Mass counts: ERP correlates of non-adjacent dependency learning under different exposure conditions

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Running head:

Non-adjacent dependency learning

Key words:

ERPs, language learning, grammar, non-adjacent dependency

Abstract

Miniature language learning can serve to model real language learning as high proficiency can be reached after very little exposure. In a previous study by Mueller, Oberecker and Friederici [18] German participants acquired non-adjacent syntactic dependencies by mere exposure to correct Italian sentences, but their ERP pattern differed from the one shown by native speakers. The present study follows up on that experiment using a similar design and material and is focused on two important issues: the influence of acoustic cues in the material and the impact of the learning procedure. With respect to the latter we compared alternating learning and test phases to a continuous learning and test phase. In addition, a splicing procedure eliminated prosodic cues in order to ensure that non-adjacent dependencies were learned instead of adjacent ones. Results for the continuous phase design showed a native-like biphasic ERP pattern, an N400 followed by a left-focused positivity. In the alternating design behavioural accuracy was lower and only an N400 was found. The results suggest an advantage of continuous learning phases for adult learners, possibly due to the absence of ungrammatical items present in the test phases in the alternating learning procedure. Furthermore, the replication of the earlier study with prosodically controlled material adds evidence to the general finding that syntactic non-adjacent dependencies can be learned from mere exposure to correct examples.

Introduction

Learners of a second language (L2) use different processing strategies and cognitive resources for language comprehension compared to native speakers. Level of proficiency and age of acquisition of L2 both have an impact on these processing differences [21]. In recent years, experience-based views on language learning argued that language can be learnt through mere exposure and linguistic experience by input-driven learning mechanisms [3]. However, the conditions under which L2 learning is efficient and can lead to a potentially native-like outcome are not well understood. One mechanism supporting possibly both native and L2 language learning is statistical learning. From early on, infants can use distributional probabilities among syllables in order to extract words and even to derive phrase structure from a continuous speech stream. In addition to statistics between segmental elements (i.e. phonemes, syllables), the distribution of prosodic cues (i.e. stress) has been shown to assist the learning of word boundaries, as well as grammatical regularities [7, for review]. Basic learning mechanisms may be functional from early on as even newborns, who have been exposed to their parents' language during the gestation period [23], react differently when presented with sentence intonations from their native language compared to a language never heard before [13].

A widely used tool for the laboratory investigation of language learning mechanisms is the artificial language learning paradigm [7, for review]. Artificial languages are created by using a limited number of pseudowords or syllables and a small set of rules resembling those occurring in natural languages. Due to the constrained set of linguistic features, artificial languages allow a better isolation of specific experimental variables compared to natural languages. Besides artificial languages, miniature versions of natural languages have also been employed to study language learning [17, 18]. They provide the advantage of better ecological validity, while still allowing a good control of the linguistic input.

A particularly interesting type of syntactic structure a number of studies have been focusing on is non-adjacent dependencies [8, 20]. Non-adjacent dependencies occur in natural languages when two words or morphemes form a grammatical relation over a distance as, for example, in sentences such as “the baby is constantly laughing”. In artificial grammars, non-adjacent dependencies can be established between two invariant syllables or words (A, B) separated by a variable middle element (X). Although non-adjacent dependencies are one of the simplest instances of a syntactic rule, they seem to be particularly difficult to learn compared to adjacent dependencies. Additional cues increasing the saliency of the non-adjacent dependency rule, as for example pauses or large variability of the middle element, seem to be necessary for the system to build distant relations [20]. While behavioural studies have revealed a lot about the conditions under which non-adjacent dependencies can be learned from speech input, not much is known about the neurophysiological basis of these processes. A particularly suitable technique for investigating language learning is event-related potentials (ERPs), which are a direct measure of neural activity with high temporal resolution and sensitivity to different types of linguistic processes. The ERP components of particular interest in the present context are the N400 (a negativity reflecting lexical access [12] and lexical-semantic integration processes [11]) and the P600 (a positivity reflecting the processing of syntactically violated as well as syntactically complex stimuli [4]). In the context of artificial language learning both components have been reported with the N400 seen as a reflection of processing of specific lexical forms and the P600 as a correlate of rule processing [14, 17].

Both the N400 and the P600 occur in L2 learners. However, they show different degrees of sensitivity depending on the level of L2 proficiency. While the N400 component seems to already occur at lower levels of proficiency, the P600 comes in only at a relatively high level of linguistic competence [15]. Furthermore, at early stages of learning an N400 component has been reported in response to syntactic violations, instead of a P600 [19], possibly due to the fact that early learners process syntactic relations lexically, i.e. they memorise morphologically complex words as wholes and expect a particular word form during grammaticality judgement.

Besides broadening the understanding of the neural implementation of language learning processes per se, neurophysiological measures might provide additional information about the outcome of artificial language learning and its relation to natural language processing. In the present study we focus on the acquisition of non-adjacent dependencies by mere exposure to an unknown miniature version of a real language.

ERP studies investigating artificial and miniature language learning have reported different results depending on the type of learning and analysis. Those studies, in which extensive and explicit training was provided before testing the processing of syntactic violations, reported the occurrence of both the N400 as well as the P600 component after learning [14, 17]. However, there is only a handful of studies that investigated if and how fast these components emerge during artificial language learning. Two studies testing non-adjacent dependency learning using synthetic syllables could not find a P600 specific to grammatical violations [2, 16]. In a similar way, a study using a miniature version of Italian could not find a P600 response in adult learners, although it clearly occurred in a native Italian control group [18].

As this latter study was the spur for conducting the present set of experiments, we will discuss it here in more detail. Mueller, Oberecker and Friederici (henceforth termed MOF) investigated if and how native speakers of German were able to extract two non-adjacent dependency rules from naturally spoken correct sentences of Italian by mere exposure. Participants were auditorily exposed to short, declarative sentences such as "Il fratello sta cantando" (*The brother is singing*) or "La sorella può cantare" (*The sister can sing-*). Critically, two auxiliaries (*sta, può*) were associated with two different verb endings (*-ando, -are*), whereas the intervening verb stems were variable. The experiment consisted of four alternating learning and test phases. Learning phases contained only correct sentences, whereas test phases, contained incorrect combinations of auxiliary and verb suffix in half of the sentences (e.g. *Il fratello sta cantare). Non-native learners showed an N400-like component in response to the violations, followed by a brief anteriorily distributed positivity, whereas native Italian speakers showed an N400 followed by a P600. The authors interpreted this pattern as indicating that the non-native learners had developed a lexical expectation, whereas only the native speakers applied a combinatorial, syntactic rule. The main conclusions were that non-adjacent dependencies can be learned by mere exposure but that they are not processed in a native-like manner by the learners.

In the current study we further developed the design of the MOF study to test two alternative explanations of this result. The first point concerns the possibility that learners did not learn non-adjacent, but rather adjacent dependencies (auxiliary and full verb form) based on prosodic cues. In this experiment naturally spoken sentences, rich in prosodic information, were used. Thus, it could be possible that the verb stems following the auxiliary contained prosodic cues predicting the subsequent correct or incorrect suffix. The second point refers to the absence of native-like ERP responses in the learners. The learning procedure used by MOF consisted of short learning phases of about 3 minutes alternated with test phases of 1.3 minutes. In many other studies, adult participants were exposed to continuous learning phases lasting 18 to 21 minutes. The fact that test phases, which occurred already in early stages of learning, contained incorrect examples could have favoured the creation and strengthening of an "incorrect" memory trace that interfered with the representation of the correct examples.

In order to tackle these two issues, we applied two important experimental variations. First, to ensure learning of real non-adjacent dependencies, rather than (prosodically-induced) adjacent ones, we applied a specific splicing procedure to the sentences ensuring that prosodic patterns contained in the verb stem could no longer predict the following suffix. If real non-adjacent dependencies were learned in the MOF study, a very similar pattern of results should appear with the novel stimulus material.

Second, we tested whether a long uninterrupted learning phase will lead to better learning and potentially to rule extraction, compared to the alternating procedure. Thus, we conducted two ERP experiments with the novel, spliced stimulus material. The first experiment consisted of 4 short alternating learning and test phases, whereas the second experiment consisted of a long learning and a long test phase. If learning benefits from long, errorless input, this should be reflected in better behavioural performance as well as in more native-like ERP patterns.

Methods

Participants

20 native speakers of German (9 women) were assigned to paradigm A (short phases). Mean age was 24.1 years (SD 3.5). 22 native speakers of German (12 women) were assigned to paradigm B (long phases). Mean age was 24.6 years (SD 2.9). All participants were right-handed, had normal or corrected to normal vision and had no previous knowledge of Italian, Spanish or Portuguese. 4 of the participants assigned to paradigm A and 3 of those assigned to paradigm B reported some basic knowledge of Latin, which might have helped them guessing the meaning of the verb stem, but not the syntactic relation between auxiliary and verb ending, as Italian and Latin grammars are quite different.

Material

A miniature version of Italian was created that consisted of two determiners (*la, il*), two nouns (*sorella, fratello*), two auxiliaries (*sta, può),* 32 different verb stems (e.g., *vol-, cant-*) and two verb endings *(-ando, -are*) that determinately depended on the form of the (non-adjacent) auxiliary. Thus, the verb form was either a gerund (sta…-ando) or infinitive (può.. -are). A complete list of the used verbs can be found in the Supplementary Material. Sentences (1) and (2) illustrate two examples the 128 correct sentences created.

(1) La sorella sta **vol**ando.

The sister is flying

(2) La sorella può **vol**are.

The sister can fly

(3) * La sorella sta **vol**<u>are</u>.

(4) * La sorella può **vol**<u>ando</u>.

(5) # La sorella fu **vol**etto.

All 128 correct and additional 32 non-sense sentences were spoken by a female native speaker of Italian and digitally recorded. The auditory material was subsequently segmented, spliced and normalised using the ReZound software. In order to avoid any prosodic influence, which could lead to the learning of prosodic regularities rather than syntactic dependencies, a splicing procedure was used. The verb stems were cut from non-sense sentences (5) and pasted into the experimental sentences, replacing the original verb stems. To produce ungrammatical sentences (examples (3) and (4)) the suffixes were taken from a sentence with the different verb form. 96 correct sentences were chosen for the learning phases, whereas the remaining 32 sentences and their incorrect counterparts were used for the test phases.

Procedure

Two distinct experimental designs were used to assess the outcomes of different learning procedures. With *design A* participants were exposed to 4 alternating learning and test phases. Each learning phase contained 64 grammatical sentences and lasted approximately 5 minutes, followed by a test phase containing 16 sentences (8 ungrammatical), and lasting approximately 2 minutes. With *design B* participants were exposed to one accumulated learning and one accumulated test phase, containing overall the same type and number of stimuli as design A. Participants were seated on a comfortable chair in a sound-attenuated booth in front of a computer monitor with two loudspeakers on either side. A button-press response device was provided for the grammaticality judgment task. During the learning phases, participants were asked to attentively listen to the sentences, to look at a central fixation point by minimizing their eye movements and blinks during the whole experiment. The sentences were played one after another with a 1800-ms inter-stimulus-interval. During the test phases participants were asked to attentively listen to the sentences and to judge their correctness by pressing one of two buttons. The trials started with a fixation cross, after

500 ms a test sentence was played. 1800 ms after the end of the sentence, a question mark at the centre of the screen appaeared, with a happy face prompting “correct” on one side and a sad face prompting “incorrect” on the other side, congruent with the answer buttons. The prompt remained until a response was given. Participants were instructed to answer according to their intuition. The sentences were presented in randomised order across participants and the button configuration was counterbalanced.

EEG Recording and Analysis

The EEG was continuously recorded during the experiment from 59 electrodes mounted on an elastic cap (Electro-Cap International, Eaton, OH). Vertical and horizontal eye-movement artefacts were monitored by using two bipolar ocular electrodes mounted at the outer canthi of each eye and above and below the right eye. The EEG was referenced on-line to the left mastoid and re-referenced off-line to linked mastoids. Impedance was kept below 5 kΩ and sampling rate was 500 Hz. Trials including eye-movements were excluded from the analysis. Artefacts were automatically rejected through a sliding window of 200 ms, during which epochs with a SD of +/- 35 μV were rejected. Manual artefact rejection was also used. EEG was band-pass filtered between 0.3 and 20 Hz. Only correctly answered trials were averaged together. ERPs were time-locked to the onset of the verb suffix and averaged from -200 to 1500 ms whereby the pre-stimulus epoch of 200 ms constituted the baseline.

To assess topographic differences in the ERPs, electrodes were grouped in four ROIs (regions of interest): left anterior (FP1, AF7, AF3, F7, F5, F3, FT7, FC5, FC3); right anterior (FP2, AF8, AF4, F8, F6, F4, FT8, FC6, FC4); left posterior (TP7, CP5, CP3, P7, P5, P3, PO7, PO3, O1); right posterior (TP8, CP6, CP4, P8, P6, P4, PO8, PO4, O2). Midline electrodes, evaluated in a separate analysis, were grouped into two ROIs (anterior midline: Fpz, AFz, Fz, FCz; posterior midline: CPz, Pz, POz, Oz).

For the statistical analyses, SAS 8.2 software was used. Separate ANOVAs were computed for the two different experiments. For the lateral electrode sites, the within-subject factors were CONDITION (correct, incorrect) x HEMISPHERE (left, right) x REGION (anterior, posterior). For the midline electrodes the within factors were REGION and CONDITION. After visual inspection, two time windows were chosen for the mean amplitude analysis. Between 400 and 550 ms after suffix onset we tested the significance of the visible negativity. Between 550 and 700 ms we tested the significance of the positive deflection.

Results

Behavioural results

Accuracy rates showed an advantage for the long phase exposure (design B) with a mean of 94.7% of correct answers (SD 8.3), compared to the short alternating phase exposure (design A) with a mean of 85.8% (SD 8.3). The difference was significant: $t(40)=3.4$, $p<.01$.

ERP results

The ERPs and topographic difference maps of the first experiment (design A) showed a broadly distributed negativity (Figure 1a) with a posterior focus for the incorrect verb suffixes compared to the correct ones. The repeated-measure ANOVA performed within the 400-550 ms time window revealed a marginally significant main effect of Condition (1,19)=3.23, $p=0.09$) and a significant REGION x CONDITION interaction ($F(1,19)=8.82$, $p<.01$). Subsequent step-down ANOVAs revealed a significant simple main effect of CONDITION over posterior electrods only ($F(1,19)=8.49$, $p<0.01$). Between 550 and 700ms, a significant interaction of REGION x CONDITION ($F(1,19)=5.41$, $p<.05$) was found, not reflected in any significant main effects though. The ANOVA of the midline electrodes revealed significant REGION by CONDITION interactions in both time windows (400-550ms: $F(1,19)=5.83$, $p<.05$; 550-700ms: $F(1,19)=6.75$,

$p<.05$). However, only the interaction from 400-550ms was confirmed by a main effect of condition over posterior electrods ($F(1,19)=8.14$, $p=.01$).

---INSERT FIGURE 1 ABOUT HERE---

The ERPs and topographic difference maps of the second experiment (design B), displayed in Figure 1b, show a greater posterior negativity and a subsequent greater left-lateralised positivity for the violating items compared to the grammatical ones. Repeated-measure ANOVAs revealed a significant REGION x CONDITION interaction between 400-550 ms ($F(1,21)=5.34$, $p<.05$). Post-hoc analyses revealed a main effect of CONDITION over the posterior region ($F(1,21)= 5.07$, $p<.05$) Between 550-700 ms, a significant main effect of CONDITION ($F(1,21)=4.12$, $p=.05$) and a HEMISPHERE x CONDITION interaction were found ($F(1,21)=9.02$, $p<.01$). Subsequent analyses revealed a main effect of CONDITION over the left hemisphere ($F(1,21)=6.41$, $p<.05$). In the midline electrode sites a significant main effect of CONDITION between 550-700ms was found ($F(1,21)=5.43$, $p<.05$).

Discussion

The present ERP study aimed to test whether non-adjacent dependencies can be extracted from correct examples of spoken language and how this ability is influenced by the presence of incorrect items in the input. Native German speakers were exposed to correct sentences from a miniature version of Italian and their learning was tested by means of a grammaticality judgement task, in which half of the sentences were syntactically incorrect. Each participant was assigned to one of two experimental designs: design A consisted of 4 short alternating learning and test phases, whereas design B consisted of a long learning and a subsequent long test phase. In a previous study [18], non-adjacent dependency learning was tested with the same procedure as in design A. In that study, however, naturally spoken full-verb forms were used and hence it could not be completely ruled out that what was learned were adjacent dependencies based on prosodic cues, instead of non-adjacent dependencies. Therefore, we applied a splicing procedure to the suffixed verbs in order exclude this possibility.

Behavioural results showed successful learning in both designs, with higher accuracy in the long phase design (B) compared to the short alternating phase design (A). The general success in learning adds further support to the findings of MOF and shows that participants are able to extract non-adjacent dependencies from mere speech input even in the complete absence of adjacent prosodic cues. Furthermore, design B seemed to favour learning compared to design A. Design B consisted of a long learning phase containing correct sentences followed by a test phase with 50% incorrect sentences, whereas design A consisted of short learning phases alternated with test phases. In this latter case the test phases could have added noise to the learning input, specifically because no feedback about the correctness of the answer was given. Even though participants were aware of the presence of incorrect items, these could still have weakened the “correct” memory trace. Thus, incorrect input at an early stage of learning may exert a negative impact on learning progress.

The ERP data from the alternating phase design (design A) suggest that the brain mechanisms supporting non-adjacent dependency learning in the MOF study (with potential adjacent prosodic cues) and in the present study (without adjacent prosodic cues) were almost identical. In both cases a negativity resembling an N400 occurred, which probably reflects the processing of the incorrect morpheme at the lexical level. The incorrect item occurred unexpectedly and hence probably led to greater difficulties in lexical access. Such lexical N400 effects in the absence of semantic meaning are known from experiments testing word segmentation from continuous speech input [1, 22]. Further, a similar finding was reported in two studies, in which L2 learners displayed an N400 component in response to grammatical violations at initial stages of learning [14, 19]. As in design A, an N400-like negativity was also found for the long learning phase design (B) between 400-550 ms for the violating suffixes. Unlike design A, a subsequent broadly distributed positivity with a left-lateralized focus between 550-700 ms was found in design B. Based on the findings in native speakers of Italian, we had expected to find a posterior positivity (P600) in this time window, once participants had reached very high proficiency. The positivity that we found does not show the typical topographical distribution and temporal characteristics of a P600, but is similar to the positivity observed in the MOF study, although the one in the MOF study had a more anterior and focal distribution. In that study the positivity was interpreted as an instance of a novelty P3 (P3a). The positivity observed in our study needs some further consideration. It could either be a novelty P3a or a P600, or even a subcomponent of P600, as found in a principal component analysis of a syntax-related P600 [5]. If the positivity were a P3a, it could be taken to reflect processes of attention orienting towards the unexpected, incorrect verb suffix that is evaluated for further action [6]; alternatively, it could be a P600 with an unusual distribution. The P600 component is not uniform in its topographical distribution; it was found to display an anterior distribution in response to syntactic complexity and a posterior distribution when reflecting ungrammaticality [9]. The present left-focused positivity could also be a variant of the P600 component for a syntactic process, for which the syntactic rule is not tightly established yet. As such, the current results could point in a similar direction to the findings of Osterhout et al. and Morgan-Short et al., who reported a change from lexical processes in early stages of second language learning, reflected by an N400, to grammatical processes in later stages, reflected by a P600, during processing of ungrammatical agreement information [14, 19]. Our results might represent the transition from lexical towards grammatical processing, as we observed both N400 and P600 at the same learning stage. It is also worth mentioning an alternative, more biologically-based approach, which suggested the interpretation of negative and positive ERP components at a less specific cognitive level, in relation to feed-forward and feedback mechanisms [10]. In this model the present transition towards a positive response at a higher level of competence would be seen as reflecting the decreasing uncertainty about the regularities of the language.

Whichever of these interpretations of the positivity is correct, it shows that the better behavioural performance in the accumulated learning design was accompanied by the emergence of an additional cognitive process, which could be either a reflection of rule processing or, at a less specific level, related to the (attention-dependent) evaluation of the unexpected event.

Conclusions

In the present study we examined the emergence of ERP correlates of non-adjacent dependency processing in a miniature language learning design. By improving the stimulus material of a previous study, we demonstrated that real non-adjacent dependencies between auxiliaries and verb endings in an unknown language can be learned by mere exposure, even after removal of potential adjacent prosodic cues. Furthermore, the application of two different learning procedures, i.e. alternating learning and test phases vs. accumulated exposure, revealed a clear advantage of a long uninterrupted learning phase with respect to higher accuracy rate and emergence of a biphasic ERP response.

Acknowledgements

Francesca Citron was funded by a one-year fellowship awarded by Settore Diritto allo Studio, Comune di Milano, Italy.

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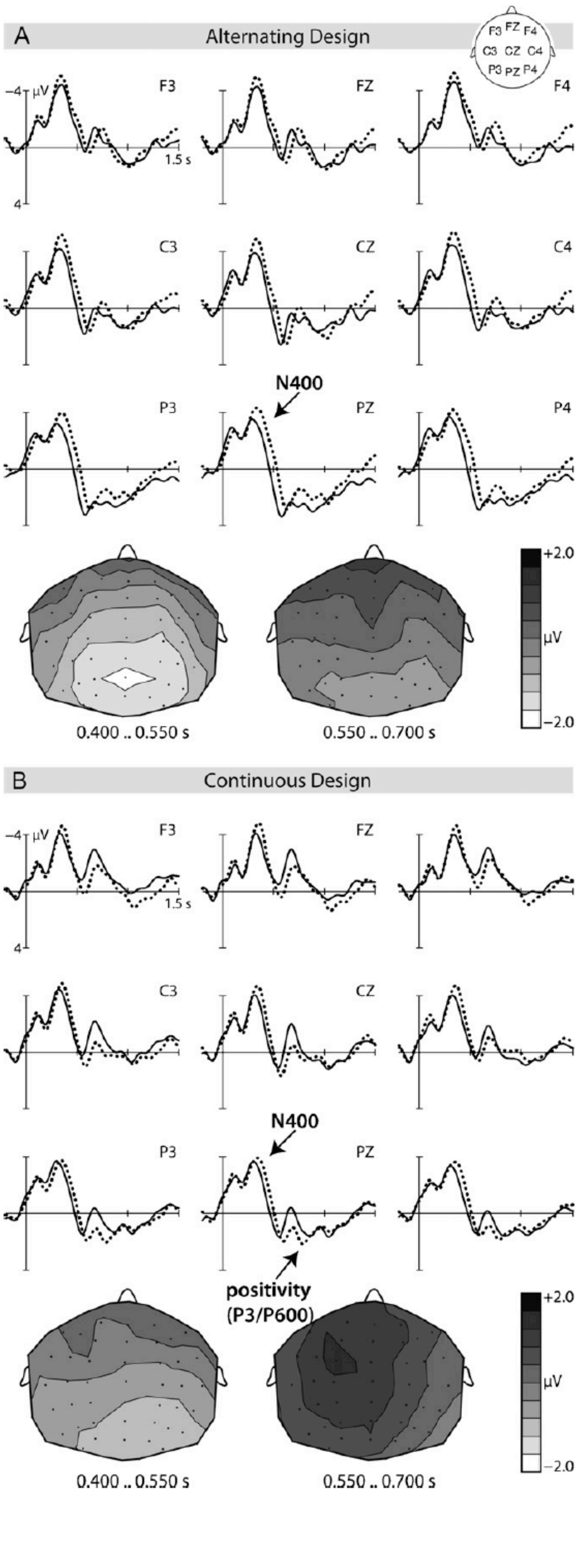
Figure Caption

Figure 1: Grand-average ERPs and topographic difference maps for design A (1a) and design B (1b). The waveforms are plotted from the onset of the critical suffix (-are,-ando), dotted lines refer to incorrect suffixes, solid lines to correct suffixes.


A
Alternating Design
F3 FZ F4
C3 CZ C4
P3 PZ P4
−4 µV
F3
FZ
F4
1.5 s
4
C3
CZ
C4
N400
P3
PZ
P4
+2.0
µV
−2.0
0.400 .. 0.550 s
0.550 .. 0.700 s
B
Continuous Design
−4 µV
F3
FZ
1.5 s
4
C3
CZ
N400
P3
PZ
positivity
(P3/P600)
+2.0
µV
−2.0
0.400 .. 0.550 s
0.550 .. 0.700 s