source analysis. There are two tasks: eye-stationary visual presentation, saccade-driven gaze contingent visual presentation. The first task is used to give a baseline with no eye-movement. The second task is used to generate controlled eye-movements with timing similar to reading time durations. Simple visual evoked potentials will result from this task (N1, M100). Algorithms will be evaluated against the baseline to see if signal integrity is maintained.

Design: There are a duplet of images associated with each trial. A star appears to indicate where a eye gaze should be directed. The vertical position of star is held constant at mid-screen; the horizontal location is randomly selected between two possible choices: $\frac{1}{4}$ from the screen edge. Once the eye saccades to the target location, the star disappears and a checkerboard appears on the screen until gaze has reached the threshold of 250ms (typical fixation duration is 200-250ms; Rayner, 1998). After threshold is exceed the checkerboard disappears. The trial sequence is then repeated. The number of trials per participant is 200.

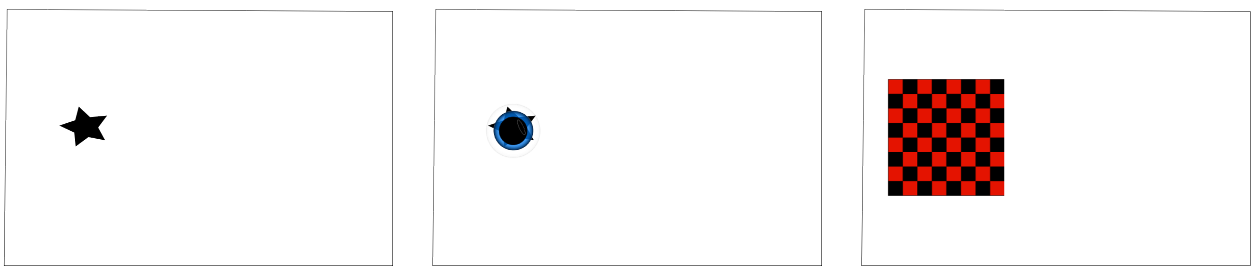

Figure 1: Gaze-Contingent display paradigm

Eye-movement Data Acquisition: Eye-movement data will be collected using a SR-Research Long Range Fiber Optic Eyelink 1000. This high-speed infrared camera has temporal sampling of 1000Hz, an average of 0.25° to 0.5° with a spatial resolution of 0.01°. The eye-tracker is mounted inside the MEG chamber.

MEEG Data Acquisition: MEG data will be collected using a Kanazawa Institute of Technology, 157-axial gradiometer MEG system. This system has 3 orthogonally-oriented magnetometers to measure and reduce noise off-line. EEG data will be collected using an SA Instrumentation, 24-channel bioelectric amplifier EEG system.

MEG Data Analysis: The MEG signal will be pre-processed using a DC recording with a low-pass filter of 200Hz and a notch filter of 60Hz. After recording, the data will be post-processed in MEG160, a companion software produced by KIT. Post-processing consists of the data being noise-reduced using the CALM procedure (Adachi et al., 2001). The analyses of interests will not be concerned high-frequency signal therefore an additional low-pass filter for 40Hz will be applied.

EEG Data Analysis: Pre- and post-processing of data will be similar to the MEG procedure with the exception to the CALM procedure.

Potential Problems: There is a possibility that the eye artifact removal algorithm may remove more signal than expected. The expected effect may not surface to significance using the extended independent component analysis since it requires isolating specific components of the signal. Although the particular component may be well correlated with eye movements, some other cognitive task may share the same source. Jung et al., 2001 finds that as the number of trials and electrode increase, the more robust the ICA becomes. The use of the ICA may prove more useful on the MEG data than the EEG data due to the number of sensors (157:24). This technique is relatively new in language research. Only a few studies have published results using it. Replication of robust effects is currently the only safeguard to testing the feasibility of these combined techniques.

Aim 2: To reliably replicate cloze probability findings seen in both eye-tracking and electrophysiological studies.

Overview:

Eye-tracking while reading focuses on fixation durations as the primary dependent measures. These fixations are typically clustered into different stages of processing. Clifton et al. (2007) proposes that single-fixation, first-fixation and gaze duration index word identification whereas regression-path duration may index text integration.Rayner (1998)discusses how these reading time measures may underlie discrete cognitive processes. Using the findings fromMeyer & Schvaneveldt (1971)'s semantic priming paradigm, Ehrlich & Rayner (1981) was able to demonstrate that eye-fixation durations were inversely proportional to the cloze probability of the sentence. Reichle et al. (1998) models these eye-movements in a computational model linking fixations and saccades to recognition and incremental integration. Although, these models make clear predictions to the eye-movement behavior, they do not provide a clear link the correspondent cognitive processes.

Neurophysiological brain responses have been used to index stages of word recognition with much more focused on a particular event-related potential, the N400. Lau et al. (2008) proposes that N400 relates to lexical access and that there is a semantic network of brain regions involved in recognizing and retrieving the meaning of a word. Earlier findings fromKutas & Hillyard (1984) show that semantic violation or word expectancy can affect the N400. They found that N400 amplitudes were inversely proportional to the cloze probability of the sentence. The time-course of lexical access for neurophysiological response seem to trail eye-movement response by 100-150ms. Both eye-tracking and neurophysiology show convergent effects of cloze probability on lexical access but these temporally disjointed results do not speak to a clear time-course model.

Neurophysiological studies employs rapid serial visual presentation (RSVP) to engage reading tasks. This has been done since oculomotor movement generate large electrical activity overshadowing the cognitive activity of interest. RSVP provides a solution but it has a processing load limit that is not present in normal reading. RSVP lacks parafoveal preview benefit that aids in reading and the ability to regress back to previous word when additional processing and repair are needed (Rayner, 1998).

The goal of Aim 2 is to replicate robust findings of the effects to word recognition due to cloze probability using simultaneous eye-tracking and neurophysiological recording. The task is a simple reading study where cloze probability is manipulated using semantic association of a prime-target word pair. We expect to see faster reading times for word pairs with high semantic association. Neurophysiologically, we expect to see larger N400 (M350) amplitudes for word pairs with low semantic association. These brain response should be present after eye-movement removal. Two sub-experiments will also be conducted: an eye-tracking only and MEEG with RSVP only. This is provide a baseline comparison. We should expect to see these effects in separate testing modality and when the two methods are combined.

Design: 120 word triplets will be generated in the following properties: *word1* is an animate entity (e.g. bird). All words within this category will be matched on word frequency and word length. *word2* and *word3* will be qualities that could possibly describe the entity. Word frequency is defined using the English Lexicon Project word frequency statistics(Balota et al., 2007). These pairs will be matched on word length and word frequency. *word2* will be a word that could plausibly describe *word1* but their semantic association will be small (LSA $<$ 0.25); this implies that the words are semantically distant (e.g. die). Semantic association is defined using the Latent Semantic Analysis (Landauer et al., 1998). *word3* will be a word that could plausibly describe *word1* but their semantic association will be large (LSA $>$ 0.75); this implies that the words are semantically close (e.g. fly). Each triplet creates a predictability contrast. Each sentence will be formed using a modal verb (e.g. can).

(1) Birds can die.

Birds can fly.

Task: Participants are asked to read a series of sentence, each of which is followed by a comprehension question. A gaze-contingent, moving window paradigm will be implemented to control for visual input (Just et al., 1982).

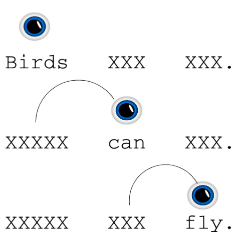

Figure 2: Gaze-Contingent, Moving Window Paradigm

Eye-movement Data Acquisition: same as above.

MEEG Data Acquisition: same as above.

MEG Data Analysis: same pre- and post-data processing. We will then apply the appropriate eye artifact removal (see Aim 1).

A sensor-space analysis will be conducted to see magnetic analogs to N400. A sensor-space targeted region of interest will be generated using the co-referenced EEG electrode area, the centro-parietal area. Trials will be rejected if signal amplitudes exceeds a threshold of 2.5pT. The data will be epoched with a baseline of 200ms prior to the onset of the target stimulus to 600ms post-stimulus presentation. The target trigger initiates once the subject saccade into the targeted area of interest. The epochs will be baseline-corrected using the pre-trigger time interval of 200ms. A peak amplitudes analysis will be conducted over the time region: 250-500ms post-stimulus, consistent with standard ERP analyses.

The peaks will be analyzed using a mixed-effect linear model package (lme4: Bates & Sarkar, 2007). This allows for modeling both subjects- and items- effect in one model. The significance of the effects will be determined using a Markov Chain Monte Carlo simulation within 10,000 trial iterations. The critical contrast will be a test of an interaction: the difference in MEG response between contrasts within RSVP experiment and within the simultaneous E-MEG after eye artifact removal.

EEG Data Analysis: Pre- and post-processing of data will be similar to the MEG procedure with the exception to the CALM procedure. The EEG bioamplifier provides the necessary noise reduction. Data analysis is the same as above. The critical contrast will be a test of an interaction of the data in RSVP versus the simultaneous E-EEG after eye artifact removal.

E-M Data Analysis: Eye-tracking recording tend to be vulnerable to vertical drift. Since the sentence presentation in this study is all on one line, drift correction can be apply such that the fixation fit within the areas of interactions. Drift correction is only allowed to fixation within 2° vertical of the area of interest. Fixation-based analyses will be conducted on areas of interest. Definitions of fixations will be taken from Clifton et al., 2007. Since readers will not have the possibility to regress backwards, only first-pass measures will be analyzed. First fixation is defined as the first fixation in a word and maximal progress on a particular line of text. Gaze duration is defined as the cumulative sum of all first-pass fixations within a word region.

Potential Problems: The moving window paradigm may be disruptive to normal reading. In self-paced reading, the reaction time to a button press to continue is much longer than the time it takes to plan and launch a saccade; participants have more time to process (Rayner, 1998). Eye jitter and accidental eye movements may also accidentally trigger the boundary change before intent.

Summary

The research proposed seeks to bring together two separate lines of research, eye-tracking and neurophysiology, by combining both methodologies simultaneously. This would significantly improved the link hypothesis of eye movements to cognitive processing by syncing these technique in real-time. Neurophysiology would be benefit in the potential explanatory power of lag of event-related response with eye-tracking methods. These techniques could finally solve questions to levels of processing in word recognition by providing reliable time-course.

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