ANALYSIS OF EVENT RELATED POTENTIALS IN A WORD RECOGNITION EXPERIMENT WITH FLUENT AND DYSFLUENT READERS

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In this work, we have analyzed the EEG recordings from a word recognition experiment undertaken by both fluent and dysfluent readers. By comparing the ERP (Event related potential) responses to words, pseudowords, and other visual stimuli we have collected evidence for both serial and parallel word recognition processes as well as their temporal activation. Characters as well as other symbols can be seen to activate the visual word form area. The sequence of characters is then recognized as a word in a process that shows a frequency effect between rare and common words, characteristic of parallel recognition. We are able to show that while semantical access would be started for common words, pseudowords show a simultaneous higher activation in a previously known serial word recognition pathway. The serial control regions also show a difference between fluent and dysfluent readers, but this difference reaches statistical significance in our data only at a relatively late time point and a single type of stimulus. More data would be needed to study the dysfluent reading process in more detail. Overall, our findings can be taken to support the dual models of serial and parallel word recognition presented in the literature.

Keywords: EEG, ERP, dyslexia, word recognition, dual route model

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Tutkimuksessa on analysoitu EEG-mittauksia, jotka on tehty sanantunnistuskokeen aikana sekä dyslektisille että sujuville lukijoille. Vertaamalla herätevastepotentiaaleja (Event-Related Potential, ERP) sanoille, pseudosanoille ja muille visuaalisille herätteille on työssä saatu tuloksia, jotka näyttävät sanantunnistusprosessin sisältävän sekä sarjallisia että rinnakkaisia piirteitä ja hahmottelevat näiden ajallista esiintymistä. Aineiston perusteella sekä kirjaimet että muut symbolit aktivoivat visuaalisen sananmuotoalueen (Visual Word Form Area, VWFA). Voidaan havaita, että kirjainjono tunnistetaan sanaksi prosessissa, jossa yleiset sanat tunnistetaan nopeammin kuin harvinaiset. Tällainen frekvenssivaikutus viittaa rinnakkaiseen sanantunnistukseen. Toisaalta ajanhetkellä, jolla sanojen tulkinta on jo pitkällä, havaitaan pseudosanoille korkeampaa aktivaatiota sarjallisen sanantunnistusreitin alueella. Sarjallisen sanantunnistamisen aivoalueilla havaitaan myös vähäinen ero dyslektisillä ja sujuvilla lukijoilla, mutta tämä ero saavuttaa tilastollisen merkitsevyyden vasta suhteellisen myöhäisessä vaiheessa ja rajoittuu yhteen herätetyyppiin. Tarvittaisiin enemmän mittauksia, jotta dyslektisten lukijoiden sanantunnistusprosessia voitaisiin tutkia yksityiskohtaisemmin. Tutkimuksen tulosten voidaan katsoa tukevan kirjallisuudessa esitettyjä sanantunnistuksen duaalipolkumalleja, joissa on sekä sarjallinen että rinnakkainen osa.

Avainsanat: EEG, ERP, dysleksia, sanantunnistus, duaalipolkumalli

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1. INTRODUCTION

Dyslexia is a developmental disability influencing word recognition accuracy and fluency. It is commonly related to developmental deficits in processing phonemes and thus has a neurobiological basis (Lyon, Shaywitz & Shaywitz, 2003). Developmental dyslexia appears despite of normal intelligence, motivation and adequate reading instruction (Ferrer, Shaywitz & Shaywitz, 2010). Dyslexia is a chronic condition (Shaywitz, 1998) and its consequent effects on reading skills of the individual can result in lower learning motivation, school achievement and self esteem across lifespan (Raskind, Goldberg, Higgins & Herman, 1999). The prevalence of dyslexia is estimated to be between 5% and 17.5%, and it is thus the most common learning disability (Shaywitz, 1998).

In this work, we study the reading processes of dyslectic and fluent readers based on measurements of brain activity in a word recognition task. By using various stimuli not restricted to actual words, we can learn about how the visual information is processed to reach a decision. We are also interested in the differences between the two groups of participants, which may help in understanding how dyslexia affects different components of word recognition pathways in the brain.

1.1. The process of word recognition

Classical word recognition tasks can be used to indirectly study the brain processes involved in reading. In a typical word recognition task individual words are presented on a screen and the participant is instructed to read the word aloud. An other alternative is the lexical decision task, in which the participant has to decide whether the presented stimulus is a word or not (Meyer & Schvaneveldt, 1971). Time taken for word recognition, error rate, eye movements and various measurements of brain activity are among the possible readouts obtained from the experiment. With masked priming techniques, information on the time delays associated with different levels of processing can be obtained (Grainger & Holcomb, 2009). In masked priming, a second stimulus is

briefly flashed before the primary stimulus, and it has been shown that such a prime can facilitate the response for the primary stimulus.

Computational models of word recognition have been devised to formalize existing experimental knowledge. The Dual Route Cascaded model (DRC) (Coltheart, Rastle, Perry, Langdon & Ziegler, 2001) and Connectionist Dual Process model (CDP+) of Perry, Ziegler and Zorzi (2007) both include two main routes. The non-lexical route relies on serial processing in either the grapheme-to-phoneme (DRC) or the letter-to-grapheme (CDP+) mapping and is needed to read nonwords. The lexical route performs more efficient parallel processing and is responsible for, for example, correct mapping of irregular words.

Information on the brain regions involved in the process of word recognition has traditionally been obtained by studying connections between lesions and language-processing deficits (Martin, 2003).

Imaging methods such as PET and fMRI are based on an indirect measurement of brain activity using the hemodynamic response as a proxy (Price, 2012). Three-dimensional reconstruction of the activity uncovers information on the brain areas related to tasks being performed.

Magneto- and electroencephalogram (MEG and EEG) are based on recording magnetic or electrical signals from electrodes on the scalp. Source localization can be used to infer imaging-like information from EEG as well. Accuracy is typically better with MEG (Michel et al., 2004).

Event-related potential (ERP) is a technique of obtaining activity profiles from EEG data by averaging measurements over a number of trials (Fabiani, Gratton & Federmeier, 2007). From the resulting ERP profile various components may be extracted. These components are commonly denoted by letter indicating their polarity (N or P) and their time of occurence or latency expressed in milliseconds after the stimulus. For example N400 is a commonly observed negative component occurring 250-500 ms after stimulus presentation (Kutas & Federmeier, 2000).

EEG, MEG and fMRI all show common regions of activation during word recognition tasks but some differences are also apparent.This is due to the fact that EEG and MEG measure neuronal activation more directly whereas fMRI relays on the blood oxygenation level -dependent (BOLD) signals (Vartiainen, Liljeström, Koskinen, Renvall, & Salmelin, 2011).

Eye movements (EM) can be used to study the reading process as well. For example, words that are easier to read typically have shorter fixation times (Rayner, 1998; Starr & Rayner, 2001). Since the fixation lengths are also affected by whether the word is a high-frequency or a low-frequency

one, it can also be seen that the lexical access must be underway by the time the fixation ends (Rayner, 1998). Eye movements can thus be used to understand the natural reading process even without an explicit word recognition task being performed.

In a number of studies, eye movements and ERP have been measured simultaneously to give further insight into the reading process (Sereno & Rayner, 2003) in several ways. First, fixation and saccade timing information allows the calculation of fixation-related potentials (FRP) by aligning the EEG signals with respect to fixation times (Dimigen, Sommer, Hohlfeld, Jacobs & Kliegl, 2011). These potentials are aligned with respect to subject activity and not stimulus presentation, which allows the study of reading full sentences instead of single words, as is typically the case. Second, direct eye movement effects may be removed from EEG data if needed. Third, the effects of different independent variables can be assessed separately for ERP and EM data for better reliability. Finally, for any effects observed we can compare the time of their occurrence to evaluate their possible meaning. For example, the ERP component N400 can be connected with word predictability, but EM measurements can be used to show that lexical access must have occurred much earlier (Dimigen et al., 2011).

1.2. Neural signature of reading and dyslexia

In the brain, word recognition creates activity in a number of areas. Occipital cortex shows bilateral activation in response to visual stimuli in general. In word recognition the left occipito-temporal cortex (LOT) shows early activation for all letter strings independent of their lexicality. Since within this area the left lateral occipito-temporal sulcus bordering the fusiform gyrus seems to respond more strongly to words than to e.g. consonant strings, it has also been called the visual word form area (VWFA) (Dehaene & Cohen, 2011). Further processing can be seen in areas of temporal cortex, parietal cortex and left inferior frontal gyrus (LIFG) (Vartiainen et al., 2011).

The time course of brain activation during a word recognition task has been studied by finding time points when various aspects of the stimuli affect the registered ERP signal. For example, word length and n-gram frequency show a difference at 90ms, indicating that combinations of letters are being processed by this time point (Hauk, Davis, Ford, Pulvermuller & Marslen-Wilson, 2006). It

has been found that word frequency shows an effect at around 110ms (Hauk et al., 2006). A difference between words and pseudowords has been found at 160ms (Hauk et al., 2006).

Dyslectic readers rely more on serial processing of visual stimuli during the reading process (Zoccolotti, 2009). This holds also in the case of individual words, at least for children (Hautala, Hyönä, Aro & Lyytinen, 2011). Even though there is some evidence that adult dyslectics may achieve whole word recognition, especially for pseudowords the word length continues to affect the time taken for word recognition (Moll, Hutzler & Wimmer, 2005).

There is evidence that dyslexia is related to developmental differences in neural networks integrating ortographic-phonological information (Blomert, 2011). In particular, Superior Temporal Gyrus (STG) and Superior Temporal Sulcus (STS) have been shown to respond differentially to congruent and incongruent letter-speech stimuli but this differential response is absent in dyslexic children (Blau, Reithler, van Atteveld, Seitz & Gerretsen, 2010).

Brain imaging studies of dyslectics show a pattern of increased activation in the inferior frontal cortex and disruptions in the functional integrity of ventral and dorsal components in left hemisphere posterior reading system (Pugh et al., 2000). The dorsal circuit (temporo-parietal) is responsible for the slower serialized reading whereas the ventral circuit (occipito-temporal) corresponds to the parallel processing route in the computational models described earlier (Pugh et al., 2001). According to a common model of developmental dyslexia (Richlan, 2012), the primary difficulty is in phonological decoding occurring in the dorsal circuit. This causes differences also in the function of the faster ventral circuit and compensatory overactivation in left inferior frontal gyrus.

1.3. Our approach

The data for this work comes from an experiment in which both EEG and eye tracker measurements are performed while the participants are performing a word recognition task.

Previously, the same task has been performed with eye tracker measurements only (Hautala & Parviainen, 2012). In this study, it was found that the deviation points of non-words occur slightly before the deviation points of pseudowords, indicating that orthographic and phonological processing occur in parallel. The location of the uniqueness point in a word was not found to have an effect

on the response, whereas the location of the deviation point in non-words and pseudowords was found to have a significant effect. The eye tracker response is slower in non-fluent readers, and the gaze is targeted more towards the initial point of the stimulus.

In this thesis, we report the results of a preliminary analysis of the ERP data recorded in the experiments. Our goal is to find the brain regions and time windows in which the word recognition process is taking place. In particular, we are interested in finding out how the serial and parallel reading pathway activity can be seen in the brain of both fluent and dysfluent participants, and how the results of this study relate to previous findings in the literature. The analysis of eye tracker measurements and combining information from ERP and eye tracker measurements is left for a future study.

2. METHODS

2.1. Participants

The target group consists of 32 native Finnish speaking adult participants. They have been recruited using a web-based questionnaire. The reading abilities of all the participants have been tested by the Assessment Battery for Reading Disabilities in Young and Adults (Nevala, Kairaluoma, Ahonen, Aro & Holopainen, 2006). Subtasks for standardized word reading, pseudoword reading and text reading were administered. Tests involving Rapid Automatized Naming (RAN) (Denckla & Rudel, 1974) were also administered.

Test scores used for defining the fluent and dysfluent participant groups were the number of words in the word list task, time in the text reading task and time in the non-word list task. In a language with regular orthography such as Finnish, dyslexia is commonly observed as a reduced reading rate, making the time variables relevant for our definition of dyslexia (Ziegler and Goswami, 2005). The reader was defined dysfluent if the participant performed at the lowest 11 percentiles in standardized scores in at least one of these three variables. Fluent readers are defined as performing above the 11th percentile in all the three variables. After taking out 7 cases where proper EEG data

was not recovered for technical reasons, there were 25 participants, 9 of which were assigned to the dysfluent and 16 to the fluent subgroup.

Table 1 shows the data used for defining the dysfluent participant subgroup. WL_time is the time taken in the word list task, Text_words is the number of words read in the text reading task and NWL_time is the time taken in the non-word list reading. For each of these variables, a group column is shown indicating the percentile range of performance in the test. A higher group number indicates a better performance, with groups 1 and 9 containing 4%, groups 2 and 8 containing 7%, 3 and 7 containing 12%, 4 and 6 containing 17% and group 5 containing 20% of scores in the population standard. A cross in the dysfluent column indicates a dysfluent reader according to the criterion described above.

Table 1. Test scores for the participants for the three variables used in determining the dysfluent subgroup. Both raw data and percentile groups are shown.

ID	WL_ time (s)	WL_ time (group)	Text_ words	Text_ words (group)	NWL_ time (s)	NWL_ time (group)	Dysfluent?
5	22	6	378	5	39	7	
8	27	4	283	2	63	3	X
10	26	5	295	2	58	3	X
13	35	2	319	3	47	5	X
27	34	2	343	4	78	1	X
41	30	3	362	5	89	1	X
42	22	6	321	3	42	6	
43	32	3	281	2	79	1	X
44	37	1	303	2	69	2	X
45	31	3	347	4	57	3	
46	30	3	287	2	70	2	X
47	32	3	361	5	56	4	
49	22	6	306	2	70	2	X
53	12	9	406	6	21	9	
55	23	6	402	6	36	8	
56	16	9	388	6	23	9	
58	13	9	416	7	38	7	
59	14	9	388	6	28	9	
60	22	6	353	5	62	3	
61	19	7	443	8	58	3	
62	15	9	452	8	28	9	
65	23	6	368	5	55	4	
101	16	9	428	7	40	6	
102	20	7	445	8	52	4	
104	18	8	390	6	38	7	

2.2. Experimental procedure and EEG recording

Each participant performed the tasks two times over the course of four months. In the first session, tests for fluency of reading were performed in addition to the word recognition task. For the statistical analyses of this thesis, only the recordings from the first session were included.

In each trial, a cross-shaped cue was presented in the middle of the screen in the horizontal direction and 25% down from the top in the vertical direction. The cross was black on a white background. After the cue and the delay of 1000 ms a stimulus was presented at the same location. The task of the participant was to indicate whether the stimulus is a word in Finnish or not. The responses were given by pressing a button if the answer was positive. The size of the stimuli was 0.57 visual degrees. In each block of trials there were 100 stimuli. The participant performed eight blocks of trials in a session with short pauses. Out of the 800 stimuli presented overall, there were 100 stimuli of each type used (see Section 2.3 for the stimulus types).

EEG signals were recorded using Electrical Geodesic Inc. (EGI, http://www.egi.com) HydroCel sensor net equipment with 128 channels using Ag-AgCl electrodes. Electrical Geodesic photogrammetry system was used to localize EEG sensor positions during the measurement. Sampling rate used in the recording was 1000Hz. Electrical Geodesic NetStation 4.2.1 computer program was used for recording the EEG measurements. The measurement data was referenced to the Cz electrode. Before the recording, we tried to keep the electrode impedances below 50 kΩ (Ferree, Luu, Russell & Tucker, 2001). The measurement was monitored throughout the experiments, and whenever excessive deviations from the baseline were observed, the electrodes in the sensor net were checked and adjusted.

2.3. Stimuli in the word recognition experiments

In the experiments, we have used words, pseudowords, nonwords, symbols and bars as stimuli. Nonword stimuli were only used for the second session for each participant, and these stimuli were consequently not included in the analyses of this thesis.

The stimuli of the first session analyzed in this work contains eight classes of stimuli: low- and high-frequency words, early and late deviation point pseudowords, early and late uniqueness point words, symbols and bars. For each type of stimulus, we have a set of 100 stimuli that are presented in the experiments.

A horizontal bar is used as a simple stimulus to discover the baseline visual response in contrast to character or other symbol strings. The light gray bar had a size corresponding to the words presented as stimuli.

Each symbol stimulus consists of a randomly generated sequence of symbols such that the length of the symbol sequence corresponds to the word length for other stimuli and the size of the symbol corresponds to font size for characters. Such symbol stimuli are used to study the brain regions and processes activated by non-character symbol strings.

Words are Finnish nouns of length 5, 6 and 7 letters. There are 100 high frequency and 100 low frequency words in the stimulus set. High frequency words are those that occur frequently in a large corpus in Finnish (Kotimaisten kielten tutkimuskeskus, 2007). High-frequency and low-frequency word responses are compared to study the effect of word frequency in the word recognition process. There are two further classes of word stimuli, one with early and the other with late uniqueness points. The uniqueness point is the first location of the word when the initial segment up to that point has a unique match in the corpus. Early and late uniqueness point stimuli are not used in the statistical analysis of this thesis. Descriptive statistics for the word stimuli are shown in table 2.

The set of pseudowords is created by taking words in Finnish and replacing either the first or the last letter by another one that is phonotactically in agreement with the Finnish language. The deviation point of the pseudoword is defined as the first location where the initial segment of the word up to that point has no matches in the corpus. The uniqueness points and deviation points were determined and neighbor words found using The Neighborhood Watch program (Davis, 2005). The full set of pseudowords consists of 200 words of 5, 6 and 7 letters. The 200 pseudowords consist of 100 early deviation point and 100 late deviation point pseudowords. The pseudowords are used in this thesis to evaluate the degree of serial and parallel word recognition processes in use by studying the effect of deviation point location. Descriptive statistics for the pseudoword stimulus set used in the experiments can be found in tables 3 and 4.

The set of nonwords is generated with a process similar to the set of pseudowords, but the replacement letters are consonants which are not used in native Finnish words (q, w, d, f, g, z, x, c, b). The nonword stimuli are not used in the statistical analysis of this thesis.

Table 2. Descriptive statistics of word stimuli. Word frequency is reported as the number of occurrences in a million words. Bigram frequency is the average in a million words. Uniqueness point denotes the letter position at which the uniqueness point is located.

		Low frequency	High frequency	All words
N		100	100	200
Frequency	mean	0.3329	36.38	18.36
	std	0.1523	122.79	88.47
Neighbors	mean	2.04	2.03	2.04
	std	2.309	2.007	2.158
Bigram frequency	mean	8754.73	9880.04	9317.39
	std	4153.37	4630.75	4423.59
Uniqueness point location	mean	5.38	5.71	5.55
	std	0.488	0.456	0.499

Table 3. Descriptive statistics of early and late deviation point pseudoword stimuli. Word frequency is reported as the number of occurrences in a million words for the word used as a basis of pseudoword construction. Bigram frequency is the average in a million words.

		Early deviation point	Late deviation point	All pseudowords
N		100	100	200
Frequency	mean	9.57	14.33	11.95
	std	18.75	37.74	29.82
Neighbors	mean	1.78	2.41	2.10
	std	1.767	2.212	2.021
Bigram frequency	mean	8332.62	9491.90	8912.26
	std	4416.16	4722.33	4597.18

Table 4. Descriptive statistics of pseudoword sublexical frequencies.

		Early deviation point	Late deviation point	All pseudowords
N		100	100	200
First bigram frequency	mean	11518.25	14451.27	12984.76
	std	12642.20	13333.48	13042.87
Middle bigram frequency	mean	10498.19	11965.71	11231.95
	std	10666.54	9742.70	10215.89
Late bigram frequency	mean	9733.73	6534.56	8134.14
	std	16388.19	10073.57	13662.59
First trigram frequency	mean	43.9336	2119.38	1081.65
	std	290.41	3323.63	2572.89
Middle trigram frequency	mean	2171.07	1584.28	1877.68
	std	4596.95	2563.45	3724.04
Late trigram frequency	mean	2731.07	1640.60	2185.83
	std	4938.53	4293.63	4647.94

2.4. Data processing

BESA 6.0 software was used for initial processing of the EEG data and for calculating the event related potentials (ERP) (http://www.besa.de). Before any processing, the recordings were filtered with a notch filter centered at 50Hz with a bandwidth of 2Hz to attenuate electrical noise from the environment.

Bad channels were first found by visual inspection of the data and they were interpolated from the surrounding electrodes by spherical spline interpolation in BESA (Perrin, Pernier, Bertrand & Echallier, 1989). Consequently, a 60 second window was located from each measurement such that the window contains at least 8 time instants that show a profile suggesting eyeblink activity and lit-

tle other variation. From this time window, Independent Component Analysis (ICA) was calculated using built-in BESA functionality. The component that best seemed to agree with the eyeblink activity was visualized as a topographical map (see Fig. 2). If the topographical map confirmed that the activity is concentrated around the eyes, this component was selected to represent the eyeblink artefact and removed from the data before further processing took place (see Fig.1).

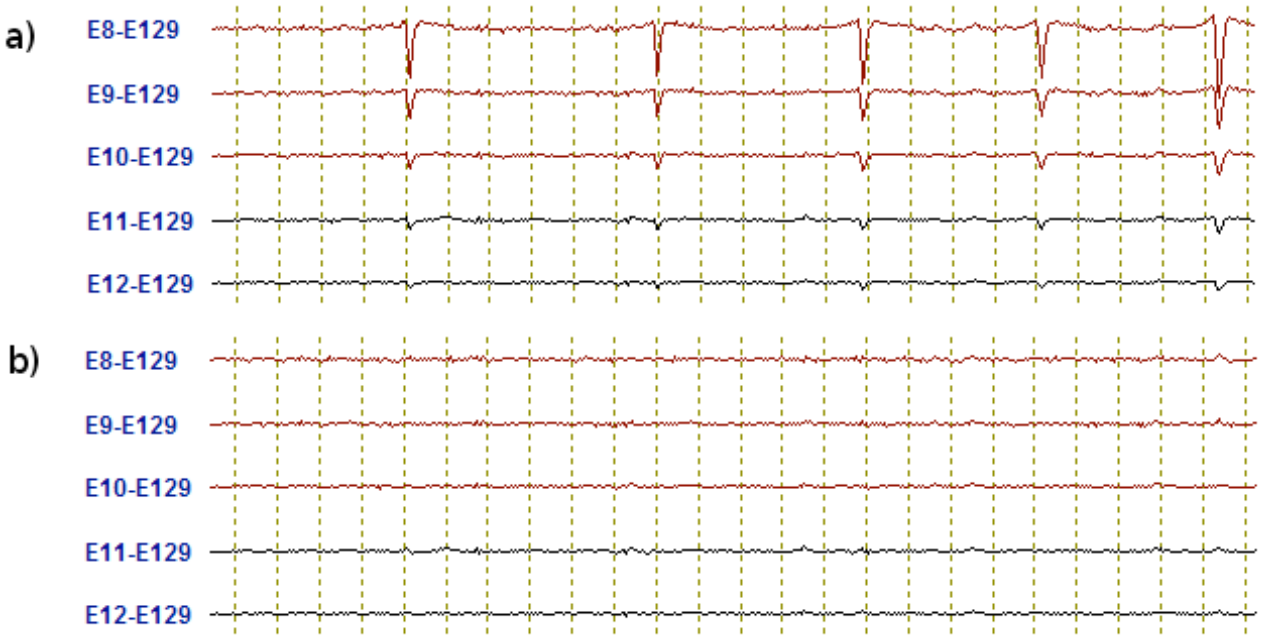

Figure 1. Example of eyeblink correction, where panel a contains a part of one of the original measurement for five channels and panel b contains the same segment and the same channels after eyeblink correction.

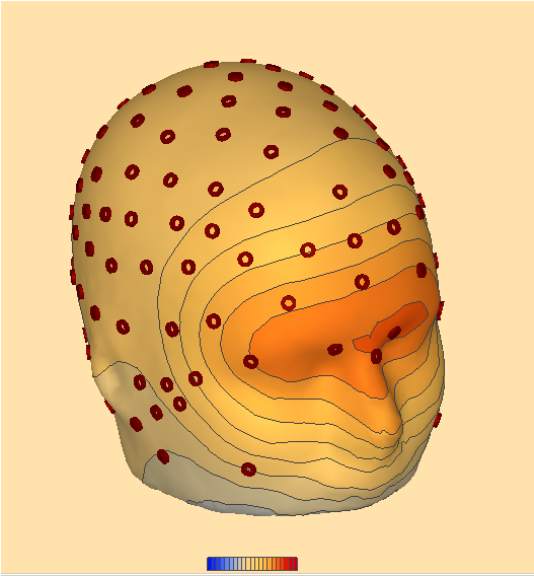

Figure 2. An example figure showing the constructed eyeblink artifact pattern for a single participant.

Event related potentials are calculated from the EEG data for each channel by aligning the measurements with respect to time point of stimulus presentation and averaging over an epoch from -200ms to 1000ms of stimulus presentation. For each averaging, we monitored the number of trials BESA accepted as being of good enough quality with the default settings, and interpolated more channels one by one as long as the rate of accepted trials was less than 80%. For most participants, the 80% level of accepted trials was reached. The ERPs are calculated for each participant and stimulus type separately. In addition, grand average ERPs for both fluent and dysfluent participants are calculated by averaging the ERPs corresponding to each type of stimulus over all the participants in the group. The grand averages are used for visualizing ERPs in the following analyses. Full set of ERPs is used in the statistical analyses comparing responses to different stimuli and to same stimulus type between fluent and dysfluent readers. In all the statistical analyses, only the trials where the participant gave the correct response were included. For the statistical analyses, the epoch from 0ms to 800ms was selected from the data.

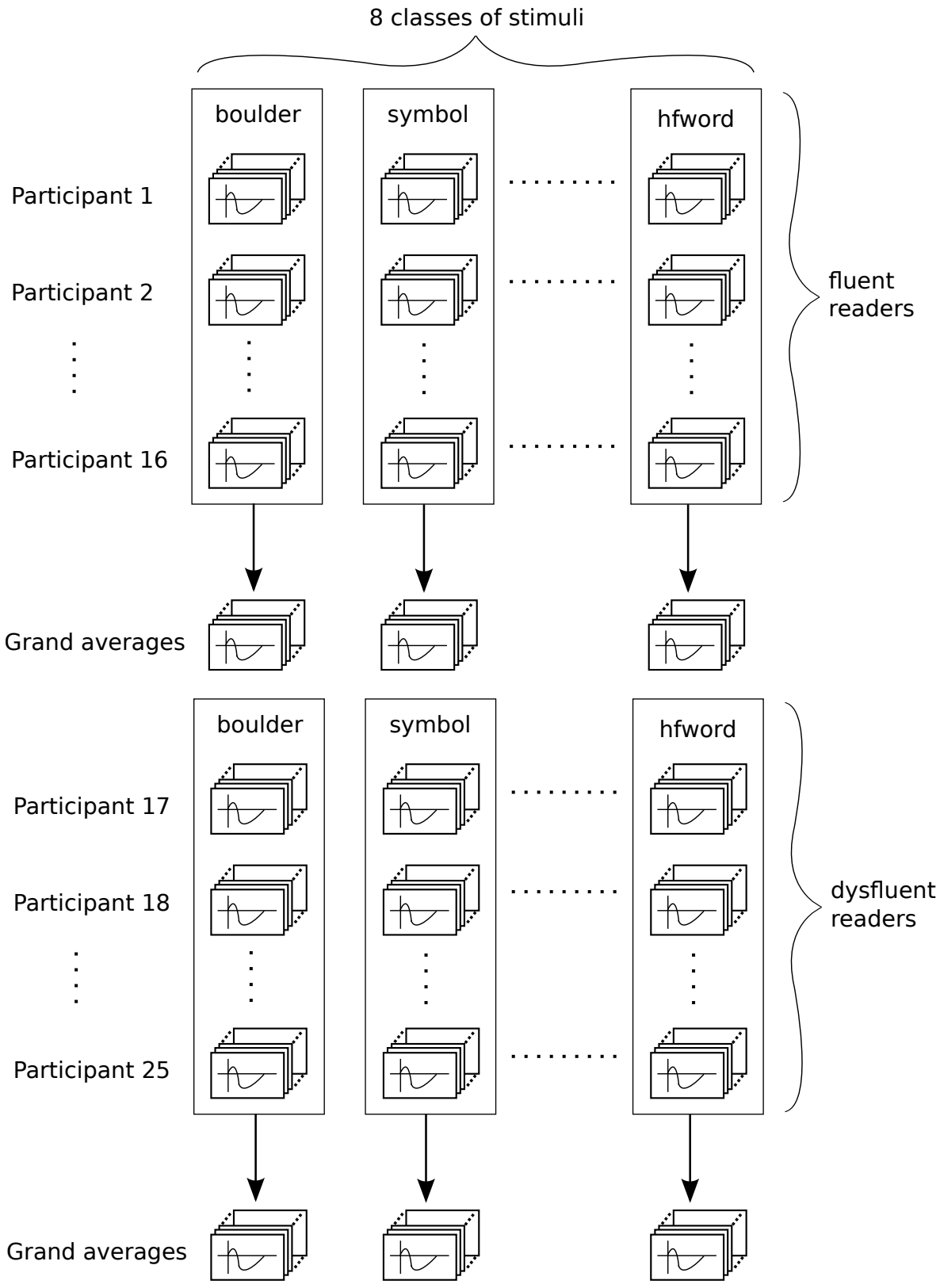

Figure 3. ERPs were first calculated for each participant and stimulus type separately. Each stack of ERPs in this figure represents the ERPs for all the 128 channels in the experiments. Grand average ERPs were calculated as averages over all the fluent and all the dysfluent readers and used for illustrations, whereas the full set of ERPs was used for statistics.

BESA Statistics is used to find clusters of electrodes and timepoints for which significant differences are observed between the responses of two types of stimuli or the same type of stimuli for fluent against dysfluent readers. The method for finding the clusters and assessing their statistical significance is reported in (Maris & Oostenveld, 2007). First, unpaired (comparisons between fluent and dysfluent subjects) or paired (comparisons of different stimuli for either fluent or dysfluent subjects) t-test is performed for each electrode and timepoint separately. The electrodes which reach significance at this initial stage are then clustered in time and space, giving contiguous regions of significant electrodes, changing in configuration with time. For each cluster, what is called the cluster value is computed by summing all the individual t-test statistics within the cluster.

As a final stage, the cluster value is used to calculate a statistical significance for the cluster. In order to calculate a p-value, permutations of class labels are used to calculate 1500 (or less, if this many different permutations are not available) cluster values corresponding to data which should have no true positive clusters at all. The permuted data sets thus allow the calculation of a null distribution for the cluster values. To perform the permutation t-test, the location of the cluster value within the distribution of permuted statistics is found, and if e.g. a proportion of 0.01 of the permuted statistics have a higher value than the actual one, the p-value is 0.01. The calculations are performed separately for positive and negative clusters, corresponding to a positive or a negative difference between the cluster averages, calculated as the average voltage over all the electrodes in the cluster.

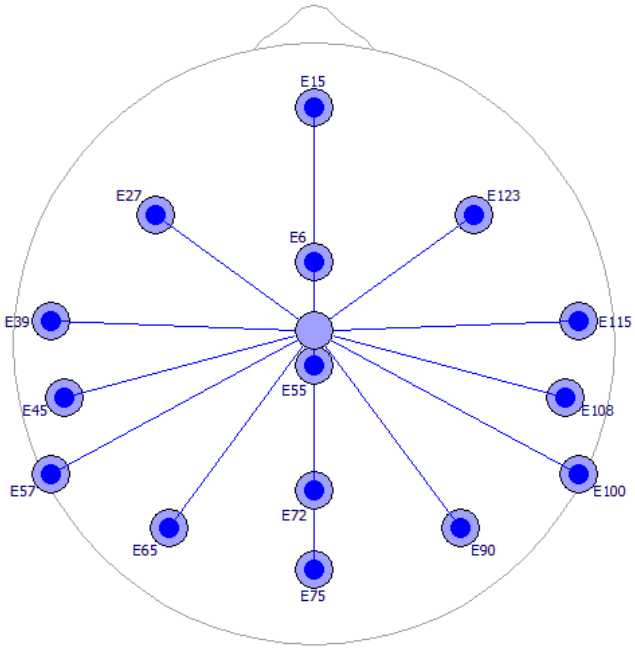

Figure 4. Electrodes selected for ERP visualization. All the electrodes are used for statistics, but this subset has been selected to simplify the representation of full ERP dataset in figures.

The statistical results are calculated for the full data collected from all the electrodes, but for visualizing the data in this work we have selected a representative set of 15 electrodes (Fig. 4), for which the ERP data is shown in the results section. This set has been selected based on a compromise allowing the presentation of the major features in all the statistically significant conclusions in this work.

The tables of significant clusters presented in the results contain a listing of all the clusters with a p-value less than 0.05. Out of these clusters, we focus our attention on the early clusters, which can be used to analyze different aspects of how different types of stimuli affect the word recognition process. Clusters occurring towards the end of our time period of observation or weakly significant clusters clearly not consistent with other results are not presented in detail in the results.

3. RESULTS

Using the methodology presented above, we compare the responses of different classes of stimuli and the responses of fluent compared with nonfluent readers. First, we compare the responses to

boulder, symbol and word stimuli in subsection 3.1. Next, we study the effect of word frequency in the responses in subsection 3.2. Finally, we study the difference in response to pseudowords compared with actual words and effects of deviation point location in pseudowords in subsection 3.3.

3.1. Comparison of boulder, symbol and word stimuli

First, we compare the response for simple visual boulder stimuli, symbol stimuli and word stimuli represented here by high-frequency words. Figure 5 shows the ERP responses from the set of representative electrodes. In the early occipital and occipito-temporal response, the symbol and word stimuli show a different pattern from the boulders starting at around 120ms, while later, boulders and symbols differ from words. The early difference between boulders and words is also illustrated in Figure 6 for the selected time point of 175ms. The latter grouping can also be seen in the frontal electrodes at later time points. Table 5 shows the significant clusters from BESA Statistics. Cluster 1 corresponds to the early difference continuing until around 500 ms. Electrodes in this cluster at 175ms are shown in Figure 7.

The early response differentiating symbols and words from the boulders corresponds to activation of the left occipito-temporal cortex, including the visual word form area represented by electrode 65 in Figure 7. It is of interest to note that the symbols seem to give rise to similar activation patterns with words in this area, confirming that the basic shape recognition process works similarly in both cases, in contrast with the boulder stimulus. Words can be distinguished from both boulders and symbols after around 175ms in the occipito-temporal cortex, and slightly later this difference can be seen throughout the brain, including the frontal cortex. This difference should, in part, arise already at the stage when the process of parallel interpretation of several symbols or characters starts. Later on, the decision-making process will make the response different in frontal areas as well.

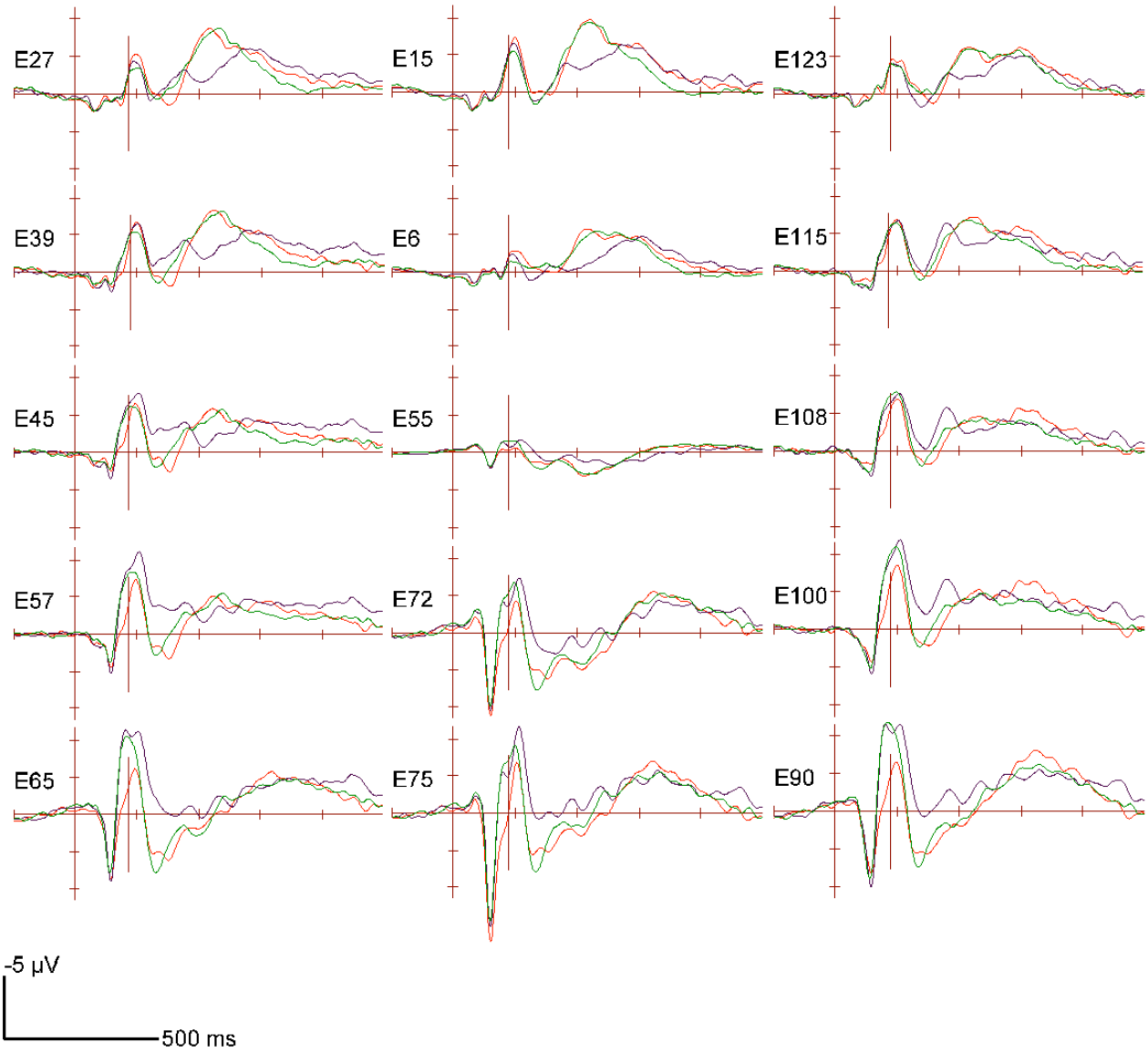

Figure 5. ERP responses shown for the selected subset of 15 electrodes. The black line indicates the response for words, the green line for symbols and the red line for boulders. The vertical line denotes the time point 175ms, which has been selected to highlight the difference between the boulder and word (and symbol) stimuli early on in the response (see Fig. 6).

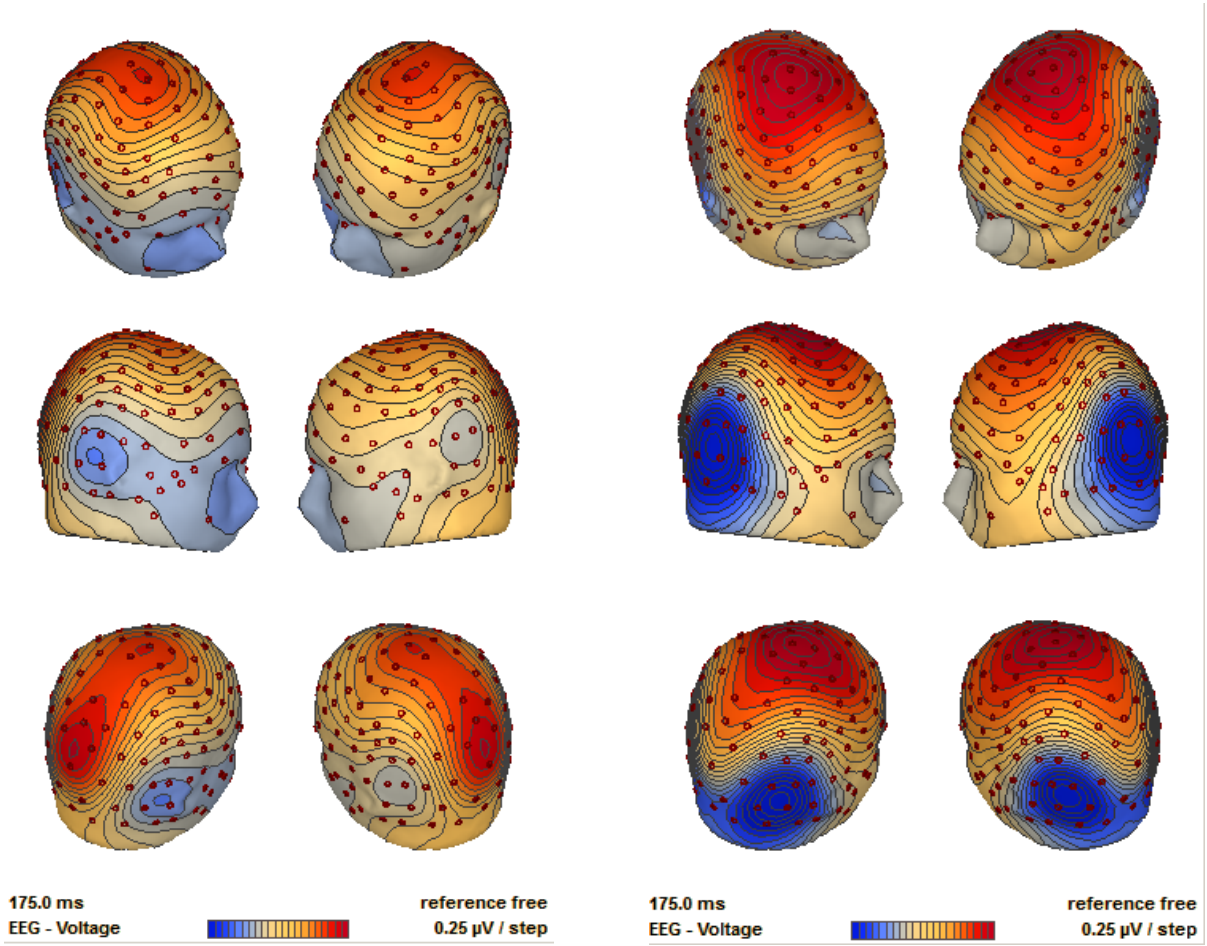

Figure 6. The difference between the voltage patterns at 175 ms shown for boulder (left) and high-frequency word (right) stimuli. In particular, a larger negative response can be seen in the occipito-temporal region for the word stimuli. This is indicative of ongoing symbol (character) -level recognition.

Table 5. Significant clusters found by BESA Statistics for the comparison of boulders with high-frequency words.

Cluster ID	p-value	Cluster value	Mean for bouldercor	Mean for hfwordcor	Start Time	End Time
Cluster 1	0	74038.5	0.594071	-1.69505	123	504
Cluster 2	0	-30103.7	-4.11708	-1.7736	366	534
Cluster 3	0.00133333	-9182.2	-2.27465	-1.18305	585	791
Cluster 4	0.00666667	-4818.21	-0.915322	0.260395	197	300

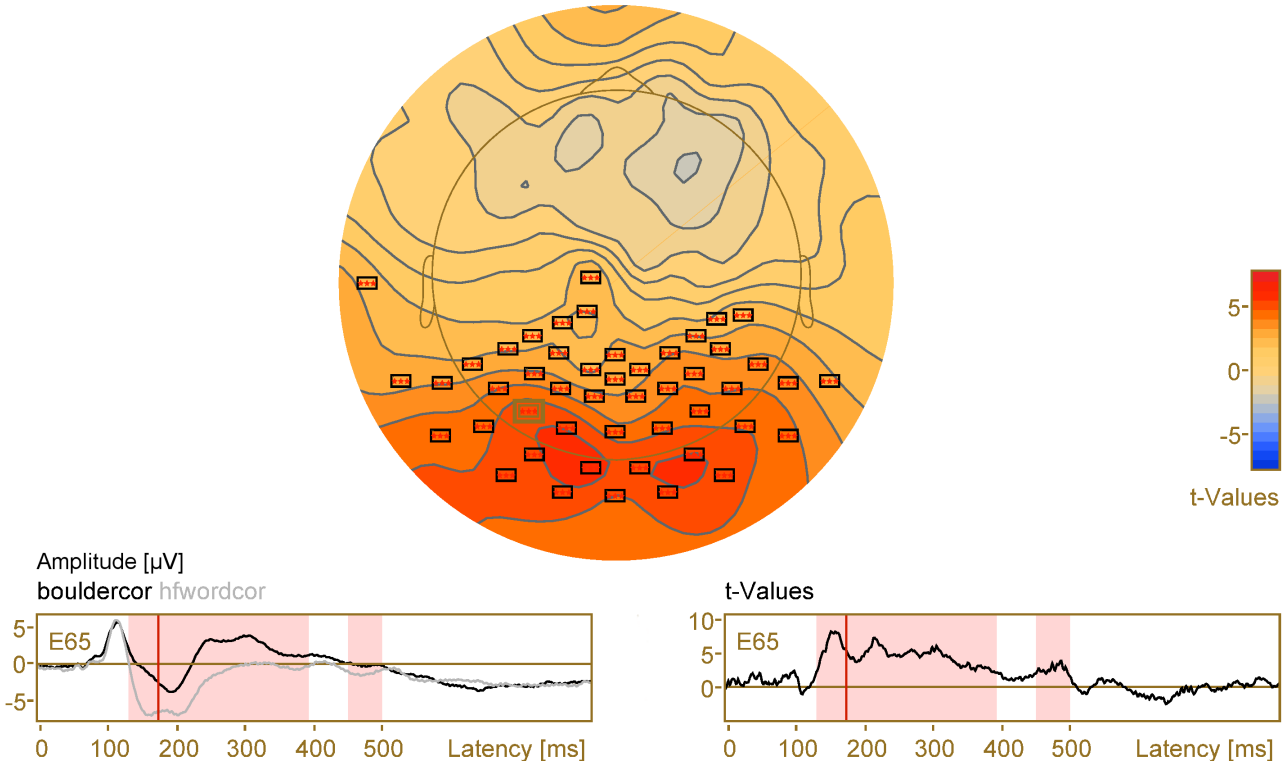

Figure 7. Cluster 1 from BESA Statistics comparing the boulder and high-frequency word stimuli. Top panel shows the cluster at 175ms, with t-values color-coded and electrode 65 highlighted. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The red bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

To separate these two effects, we also looked at the comparison between the symbol and high-frequency word stimuli. From the cluster results shown in Table 6, we can see the main cluster (cluster 1) start at 194ms. This is therefore the latest point at which the recognition process has moved from individual symbols to the full word level. The cluster starts from around the visual word from area and spreads to wide regions in the occipital and occipito-temporal cortices. There is, however, an earlier cluster 6 starting at 113ms. Even if this cluster is only borderline significant (p=0.035) and not very large in temporal scope, it is interesting to speculate that it might indicate an early recognition of the types of symbols being presented as a stimulus sequence. This hypothesis would be supported by the observed region of the cluster, which is located in the occipito-temporal cortex, where control mechanisms for serial processes reside (see Fig. 8).

These observations agree with known visual stimulus and word recognition processes, and show how symbols activate partly the same meaning-deciphering regions as the words do.

In a direct comparison between fluent and dysfluent readers, no significant differences were found for these stimuli.

Table 6. Significant clusters found by BESA Statistics for the comparison of symbols with high-frequency words.

Cluster ID	p-value	Cluster value	Mean for symbolcor	Mean for hfwordcor	Start Time	End Time
Cluster 1	0	46463.1	0.993366	-1.27359	194	487
Cluster 2	0	-31380.8	-4.17981	-1.81055	359	533
Cluster 3	0.0006667	29680.9	-0.885403	-2.29028	533	800
Cluster 4	0.008	-4143.83	-1.45032	-0.611312	584	764
Cluster 5	0.032	-1854.99	-0.17051	0.807997	227	302
Cluster 6	0.0353333	-1768.37	1.14745	2.13275	113	137

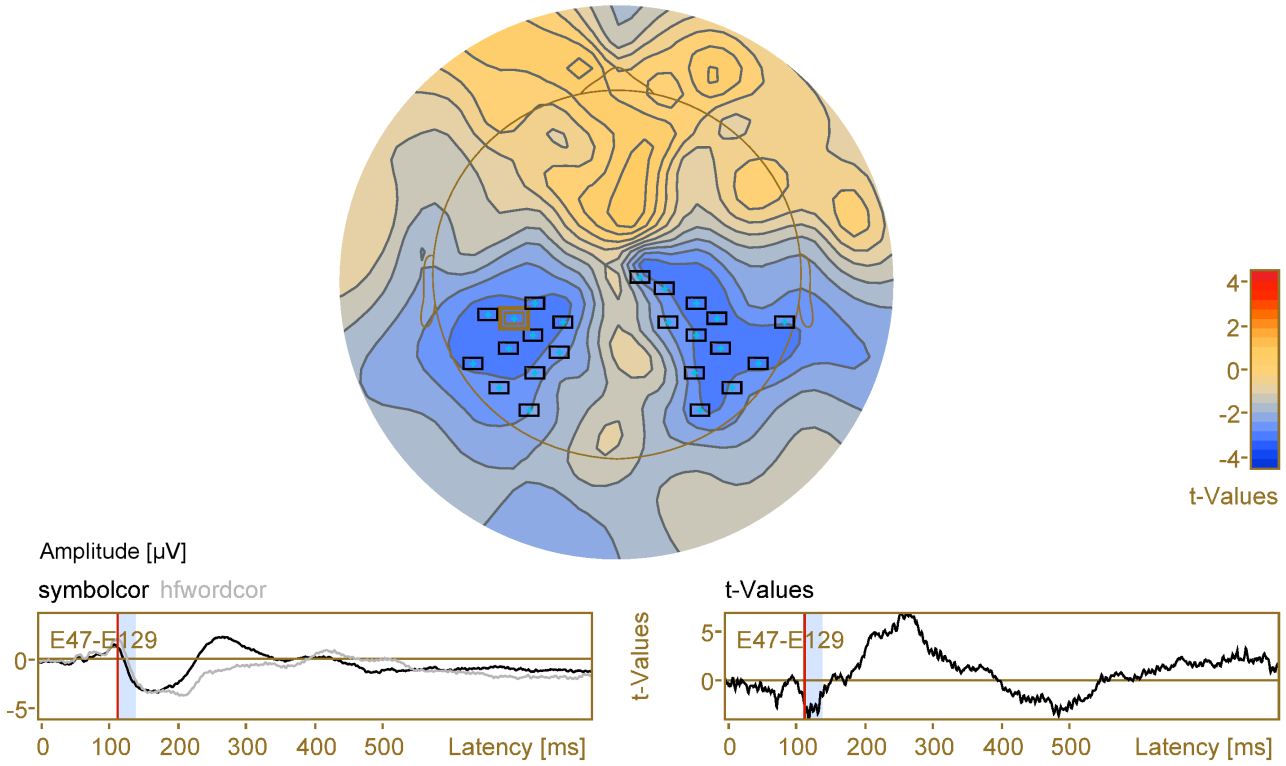

Figure 8. Cluster 6 from BESA Statistics comparing the symbol and high-frequency word stimuli. Top panel shows the cluster at 115ms, with t-values color-coded and electrode 47 highlighted. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The red bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

3.2. Word frequency effect

Next, we compared the responses between low- and high-frequency word stimuli. As can be seen from Fig. 9 showing the ERPs from the representative set of electrodes, the response at around 450 ms is faster for high-frequency words, suggesting that these are identified faster than low-frequency words. Figure 10 shows the voltage patterns at this time point, clearly showing the higher response for the more common words. Table 7 shows the significant clusters found by BESA Statistics, out of which cluster 1 is frontally located. This cluster is further illustrated in Fig. 11, with electrode E6 highlighted. As can be seen, the low-frequency words in the stimulus set have an average delay of around 50ms in their response in these frontal regions compared with the high-frequency words.

The frontal areas in which this cluster is centered are involved with high-level control of the word processing task and in preparing for the response. This is, however, not where the word recognition itself occurs.

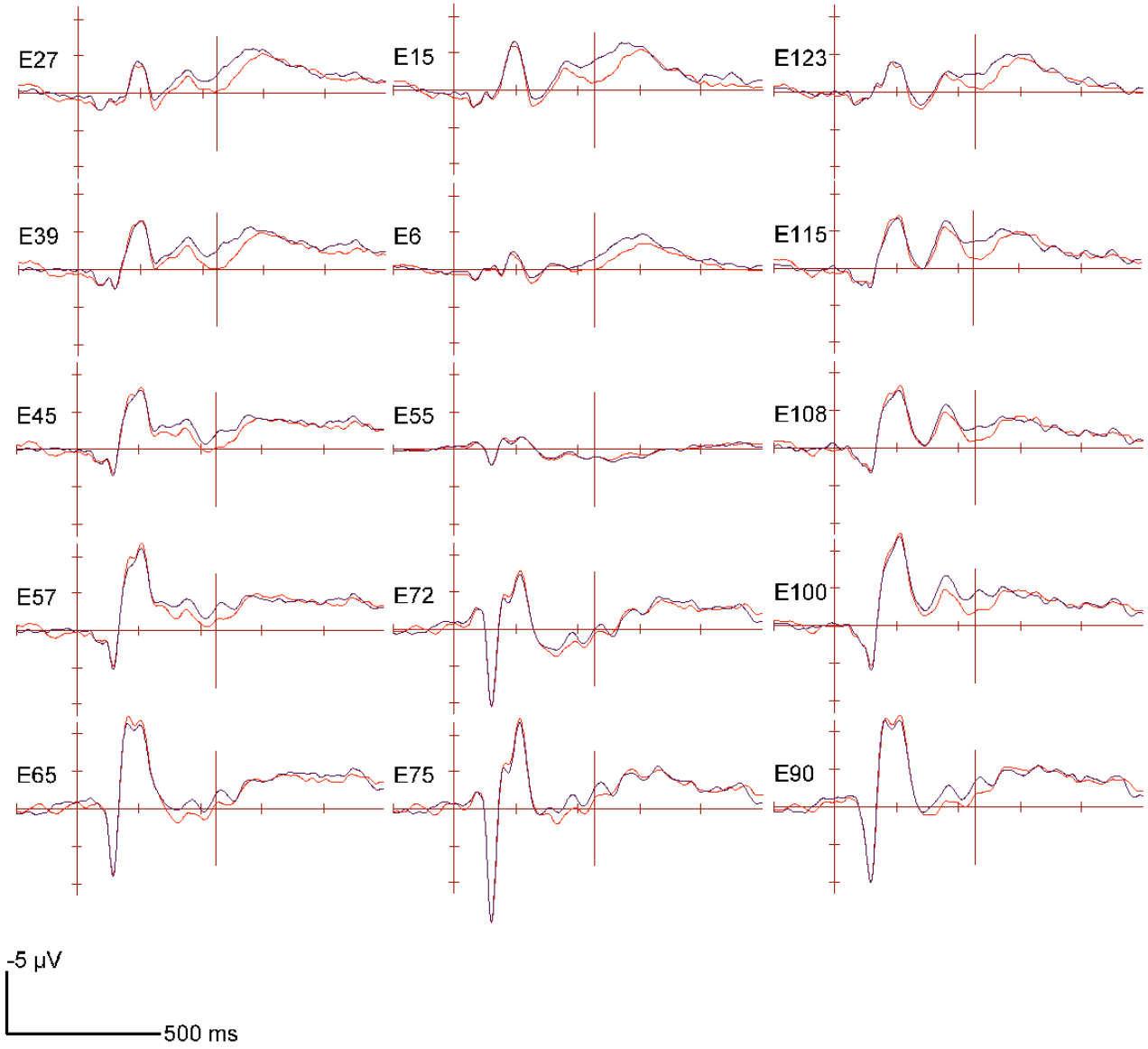

Figure 9. ERP responses shown for the selected subset of 15 electrodes. The black line indicates the response for high-frequency words and the red line for low-frequency words. The vertical line denotes the time point 450ms, which has been selected to highlight the difference between the low- and high-frequency stimuli (see Fig. 10).

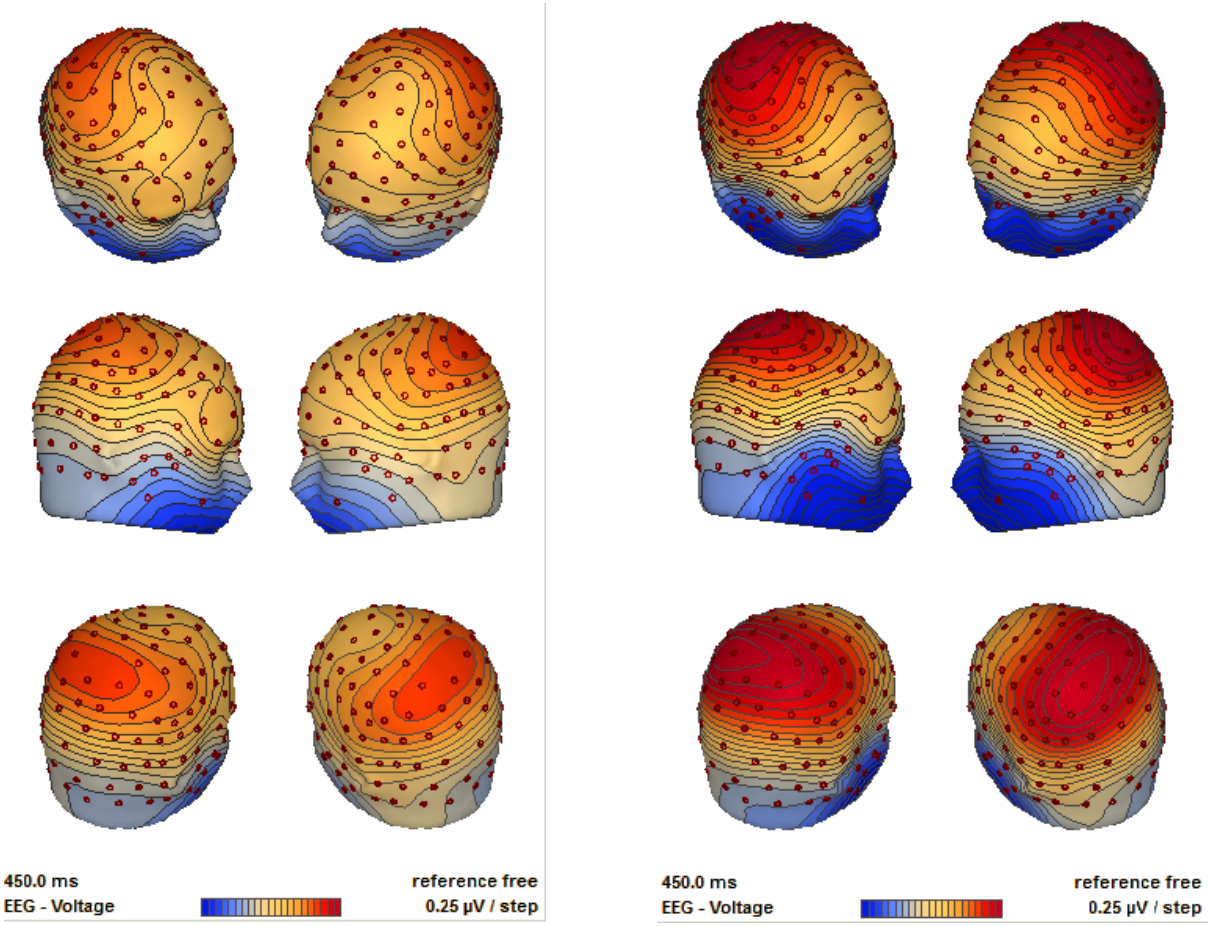

Figure 10. The difference in voltage patterns at 450ms for low- (left panel) and high-frequency (right panel) word stimuli.

The more widely dispersed cluster 3 in Table 7 suggests that the first statistically significant differences between the two classes of stimuli occur at 231ms. If word frequency had a real effect on the responses at this time, semantical access and therefore also word recognition must be well underway by this time point. However, since this cluster is only borderline significant, the starting time point of cluster 2, 299ms, can be taken to be a more definite limit on the time taken before semantical access begins to show its effects.

Table 7. The significant clusters found by BESA Statistics for the comparison between low- and high-frequency words.

Cluster ID	p-value	Cluster value	Mean for lfwordcor	Mean for hfwordcor	Start Time	End Time
Cluster 1	0	38045.1	-1.02212	-2.34623	397	585
Cluster 2	0.00066667	13821.7	-0.604646	-1.54208	299	398
Cluster 3	0.0406667	1486.63	0.566747	-0.230487	231	268

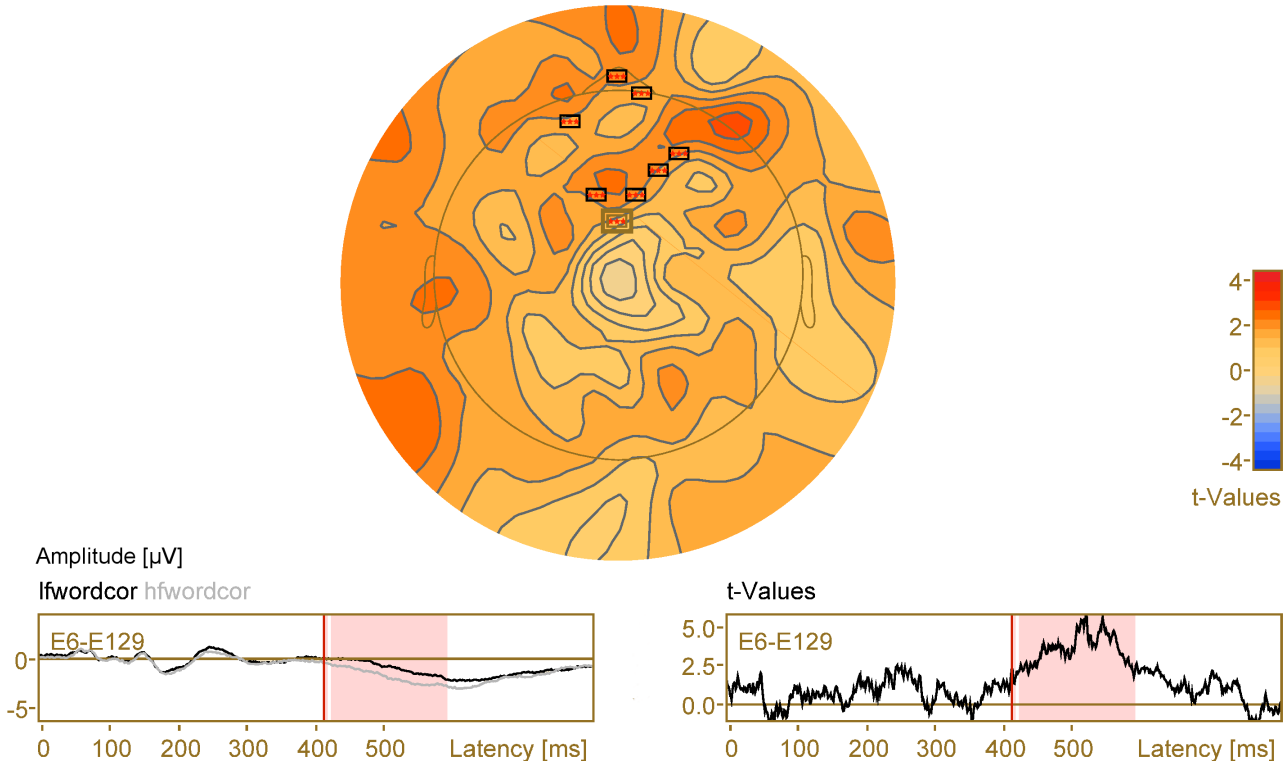

Figure 11. Cluster 1 from BESA Statistics comparing the low- and high-frequency word stimuli. Top panel shows the cluster at 411ms, with t-values color-coded and electrode 6 highlighted. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The red bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

3.3. Pseudoword response

Next, we looked at responses to pseudowords. Figure 12 shows ERPs from the set of representative electrodes for early and late deviation point pseudowords as well as high-frequency words for comparison. As a first observation, the late deviation point response is in part delayed after around 300ms compared with the early deviation point one, indicating that the location of the deviation point affects the recognition process and thus that there are characteristics of a serial process evident in the case of pseudowords. Figure 13 shows how the voltage patterns in the two cases differ at time point 310ms, when the early deviation point response clearly precedes the late deviation point one.

Table 8 shows the full list of clusters with statistically significant differences between the early and late deviation point responses. In this case, the electrode clustering results in a number of clusters with diverse locations and time periods. The earliest cluster starting before 100ms seems suspect and with p=0.019 can be considered a false positive. Cluster 4 starting at 185ms is the first likely timepoint when the early and late deviation point responses can be distinguished. Comparing this timepoint with our earlier observations, we notice that this is close to concurrent with the inferred time of when recognition moves from individual symbols to combining the information from sequences. This suggests that the difference at this point is due to differences in local statistical characteristics of the stimulus based on first observations being processed. For example, the difference at least in the beginning of this cluster may be based purely on the difference in the early trigram frequencies (see Table 4 in Section 2.3) between the two stimulus classes. This cluster also has a peculiar location in the right hemisphere parieto-temporal region.

The next significant cluster occurs at 281ms. Figure 14 shows this cluster 3 with electrode E57 highlighted. The cluster is localized around the parieto-temporal region, connected with the serial reading circuit in the dual pathway model. This is the cluster connected with the activation patterns of Fig. 13 referred to above.

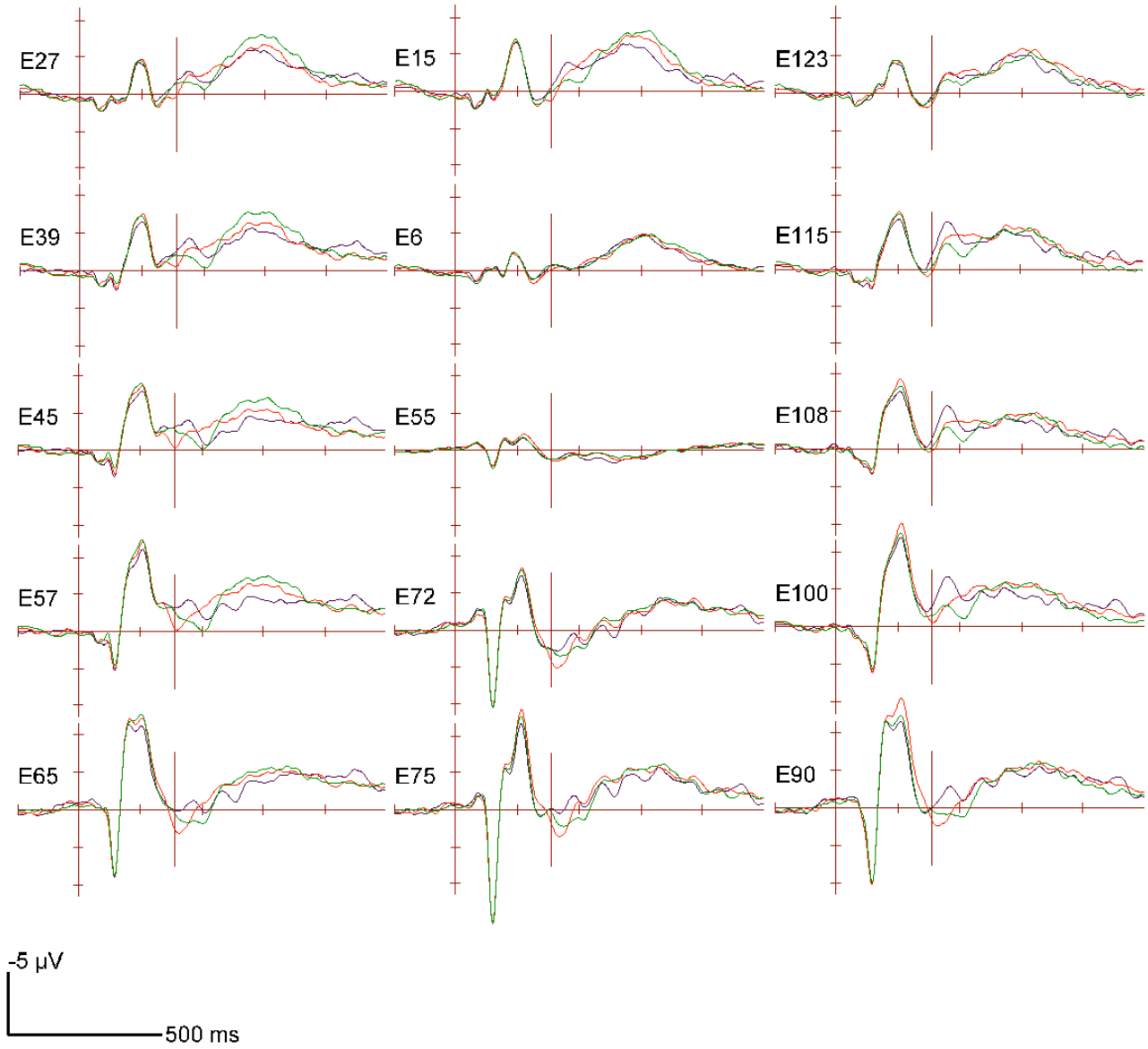

Figure 12. ERP responses shown for the selected subset of 15 electrodes. The black line indicates the response for words, the red line for early and the green line for late deviation point pseudowords. The vertical line denotes the time point 310ms, which has been selected to highlight the difference between the early and late deviation point pseudoword stimuli at the moment when the early response precedes the late one (see Fig. 13).

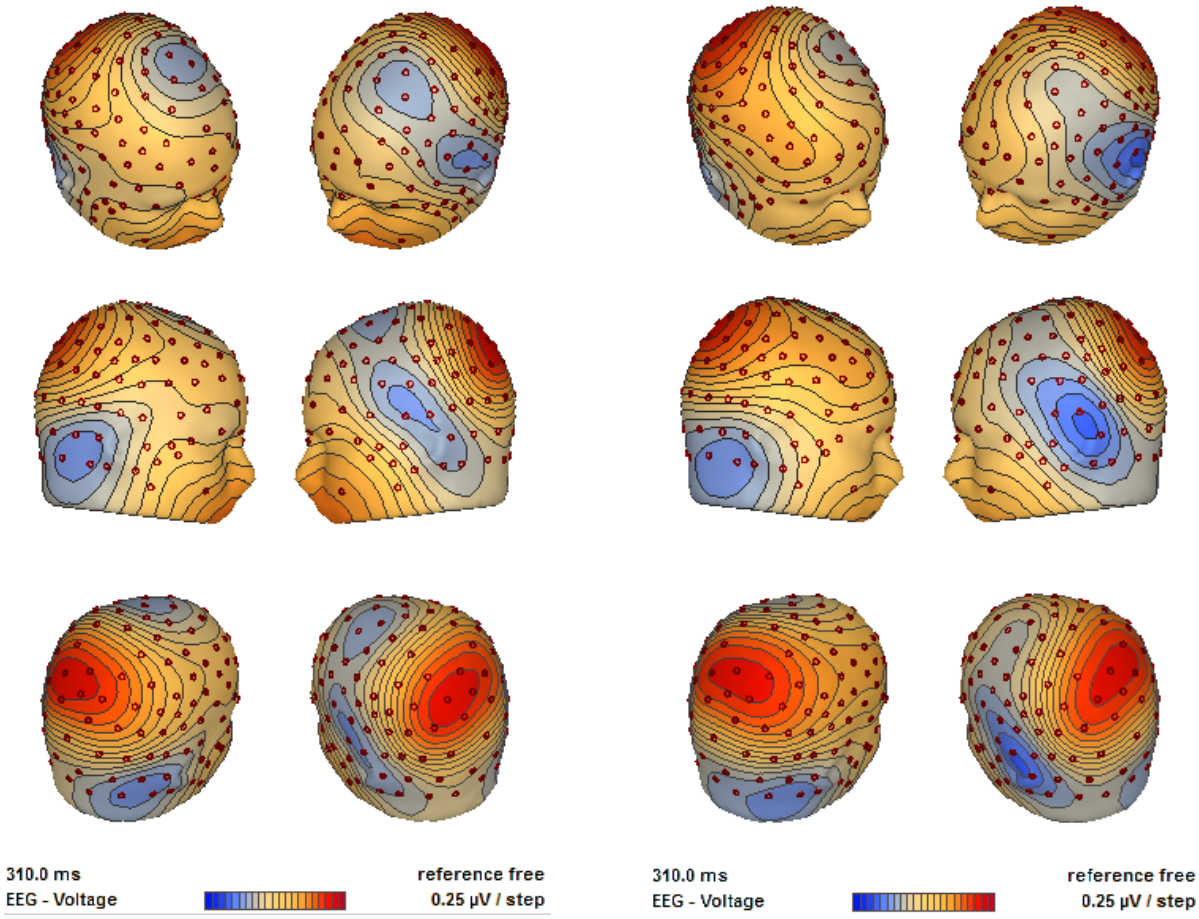

Figure 13. The difference in voltage patterns at ms for early (left panel) and late deviation point (right panel) pseudoword stimuli at 310ms .

Table 8. The significant clusters found by BESA Statistics for the comparison between early and late deviation point pseudowords.

Cluster ID	p-value	Cluster value	Mean for earlydpcor	Mean for latedpcor	Start Time	End Time
Cluster 1	0	-24931.6	-1.91212	-0.648372	346	497
Cluster 2	0	18883.2	-2.70581	-3.73284	456	735
Cluster 3	0.000666667	7698.05	0.925328	-0.0415051	281	354
Cluster 4	0.000666667	-6070.09	-3.70938	-2.78859	185	282
Cluster 5	0.0153333	-1404.63	-1.92809	-1.26863	722	754
Cluster 6	0.0193333	1387.68	0.750825	0.116025	86	103
Cluster 7	0.018	-1188.65	-4.53589	-3.40492	524	618
Cluster 8	0.02	-1052.81	-1.96345	-1.39966	778	800
Cluster 9	0.0313333	957.844	-0.925106	-1.72083	767	798
Cluster 10	0.0466667	-603.065	-2.01004	-0.801627	717	780

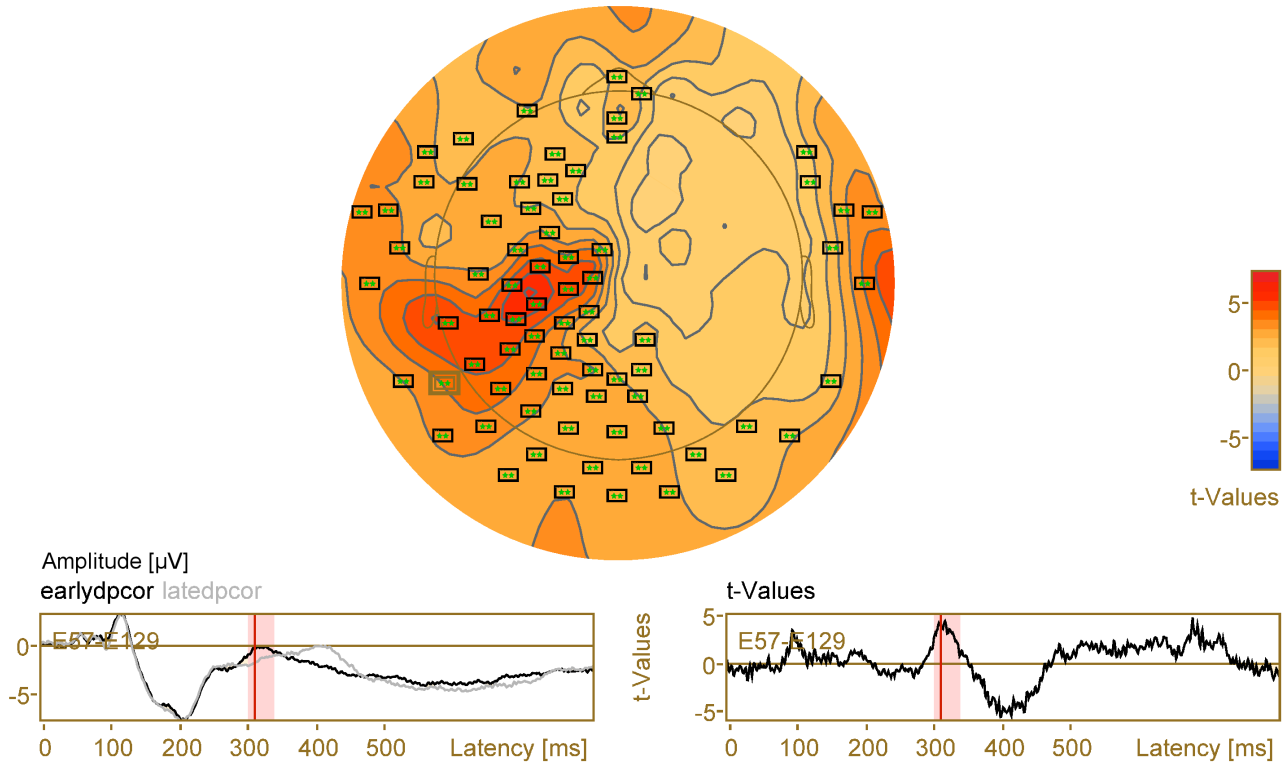

Figure 14. Cluster 3 from BESA Statistics comparing the early and late deviation point pseudoword stimuli. Top panel shows the cluster at 310ms, with t-values color-coded and electrode 57 highlight-

ed. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The red bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

The same region is implicated in the comparison between late deviation point pseudowords and high-frequency words, for which the significant clusters are shown in Table 9. Cluster 2 starting at 293ms is dispersed around the brain but temporally overlaps the significant cluster between early and late deviation point pseudowords. This is only just before the effects of semantical access were seen in our data, indicating that the late deviation point is not recognized until when the word interpretation is already starting to move into the semantical stage. Figure 15 shows cluster 1 at around 500ms with electrode E72 highlighted, showing that pseudoword and word responses also differ later on in the activation of this region of the reading circuit. At this point, the observation has presumably been confirmed as not being a word and the different activation at serial control regions shows that pseudoword processing indeed requires the serial pathway, used more whenever the word pattern is not recognizable with the quicker parallel mechanism. After this time point, the cluster moves to more frontal regions, indicating control mechanisms leading to response.

Table 9. The significant clusters found by BESA Statistics for the comparison between late deviation point pseudowords and high-frequency words.

Cluster ID	p-value	Cluster value	Mean for latedpcor	Mean for hfwordcor	Start Time	End Time
Cluster 1	0	-39357.2	-3.3772	-1.97742	417	729
Cluster 2	0	26535.5	-0.47415	-2.0464	293	435

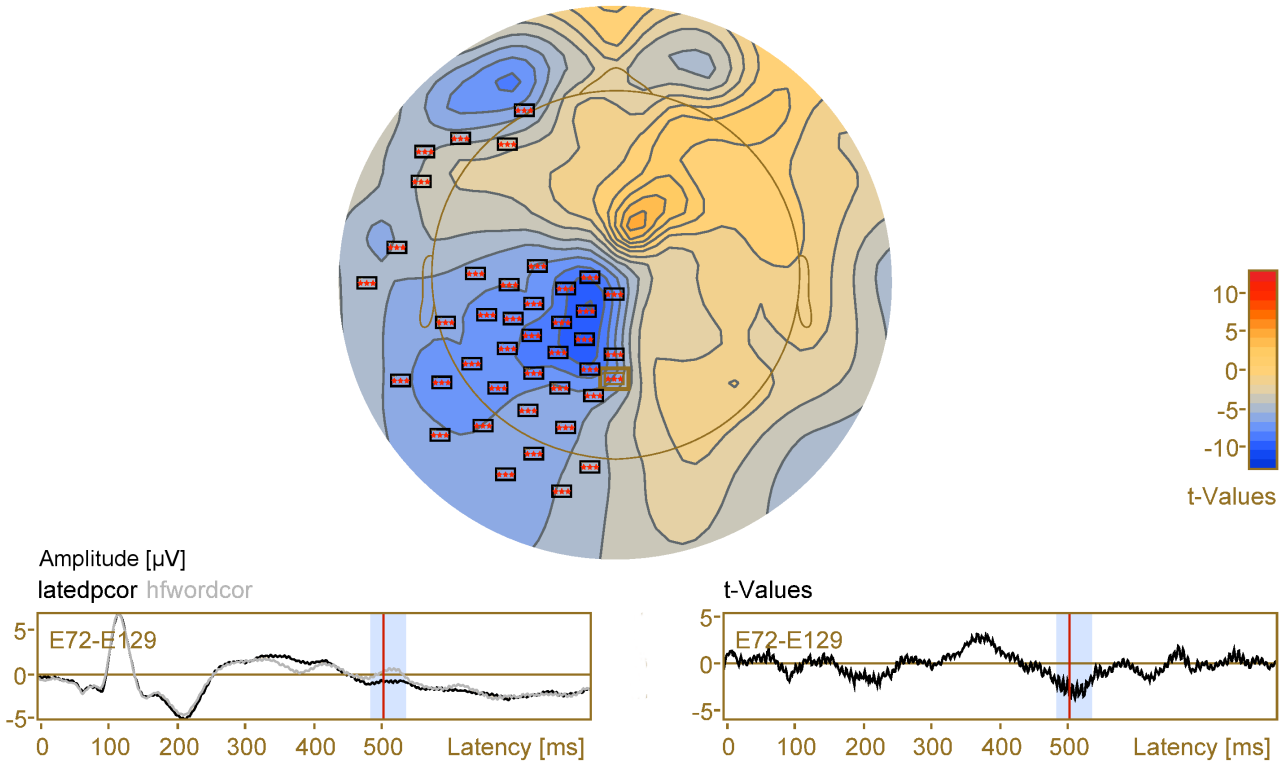

Figure 15. Cluster 1 from BESA Statistics comparing the late deviation point pseudoword and high frequency word stimuli. Top panel shows the cluster at 500ms, with t-values color-coded and electrode 57 highlighted. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The red bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

Finally, we looked at pseudoword responses for dysfluent readers. ERPs from the selected set of representative electrodes are shown in Fig. 16. Performing a statistical test between late deviation point responses in fluent and dysfluent readers results in the only statistically significant cluster obtained in such unpaired comparisons for any set of stimuli (Table 10). Figure 17 shows this cluster with electrode E72 highlighted. The difference between fluent and dysfluent readers is localized in the parietal cortex, in both left and right hemispheres and occurs after 573ms. Due to our limited amount of data from dysfluent readers, the only significant difference is observed at such a late time, presumably after most of the interesting steps in the recognition process have already taken place. At this time point, the fluent readers' recognition result is already on its way to becoming a response. Since the difference is localized at the regions connected with serial control processes, it can however be considered an indication of differential activation of the serial word recognition pathway in dysfluent readers.

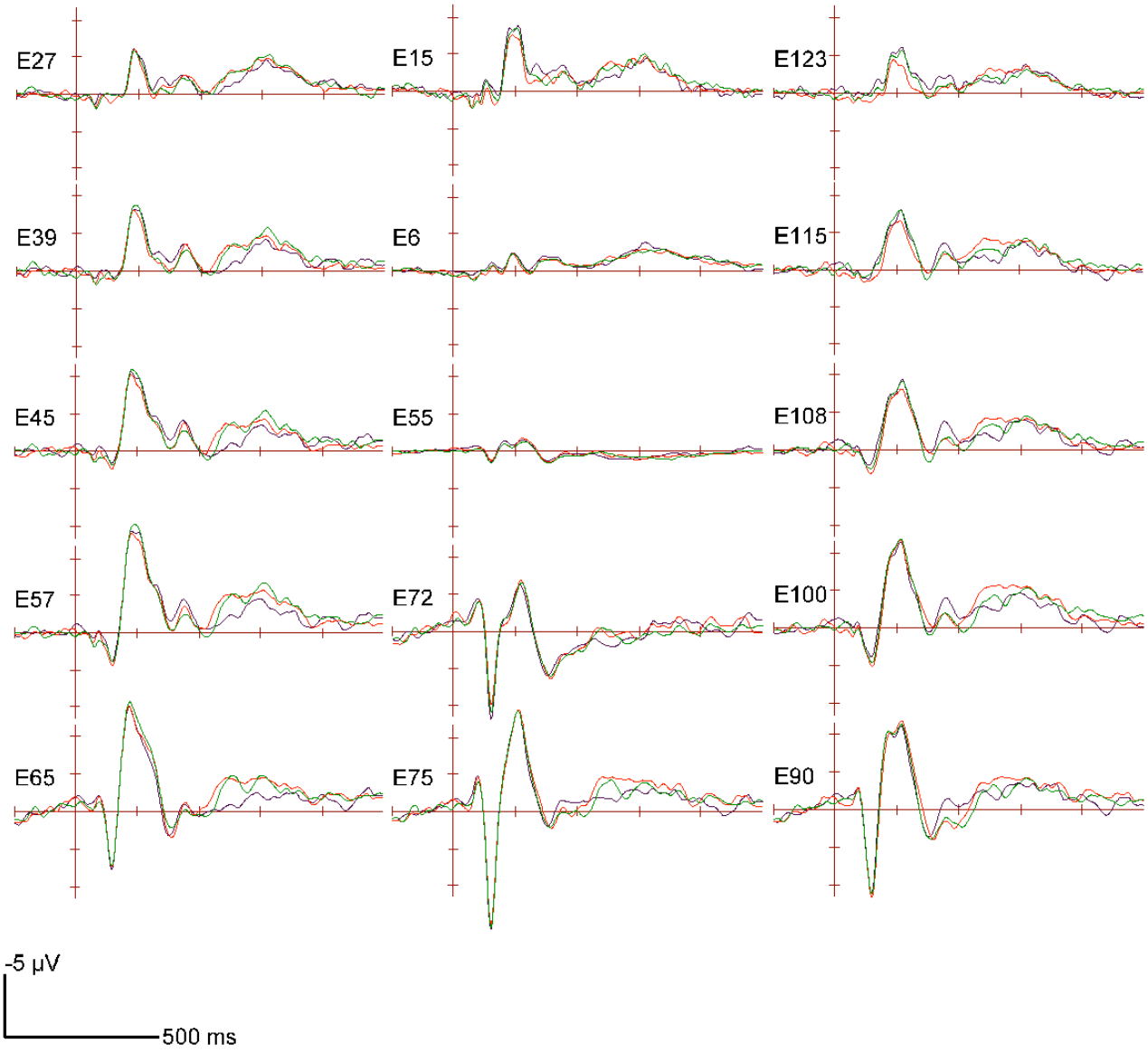

Figure 16. ERP responses for dysfluent readers shown for the selected subset of 15 electrodes. The black line indicates the response for words, the red line for early and the green line for late deviation point pseudowords. (see Fig. 17).

Table 10. The significant cluster found by BESA Statistics when comparing late deviation point pseudowords between fluent and dysfluent readers.

Cluster ID	p-value	Cluster value	Mean for fluent	Mean for dysfluent	Start Time	End Time
Cluster 1	0.028	-15206.2	-2.05042	-0.527837	573	800

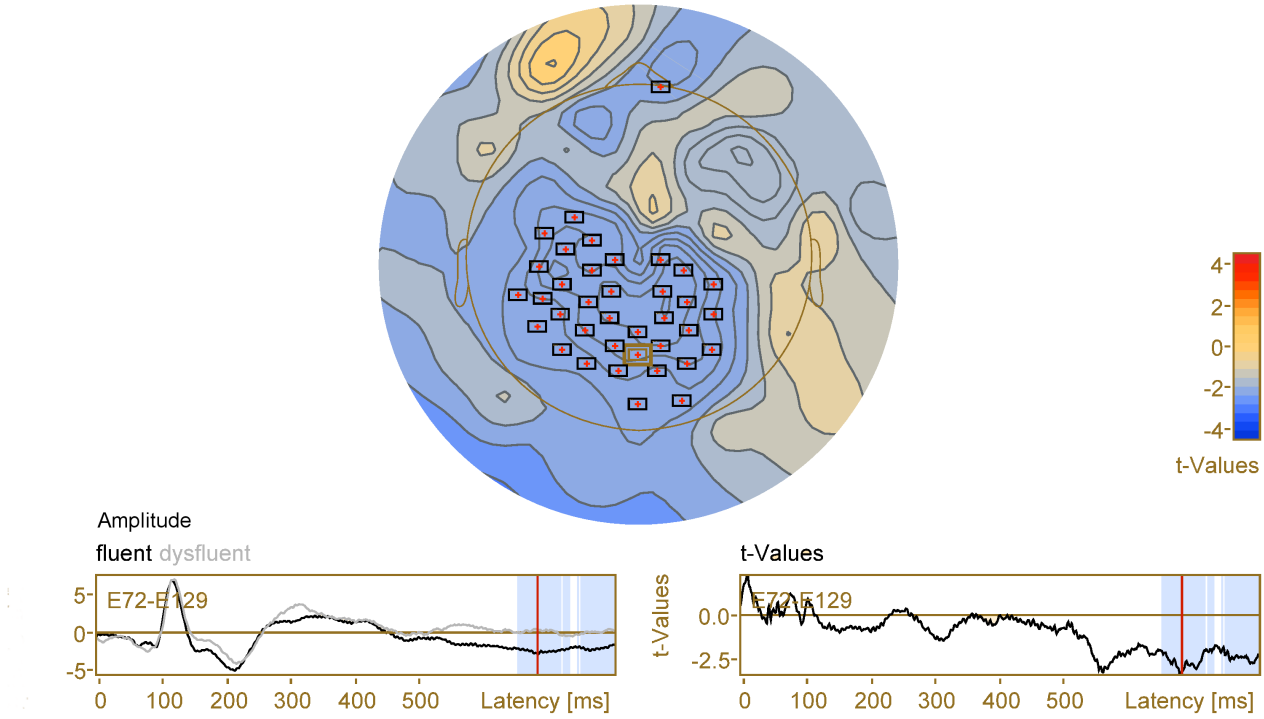

Figure 17. Cluster 1 from BESA Statistics comparing the late deviation point pseudoword stimuli between fluent and dysfluent readers. Top panel shows the cluster at 680ms, with t-values color-coded and electrode 72 highlighted. For this electrode, ERP responses (bottom left) and t-values from the statistical testing (bottom right) are also shown. The blue bands in the bottom panels indicate the time points when this electrode is part of the significant cluster.

4. DISCUSSION

In our experiments, we have been able to characterize the process of word recognition in terms of brain regions and the temporal sequence of brain events. Simple visual stimuli can be distinguished from symbol and word stimuli after around 120ms, and the activation patterns characteristic of words can be localized in well-known areas of left hemisphere posterior reading system (Pugh et al., 2000). We found weak evidence for early capability of distinguishing characters from other symbols at around the same time in a brain region connected with serial control of e.g. reading processes. This implies that the brain would start the reading process as soon as the stimulus has been identified as characters, which in its turn would be at the same that generic symbol shapes can be

distinguished from basic boulder stimulus. At the latest, the recognition process moves from individual characters to sequence level at around 190ms. Presumably due to our limited amount of participants in the experiments, this is much later than the around 100ms reported in the literature (Hauk et al., 2006).

In our experiment, low and high frequency words show a first weakly statistically significant difference in responses after 231ms, suggesting that full word -level processing has occurred before this time point and that word frequency affects the time taken for word recognition. A more definite limit for this time can be set based on clearer statistical significance at 299ms. This is also indirect evidence of parallel reading processes in action, since one of the effects of such a model of reading is to enable familiarity to affect the retrieval speed of words from memory. Based on the observed delay in average responses after around 400ms, we find that the difference in the speed of retrieval is around 50ms between low- and high-frequency words in our experiment. The word frequency effect has also been reported in the literature to arise much earlier, at around 110ms (Hauk et al., 2006).

We found that pseudoword-specific activation patterns occur in posterior parietal regions, corresponding with known parts of serial reading pathways. Deviation point location in pseudowords shows a definite effect at around 300ms. Since this is at around the time when full words are already being processed, this suggests that the serial pseudoword processing pathway is more clearly activated as soon as the parallel word recognition process starts to find the stimulus sequence untypical. Soon after this time point, a delay between early and late deviation pseudoword responses can be observed, confirming that the difference is indeed part of a serial process. In terms of the brain region activation, our results can thus be taken to support dual pathway -type models of word recognition (Coltheart et al., 2001; Perry et al., 2007). We cannot observe the early differences between words and pseudowords reported in the literature to arise at around 160ms (Hauk et al., 2006).

The only statistically significant differences we observed in direct comparisons between fluent and dysfluent readers were obtained for late deviation pseudowords. Our relatively small number of dysfluent readers presumably contributed to this result. In particular, we were unable to find any differences in ERP signals during the early time periods when the most interesting processes in the word recognition task take place. The later difference at around 500ms does occur in the regions

involved in serial control, suggesting a connection with the increased serial pathway activation in dysfluent readers.

As can be observed from our results, the limited amount of participants will tend to bias all our timepoint estimates so that they have a delay compared with what is actually the case. Statistical significance in our data will only be reached some time after it has already appeared in the brain, when the difference has grown large enough.

In future work, studying the eye tracker measurements recorded in the same experiments should allow for more statistically significant results. For example, the alignment of EEG measurements for averaging can be based on eye movements instead of stimulus presentation, which should increase the statistical significance of differences reported here. The comparisons between fluent and dysfluent readers should also be facilitated by incorporating information based on eye tracking on how the word recognition process is proceeding in individual trials. Having more dysfluent readers in such studies would also make it more likely that significant differences in the early parts of the word recognition process can be found.

Eye tracker allows experiments not just of individual word recognition, but of more natural text reading. The goal of this thesis, understanding word recognition processes in the brain, is important as a bridge towards understanding reading processes, which are of crucial importance to individuals to cope in modern societies. Research on this topic and deeper understanding of differences in brain functions can help to improve diagnosis and rehabilitation of dysfluent readers.

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