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**Abstract:** Background: text reading and comprehension are the most ecological forms of reading. However, there is little knowledge about their neurophysiological correlates, mainly due to the constraints of paradigm design in event-related potential (ERP) and electroencephalography (EEG), that require the temporal segregation of stimuli.

**Aim and Methods:** To understand the neurophysiological markers of continuous reading we compared ERPs elicited by a) words in text b) words presented in random order and c) false fonts words, presented at a regular and similar frequency to simulate continuous reading. Participants were 16 healthy volunteers (6 females) aged between 23 and 35 years.

**Results:** While earlier ERP components were similar between the different experimental conditions and mid (210 to 320 ms) components was only different for the false font stimuli, for later (>400 ms) components were significantly different at the frontal and at the occipital electrodes, for the word within context than non-word stimuli and random words. Also for the later components there was a lateralization difference between the segmented text and false font conditions. These results suggest that the late ERP component correspond to semantic integration across text.

**Discussion and Conclusions:** The finding of late and anterior ERPs waves associated to text reading shows that it might be possible to identify specific biomarkers of spontaneous reading, which can be of extreme relevance for the design of brain-machine interface devices. Future research is necessary to corroborate these preliminary findings and to allow the tracking of these correlates in online EEG.

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Prof. Irwin B. Levitan  
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7<sup>th</sup> April, 2014

Dear Sir

Please find enclosed the article “Neurophysiological correlates of continuous reading” that we are submitting to Brain Research in the section Cognition and Computation. The article addresses the use of electroencephalography (EEG) in the study of language processing and continuous reading detection and analysis. The work was carried in the RAPS project (Reading Analysis using Physiological Signals) funded by FCT, Portugal.

The project was grounded on the beliefs that the detection of reading processes are relevant in the evaluation of interactive situations and that there are unanswered questions interest in the analysis of the mechanisms of continuous reading.

The use of EEG for this study is justified by the growing research on reading processes using this neurophysiological technique and the better understanding of the neural mechanisms associated with continuous reading we can draw from this approach.

The experiments were conducted on the EEG laboratory of the Hospital Sta. Maria, Lisbon, PT, as a partner of the project. The EEG data was obtained in a clinical setting, with a 71-channels Nihon Koden system. The participants recruited for the study were all healthy subjects with no history of neurological disorders and with a high degree of education.

This study sheds new information on the neuronal mechanisms during continuous reading processes and also provides a basis for future research on how to automatize the detection of reading.

There are no previous or concurrent submissions of this article.

Looking forward to your reply,

Yours

Sincerely

Nuno Guimarães

## Highlights

- We study reading processing in a wider discourse.
- We design an innovative paradigm that allows the understanding of neurophysiological basis behind continuous reading using ERPs.
- Continuous reading elicits different later ( $> 400$  ms) ERPs components.
- Continuous reading elicits a right frontal and temporal cortex activation at later stages.
- We identified possible biomarkers of spontaneous reading.

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# Neurophysiological correlates of continuous reading

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## 1. Introduction

The understanding of the neural mechanisms underlying word and sentence comprehension has evolved through the analysis of event-related potentials (ERPs), which provide information about the neural processes underlying ongoing cognitive processing with an adequate temporal resolution. The earliest and pioneer studies began in the late 1970s with the discovery of a negative potential occurring 400 ms after the stimuli, hence designated N400, in response to semantic errors (Van Berkum, 2004).

Subsequent studies addressing the visual and semantic processing of written language comprehension used isolated sentences or isolated words as experimental stimuli. However, those two classes of stimuli do not address the broader process of reading a text, continuously and intelligibly. The understanding of this process is particularly relevant if one wants to understand the neural mechanisms underlying the most natural form of adult reading or to develop devices that monitor those processes in brain-machine interfaces. Besides, there are specific types and subforms of developmental reading difficulties that are characterized by difficulties at the level of text comprehension but not word reading (Hulme and Snowling, 2009, 2012).

Reading processes and their neural basis have been extensively addressed in several studies (Barber and Kutas, 2007; Cohen and Dehaene, 2004; Ojemann, 1991; Proverbio and Riva, 2009). It is known that reading can be decomposed in several stages, which are linked to ERPs (for an extensive review see Grainger and Holcomb, 2009). Two main stages have been identified: one corresponding to the visuo perceptual processing and another to the semantic processing and mean extraction.

The earlier and low level sensorial processing of the visual stimuli triggers an ERP at approximately 100 ms (P100) [Dien, 2009], followed by N170, a component sensitive to word shape, which has been shown to be specific for words when compared to strings of symbols (Bentin et al., 1999). It is now generally accepted that the left occipito/temporal cortex is responsible for identification of visual words and this first stage has been attributed to the activation of the *visual word form area* (VWFA) responsible for word detection and identification (reading), located in the middle portion of the left fusiform gyrus (Cohen and Dehaene, 2004; Proverbio et al., 2008). The second stage develops as the brain engages in the reading activity, and other brain regions are activated leading to later ERPs. Several neurometabolic studies suggest that prefrontal cortex and inferior frontal regions play an important role on semantic processing (Cloutman et al., 2011; Petersen et al., 1990; Proverbio and Riva, 2009). ERP-based research shows that one of the most studied ERPs in language occurs around 200 ms to 400 ms (N400) [Barber and Kutas, 2007].

Again, although these studies address the most elementary reading processes there is still a lack of understanding of the mechanisms of reading and comprehension in a wider and continuous discourse. The study of auditory understanding of spoken speech

has shown that narrative integration across the discourse elicits brain patterns that are not observed in single word processing (Friederici, 2002). Likewise it is possible that identical mechanisms can be found during text reading or even correlate with text comprehension speed and accuracy. One of the reasons for the scarcity of ERP-based studies in continuous reading or discourse-level analysis is the set of constraints that ERP imposes on the design of the experimental paradigms. One example is the requirement for a high number of target stimuli in order to increase the signal-to-noise ratio. However, in continuous reading, the brain necessarily executes concurrent and overlapping processes and the EEG signal is a sum of these concurrent activities, making it hard to interpret the ERPs waveforms (Van Berkum, 2004).

The main research question is whether ERP responses differ in the context of attentive and silent continuous reading of a text, when compared to the same words presented in an isolated manner. Small texts were built, containing a simple story, and two versions of them were designed. One randomized their words to remove contextual meaning while retaining single word semantic information; the other used a false unreadable font, providing similar visual features without any semantic content. Each participant saw the three conditions.

The goal of this work is to identify and describe elements of the brain response during continuous reading, based on the study of several ERP components with the hypothesis that earlier ERP components will be similar for reading isolated words and words in context, but later frontal ERPs will be sensitive to the difference between continuous and isolated words reading. Also there should be a lateralization effect while the brain processes words in context stimuli. It is known that the left inferior frontal lobe is involved in semantic processing and that the right hemisphere is involved in comprehending contextual meaning (Bookheimer, 2002). We propose a pre-model that can be used with Brain Computer Interfaces (BCI) algorithms that would detect if a person is reading. This study will enable the design and development of tools for analysis and support of reading processes, which are pervasive in intellectual tasks, especially in the context of human-machine interaction.

## **2. Results**

The analysis of ERP data shows that the three types of stimuli – segmented text, isolated words, and false font words - elicit a similar initial ERP waveform – P1 - observed between 90 and 140 ms. However, by 210 and 320 ms there is a greater positive peak elicited non-word stimuli. Subsequently, both false font and isolated words stimuli produce similar waveforms while the segmented text condition causes a more negative amplitude at occipital regions and positive amplitude at frontal regions. Figure 1 (a), (b), (c) and (d) show the obtained ERPs for the three different conditions at the three regions previously described. The results will be now described along the temporal axis.

[Figure 1 (a). Grand average ERPs recorded at: left-occipital region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.]

[Figure 1 (b). Grand average ERPs recorded at: right-occipital region for: (1) segmented text in black line, (2) isolated words in red, and (3) false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.]

[Figure 1 (c). Grand average ERPs recorded at: left-frontal region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.]

[Figure 1 (d). Grand average ERPs recorded at right-frontal region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.]

### *2.1. Early latency (90 to 140 ms)*

In the earlier ERP components like P100 and N170 [Fig. 1 a), b), c) and d)] no significant differences between the three conditions were found. A marginal difference was obtained when comparing the interaction between posteriority and laterality [ $F(1,15) = 4.333, p = 0.055$ ]. This suggests that the initial response is identical and independent from the condition. The figure 2 shows the voltage distribution in the scalp, for this early stage and for the three conditions.

[Figure 2. Topographical map of the mean activity from 90-140 ms for Isolated Words (left), False Font (middle) and Segmented Text (right).]

### *2.2. Mid latency (210 to 320 ms)*

The subsequent components were more sensitive to the difference of the conditions or tasks. False font stimuli elicited, at approximately 270-300 ms (black region in figures 1), larger peak amplitude at occipital regions, as well as larger negative peak at frontal regions. In fact, there was a significant difference between the three stimuli [ $F(1.650,24.753) = 16.581, p < 0.001$ ] for the time range 210-320 ms, and also between condition\*posteriority [ $F(1.745,26.169) = 5.558, p = 0.012$ ]. Because no latency effect was obtained, a one-way ANOVA was performed for the occipital and frontal regions between the three conditions. Differences between conditions were only obtained for the occipital region [ $F(1.637,24.558) = 9.868, p = 0.001$ ]. The post-hoc analysis using Bonferroni correction has shown that false font stimuli ( $M = 2.227 \pm 0.373$ ) differs from segmented text ( $M = 0.947 \pm 0.392, p < 0.001$ ) and from isolated words ( $M = 1.235 \pm 0.376, p = 0.038$ ), while these last two conditions remain similar.



The topographical maps also illustrate this difference. In this middle stage, the false font stimuli causes a different reaction in the brain (Fig. 3 and Fig. 4), while words, isolated or in context, are being read.

[Figure 3. Topographical map of the mean activity from 210-320 ms for Isolated Words (left), False Font (middle) and Segmented Text (right).]

[Figure 4. Sequential topographic maps of the mean activity from 100 to 260 ms with intervals of 20ms for Isolated Words (top), False Font (middle) and Segmented Text (bottom).]

### *2.3. Late latency (380 to 540 ms)*

At later latencies (red region in figures 1), the ERP waveform becomes significantly different in the case of segmented text stimuli. At the occipital regions there is a larger negative modulation, and at the frontal regions a larger positive modulation. The repeated measures test revealed differences in condition [ $F(1.190,17.851) = 6.542, p = 0.016$ ], with and interaction between condition and posteriority [ $F(1.848,27.726) = 14.148, p < 0.001$ ] and between condition and laterality [ $F(1.775,26.624) = 4.649, p = 0.022$ ]. One-way ANOVA was performed for the occipital and frontal regions and also for the left and right hemisphere. A difference between conditions was obtained for the occipital site [ $F(1.834,27.507) = 7.777, p = 0.003$ ]. Post-hoc analysis indicated that segmented text stimuli ( $M = 0.034 \pm 0.457$ ) was different from isolated words ( $M = 0.812 \pm 0.460, p = 0.012$ ) and from false font ( $M = 0.958 \pm 0.358, p = 0.017$ ). Also at the frontal region mean amplitude was different between conditions [ $F(1.686,25.293) = 4.075, p = 0.035$ ]. Again, the segmented text response ( $M = 0.235 \pm 0.288$ ) was different from the isolated word response ( $M = -0.239 \pm 0.332, p = 0.021$ ) but not for the false font condition.

In the comparison of the laterality effects, a difference between conditions was observed for the right hemisphere [ $F(1.459,21.888) = 7.224, p = 0.007$ ]. The segmented text condition ( $M = -0.317 \pm 0.164$ ) showed differences from the false font stimuli ( $M = 0.276 \pm 0.164, p = 0.021$ ). Figure 5 also illustrates that the response to segmented text presents a higher voltage in the frontal regions, mainly on the left side, in comparison with the other stimuli.

[Figure 5. Sequential topographic maps of the mean activity from 320 to 600 ms with intervals of 40ms for Isolated Words (top), False Font (middle) and Segmented Text (bottom).]

## **3. Discussion**

The main goal of this study was to study the neurophysiological activity that occurs during continuous, attentive and silent reading. Most studies on reading using ERPs do concentrate on the continuous and discourse level of reading (Van Berkum, 2004), so

we paid special attention to this process during the design of the experimental paradigm. Following the principle of a similar study that compares words vs. false font stimuli (Appelbaum et al., 2009), the current paradigm compares words, false font and an additional third stimuli - the segmented text, which simulates a continuous reading task, while maintaining the quality of the subjective experience and the level of comprehension of the text (as studied in previous work).

### *3.1. Early latency*

At the early stages of the stimuli processing, no differences between the three conditions were found. During an initial stage recognition of the shape of the visual input occurs, which is the same for all visual stimuli. After that, visual word-form processes happen only for word-like stimuli on the left fusiform gyrus (Dien, 2009; Ruz and Nobre, 2008). Although no significant difference was found, observing the figure 1 a) shows that the N170 (green region from 160 to 190 ms) is more negative for word-like stimuli than for the false font stimuli. This visual difference is consisted with the theories of an existing wordform area on the left-occipital region (Appelbaum et al., 2009).

### *3.2. Mid latency*

In the second stage (210-320 ms) the ERP components are more sensitive to the false font stimuli in the occipital sites. Following this activation, a bilateral occipital activation is observed and remains in later components. In the isolated words and segmented text stimuli, this modulation only occurs on this mid latency.

This activation agrees with earlier studies, and suggests that the brain is attempting to match the strange forms with previous stored orthographic representations (Appelbaum et al., 2009). While this bilateral activation last less time for familiar word forms (isolated words and segmentation text stimuli), it goes on until 320 ms for the false font stimuli, as shown in the maps of figures 3 and 4.

### *3.3. Late latency*

Beginning around 300 ms, a slow wave component is observable in all the three conditions. However, the segmented text elicits a quicker and broader wave as shown in figure 1. In the posterior regions, the segmented text condition elicited a less positive wave than the other two, with larger amplitudes for the false font. In the anterior regions, the reverse was observed (higher positivity for segmented text). The literature describes two major components occurring at this latency, N400 and P300 (Appelbaum et al., 2009). The P300 responses occur in detecting target stimuli tasks. Because of the way the paradigm was built, it seems unlikely that the observed effect is related to the P300. There are different theories about the N400. One line of thought theorizes that the N400 reflects the late linguistic process of word's meaning integration, while a more recent one claims that it represents the process of accessing semantic memory (Kutas and Federmeier, 2011).

In our results, the late left activation in the frontal electrodes is clearly and significantly stronger for the segmented text stimuli (380-540 ms). This can be interpreted as the evidence of the specific linguistic process that occurs in the continuous discourse level reading task. This type and level of activation is not observed in the reading of isolated words.

The interesting aspect of these results is that, in spite of the fact that isolated words and segmented text are visually and neurophysiologically identical, this late latency effect supports the claim that the N400 reflects the integration of the word's meaning not only into a preceding context but as a whole, i.e., in the integration of information in context, monitoring of meaning, syntactic congruency and maintenance of information active as more information is added.

#### **4. Conclusion**

The present study confirms previous research on the sequences of linguistic processes that occur in the brain but also introduces a new way of approaching the study of continuous reading. The ERP analysis shows an initial visual process that is independent of the structure and level of the visual stimuli (symbols, words or text), followed by late latency effects that illustrate a high-order process specific to word-like stimuli and concluding on an even more specific process that occurred for the continuous reading, and not in the previous conditions.

The results are therefore in consonance with the earlier studies that focused on the difference between words and false font paradigms (Appelbaum et al., 2009), but introduce a possible neurophysiological marker of the linguistic processing that occurs on a continuous reading, using ERP methodology. The study shows how ERPs can be a useful tool to the study of the continuous discourse-level of reading.

#### **5. Experimental Procedure**

##### *5.1. Subjects*

Sixteen healthy participants (6 female) were recruited among students and faculty staff after written informed consent. Their ages ranged between 23 and 35 years ( $M = 27.75$  years), all were Portuguese native speakers with no visual or language disorders and no history of reading difficulties.

##### *5.2. Stimuli and procedure*

Following a previous study that analyzed the impact of alternative text segmentations, this study uses an experimental set-up designed and evaluated in previous work, namely

the validation of alternative stimuli designs to enable the realistic analysis of the continuous reading activity.

The stimuli presented in the experiment were based on previous work, with a focus on the differences between a segmented text with a readable font and a segmented text with a false font.

Texts were designed with a matched number of words (73-76), word frequency (Bacelar do Nascimento, 2001) and readability scores as measured by a Flesch Reading Ease Score index (Aluisio, Specia, Gasperin, and Scarton, 2010). Texts were qualified as easy, ranging from 52 to 72 (range from 0-100, with higher scores corresponding to easier texts).

For the purpose of this study, a word-by-word text segmentation was used. Additionally, isolated-word stimuli built from the randomization of the words of each text were presented to the subjects. In the comparison between the text segmentation and the isolated word stimuli, we expect no significant differences at the visual level, and differences in the EEG, if any, should be related or constrained to the reading processes.

All participants were seated comfortably in an electrically shielded room. Participants were fitted with an electrode cap after the cleansing with alcohol of all electrode locations. Stimuli were presented on a 19-inch computer screen, with a refresh rate of 74 Hz, located 60 cm apart from the participant, using E-Prime software (Psychology Software Tools).

The experiment consisted on the random presentation of three blocks: (1) segmented text in a readable font [Fig. 6(a)], (2) isolated words (created by text randomization) [Fig. 6(b)], and (3) segmented text in a false font [Fig. 6(c)]. The segmented text presentation displayed each segment for 200 ms followed by an ISI of 800 ms (see Fig. 1). In the isolated words block and in the false font block, words were also displayed for 200 ms followed by an ISI of 800 ms.

In the false font block an additional task was added. Participants had to search for a non-existent small circle between the symbols and count (silently) them. The purpose of this task was to keep subjects (who were unaware that there were no small circles) attentive to the symbols, while no ERP would be elicited since no circle was shown.

[Figure 6. *Blocks of stimuli (a) WbW segmentation; (b) Isolated Words; (c) False Font.*]

### 5.3. EEG recording and analysis

The electrode cap used in signal capture had 71 channels, positioned according to the 10-10 System. The impedances were corrected to be lower than 5k $\Omega$ . The horizontal electrooculogram (HEOG) and vertical electrooculogram (VEOG) were also recorded. The references used while recording were C3 and C4, which were changed to an average reference afterwards. The sampling frequency of the EEG record was 1000 Hz

and a Nihon Kodan equipment for the EEG recording was used, in a clinical setting with specialized and experimented technicians.

The processing of the EEG data was performed with EEGLab toolbox (Delorme and Makeig, 2004) for MatLab following their tutorial. Extracted data was re-referenced to the average of all electrodes, re-sampled to 256 Hz and filtered with a basic Finite Impulse Response (FIR) filter with a low and high frequency pass band of 30 Hz and 0.3 Hz, respectively. Trials were excluded from averaging if they contained eye movements, blinks (which could be detected based on the electrooculogram (EOG) recordings) or excessive muscle potentials artifact.

The average ERPs were computed for each participant with a baseline correction from the 200 ms previous to each trial and then a grand average of all subjects was obtained. For the purposes of this study four locations were defined: Left-Occipital region (average of P5, P7 and PO7 electrodes), Right-Occipital region (average of P6, P8 and PO8), Left-Frontal region (average of F3, F5 and AF3) and Right-Frontal region (average of F4, F6 and AF4). The mean amplitude was measured for the time ranges: 90-140 ms (P100), 210-320 ms (P300) and 380-540 ms (late potentials). A repeated measures ANOVA was performed to evaluate the main effects of the three conditions on the corresponding ERP waveforms. The analysis was made for each time range between condition (the stimuli type), posteriority (occipital vs. frontal regions) and laterality (right vs. left hemisphere) and Greenhouse-Geisser correction (Greenhouse and Geisser, 1959) was used.

The selection of the electrodes and time ranges was based on the knowledge gathered from previous research, where the occipital regions were indicated as the main sites for reading and the time ranges also reflect key stages on the linguistic processes. The frontal regions were chosen to compare the later stages of the reading processing.

In addition, voltage ERPs scalp maps were calculated using the EEGLAB toolbox of MatLab. These topographical maps offer a holistic view of what is happening at a given instant in the brain, a perspective that would not be observable with only the ERPs of specific regions.

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## Figure Legends

Figure 1 (a). Grand average ERPs recorded at: left-occipital region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.

Figure 1 (b). Grand average ERPs recorded at: right-occipital region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.

Figure 1 (c). Grand average ERPs recorded at: left-frontal region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.

Figure 1 (d). Grand average ERPs recorded at right-frontal region for: segmented text in black line, isolated words in red, and false font in dashed (gray) line. Blue box delimits the interval from 90 to 140 ms; green box from 160 to 190 ms; black box from 210 to 320 ms; and red box from 380 to 540 ms.

Figure 2. Topographical map of the mean activity from 90-140 ms for Isolated Words (left), False Font (middle) and Segmented Text (right).

Figure 3. Topographical map of the mean activity from 210-320 ms for Isolated Words (left), False Font (middle) and Segmented Text (right).

Figure 4. Sequential topographic maps of the mean activity from 100 to 260 ms with intervals of 20ms for Isolated Words (top), False Font (middle) and Segmented Text (bottom).

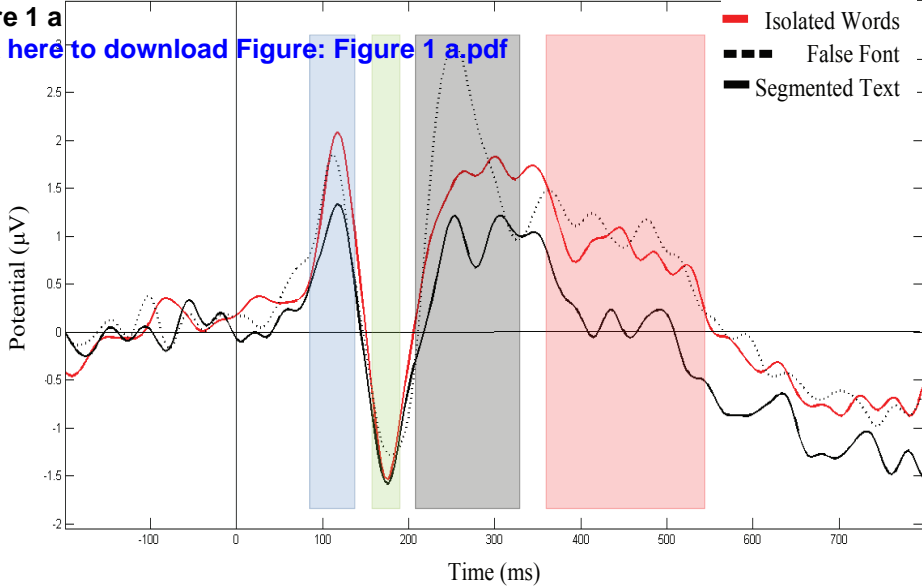
Figure 5. Sequential topographic maps of the mean activity from 320 to 600 ms with intervals of 40ms for Isolated Words (top), False Font (middle) and Segmented Text (bottom).

Figure 6. *Blocks of stimuli (a) WbW segmentation; (b) Isolated Words; (c) False Font.*



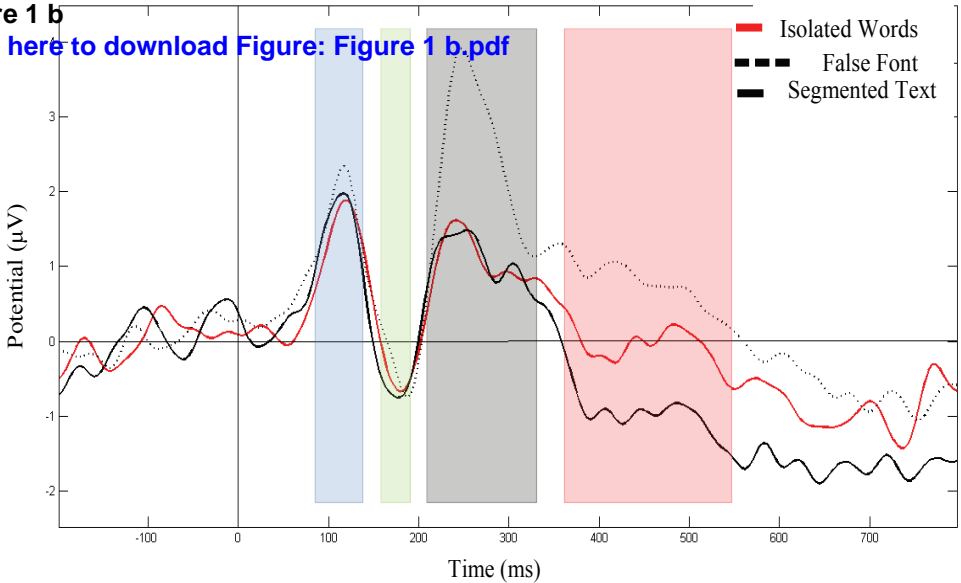
**Figure 1 a**

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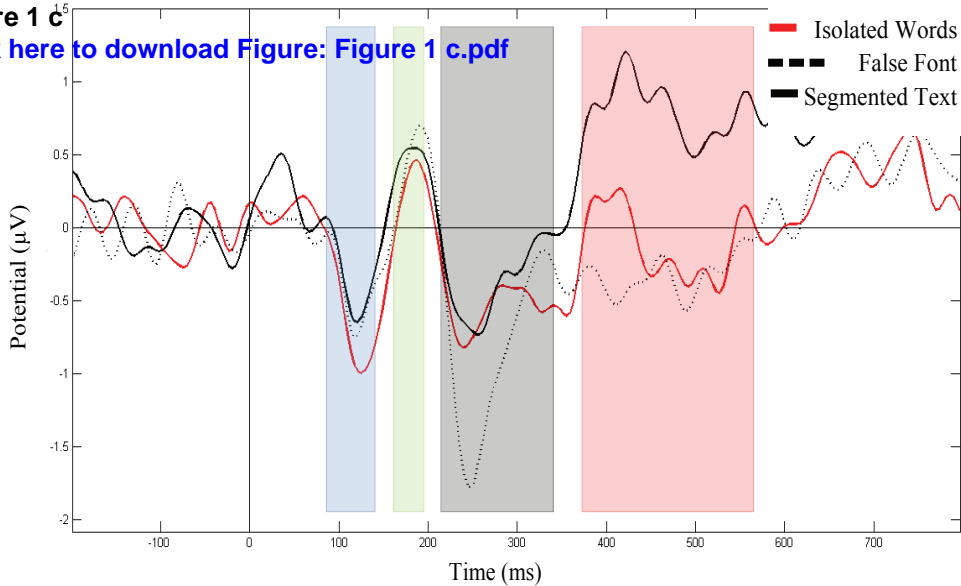
**Figure 1 b**

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**Figure 1 c**

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**Figure 1 d**

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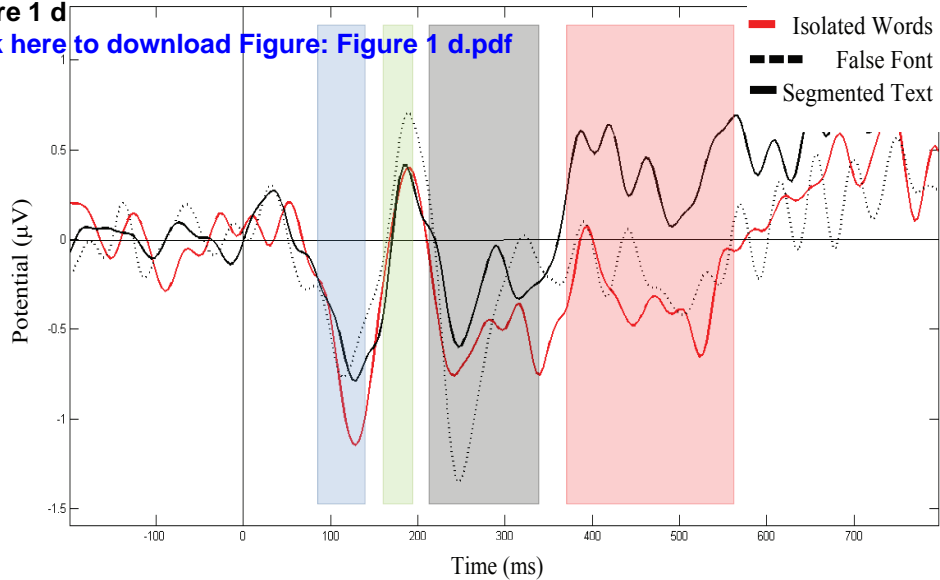


Figure 2

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Isolated Words, 90 – 140 ms    False Font, 90 – 140 ms

Seg. Text, 90 – 140 ms

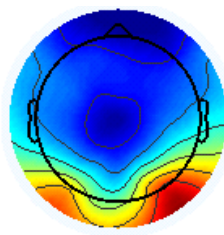
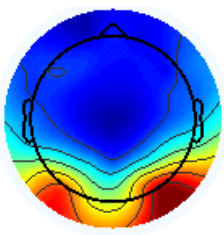
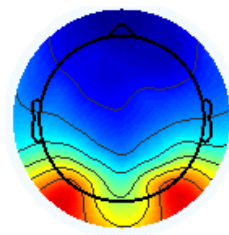


Figure 3

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Isolated Words, 210 – 320 ms   False Font, 210 – 320 ms   Seg. Text, 210 – 320 ms

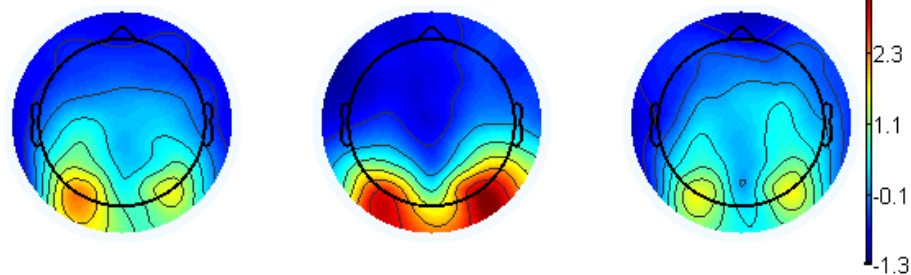


Figure 4  
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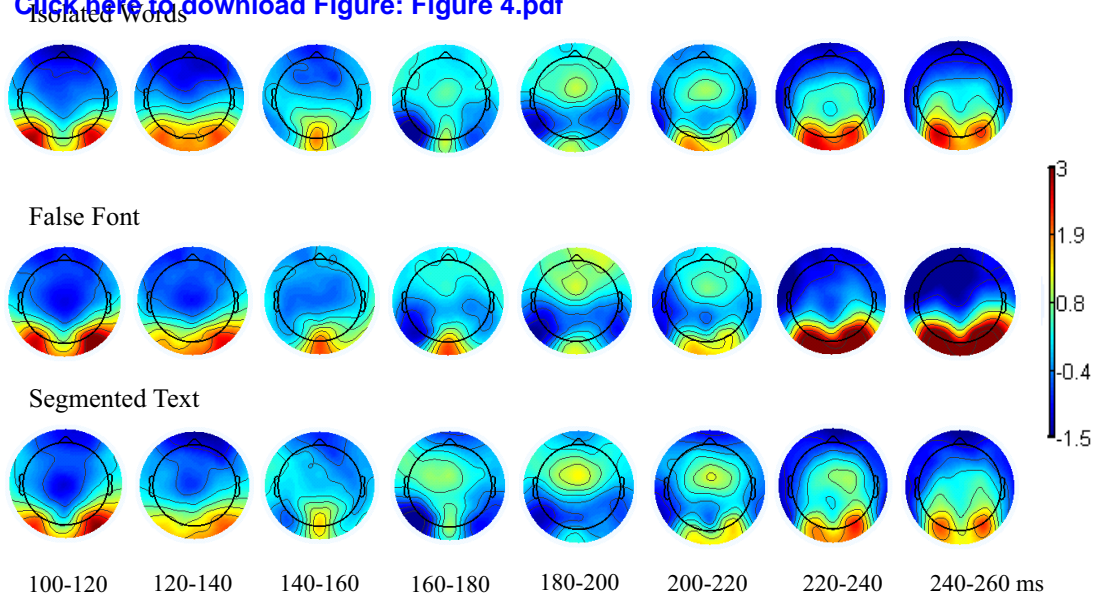
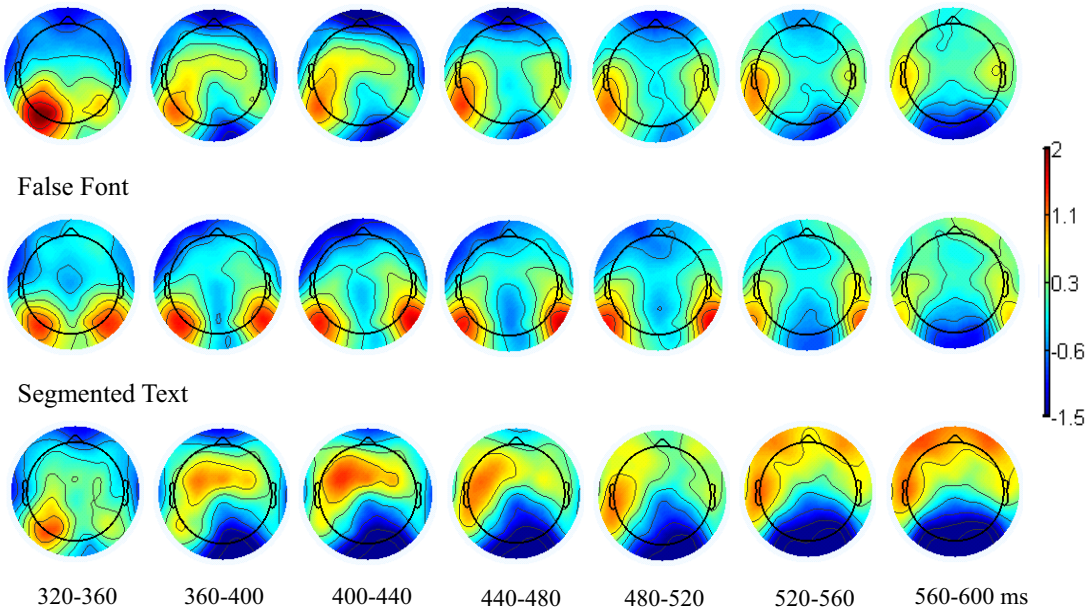


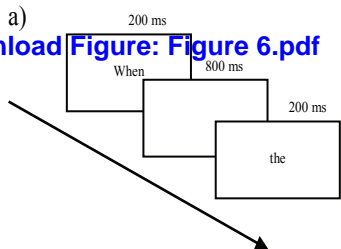
Figure 5  
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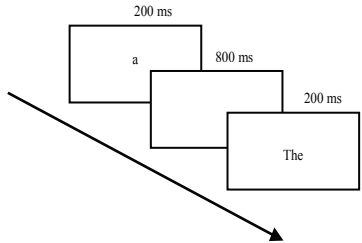


**Figure 6**

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b)



c)

