ERP analysis of cognitive sequencing: a left anterior negativity related to structural transformation processing

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A major objective of cognitive neuroscience is to identify those neurocomputational processes that may be shared by multiple cognitive functions *vs* those that are highly specific. This problem of identifying general *vs* specialized functions is of particular interest in the domain of language processing. Within this domain, event related brain potential (ERP) studies have demonstrated a left anterior negativity (LAN) in a range 300–700 ms, associated with syntactic processing, often linked to grammatical function words. These words have little or no semantic content, but rather play a role in encoding syntactic structure required for parsing. In the current study we test the hypothesis that the LAN reflects the operation of a more general sequence processing capability in which special symbols encode structural information that, when combined with past elements in the sequence, allows the prediction of successor elements. We recorded ERPs during a non-linguistic sequencing task that required subjects ($n = 10$) to process special symbols possessing the functional property defined above. When compared to ERPs in a control condition, function symbol processing elicits a left anterior negative shift between temporal and spatial characteristics quite similar to the LAN described during function word processing in language, supporting our hypothesis. These results are discussed in the context of related studies of syntactic and cognitive sequence processing. *NeuroReport* 11:3187–3191 © 2000 Lippincott Williams & Wilkins.

Key words: Cognition; ERP; Function word; Human; LAN; Language; Neural network; Syntax

INTRODUCTION

Understanding the functional neurophysiology of the human language faculty, including the characteristics that separate language from other cognitive functions, remains one of the major open challenges for cognitive neuroscience. A primary achievement in this effort has been the revelation of neurophysiological processes associated with the treatment of semantic *vs* syntactic aspects of language, through the analysis of event-related brain potentials (ERPs) during word and sentence processing. Over the last two decades, at least three specific language-related ERP signatures have been identified and analyzed, including the N400, P600 or SPS and the LAN. The N400 is an enhanced centroparietal negative-going component for semantically inappropriate words, peaking at about 400 ms after the offending word [1]. The P600 [2,3] or syntactic positive shift (SPS) [4] is a late centroparietal positivity associated with the processing of syntactic anomalies. The left anterior negativity (LAN) is a late negative-going potential that can occur between 300 and 700 ms, with a left anterior spatial distribution, associated with syntactic structural processing complexity [5]. The LAN effect has been explored in several ERP studies of the processing of content (or open-class) words including nouns, verbs and adjectives that carry meaning, *vs* function (or closed-class) words including prepositions or determiners that are essentially empty of meaning but contain information that is crucial for syntactic parsing. Function word processing has consistently been shown to elicit this LAN effect, though this structural effect can be elicited by open class words as well, when they signal structural complexity [5–10].

An important question remains as to whether these language-related ERP signatures are also language specific. While the N400 and SPS/P600 are traditionally associated with language processing, both have also been evoked in appropriate non-linguistic cognitive sequence processing tasks. For the N400, it has been demonstrated that in arithmetic problem solving, semantically anomalous conditions such as the presentation of '26' in the sequence '$7 \times 4 = 26$' evokes an N400 effect quite similar to that evoked by the presentation of 'dreamed' in the sentence 'The ball has dreamed' [11]. More generally [12,13] it appears that, independent of the input code, the N400 effect is evoked only if a particular stimulus does not fit into a pre-established semantic context [11].

Similarly, the SPS/P600 can be evoked in linguistic and non-linguistic conditions in which an element of a rule-governed sequence is difficult to integrate. Thus, in English, where active transitive verbs are normally followed by a noun phrase, an SPS/P600 will typically be evoked in conditions such as the presence of 'to' in the sentence 'The broker persuaded to sell the stock got rich', but not by 'his' in 'The broker persuaded his client to buy the stock' [2–4]. This is due to the increased complexity of integrating a preposition (to) rather than a noun phrase (his client) after a verb (persuaded). Interestingly, this SPS/P600 can also be evoked in non-linguistic contexts including the processing of musical phrase structure violations [14], and in the processing of non-linguistic sequences that violate a learned rule in an artificial grammar task [15]. These observations indicate that the N400 and SPS/P600 can be evoked under appropriate conditions in non-linguistic tasks.

In this context, the objective of the current study is to test the hypothesis that the LAN reflects the processing of structural transformation rules associated with informative symbols, such as function words, in linguistic or non-linguistic contexts. Such structural rules allow prediction of the subsequent organization of a sequence, based in part on the previous context. Our hypothesis thus predicts that a LAN effect could be elicited in non-linguistic cognitive sequencing tasks that fulfill the required structural processing conditions.

This cognitive sequencing approach is motivated in part by our simulation studies that predict a functional equivalence for linguistic and non-linguistic rule-based transformation processing [16–18]. We have taken this approach in the exploration of syntactic function in aphasic patients, and have demonstrated correlated deficits in their processing of syntactic and non-linguistic rule-based sequential structure [19–20]. Likewise, in a recent ERP study in control subjects we demonstrated a P600-like profile in response to structural anomalies in non-linguistic rule-based sequences [15].

In order to test our current hypothesis, we developed a cognitive sequence processing task in which letter sequences are to be judged as acceptable or unacceptable based on prelearned rules. In one condition, the target symbol within the sequence indicates how the subsequent sequence elements are to be organized, and is thus considered a function symbol, analogous to a function word. In the control condition, the target symbol at the same position contains no information about subsequent sequence organization, but must be analyzed for treatment at the end of the sequence. We predict that the function symbol will elicit a negative shift, similar to the syntactic LAN, that will not be observed in the control condition.

MATERIALS AND METHODS

Ten subjects, aged 22–39 years, all right-handed, and free of neurological impairment or language deficit entered the study. Subjects were advised of the physical details of the experiment and gave their informed consent. Subjects were seated 50 cm in front of a 14-inch video monitor, where sequences of letters were presented.

Stimulus presentation and timing: The sequences were composed of eight successively presented elements, each consisting of a white rectangle (3.5×6 cm) showing a black letter at a centered fixation point. Letters were presented for 400 ms followed by a 400 ms pause, yielding an 800 ms interval between the onset of two successive stimuli. Elements in positions 1–8 of all sequences were constructed along the following template: Positions 1–3 consisted of an initial triplet of three different letters (randomly chosen between A and V). Position 4 was a target element (either X or Z), and was the stimulus for which ERP analyses were performed. Positions 5–7 consisted of a second triplet of three letters. Finally, position 8 was a repetition of the target element in position 4. Subjects were required to categorize the sequences as acceptable or unacceptable with respect to two pre-learned conditions. In the control condition, after presentation of elements 1–3 the letter Z appeared in target position 4. Subjects were asked to consider the sequence as acceptable if the position 8 element was a repetition of the target element Z in position 4 (acceptable: ABCZDEFZ, unacceptable: ABCZDEFG). In the function-symbol condition, after presentation of elements 1–3 the letter X appeared in target position 4. Subjects were asked to consider the sequence as acceptable if the elements in positions 5–7 were a transformed version of elements 1–3 following the rule 123-312 (acceptable: ABCXCABX, unacceptable, ABCXBACX). This condition fulfills the requirement that a specific symbol (X) allows the prediction of subsequent sequence organization based on a transformation of the previous context.

Trial presentation: The control and function-symbol conditions were mixed in two blocks of 30 trials (sequences). Each block containing sequences from both conditions in a randomized order. Thus, for a given trial, subjects did not know the condition until the presentation of the target element in position 4. Subjects were asked to carefully analyze each sequence and indicate whether it was acceptable or unacceptable by pressing the designated keys on a response pad. Subjects were told that the frequency of unacceptable sequences was low, in order to maintain their attention on the task, whereas in fact, no unacceptable sequences were presented. After a verbal and graphic presentation of the task requirements, we verified subjects' understanding of the task in a 20 trial practice session.

EEG recording: Scalp voltages were collected with a 65-channel Geodesic Sensor Net and amplified with an AC-coupled, 65-channel, high input impedance amplifier (200 MΩ, Net Amps, Electrical Geodesics Inc., Eugene, OR, USA). Amplified analogue voltages (0.1–200 Hz bandpass) were sampled at 500 Hz. Individual electrodes were adjusted until each reached an impedance of < 50 kΩ. Trials were rejected from analysis if they contained eye movements, as monitored by EOG.

EEG analysis: EEG recordings were segmented from 100 ms before to 900 ms after the onset of the target element in position 4 that indicated whether a given trial was of the control or function-symbol condition. Segments were then filtered by a low-pass filter of 30 Hz, referenced to the left–right mastoid average, and a baseline correction was applied based on the first 100 ms. In order to facilitate statistical analyses of scalp topography effects, four different locations were defined (central, parietal, left anterior and right anterior), each composed of five electrodes, corresponding to the 10-20 coordinates Fz, Cz (central); P3, Pz, P4 (parietal); F3, F7, Fp1 (left anterior); and F4, F8, Fp2 (right anterior), respectively.

Scalp voltages were obtained in an early time window lasting from 200 to 400 ms after the onset of the position 4 element, and a late time window from 400 to 600 ms in order to be centered in the 300–700 ms LAN range. These data were then analyzed in a 4-way repeated-measure ANOVA on time window (early, late), condition (control, function-symbol), spatial location (central, parietal, left anterior and right anterior), and electrode (five per location). Mean voltage amplitude for the 30 trials of a given condition, expressed in μV, was taken as the dependent variable.

RESULTS

The recording duration was ~20 min and allowed subjects to maintain their attention on the task. All subjects performed the task correctly, with error levels < 5%. The observation that all subjects made several incorrect responses, despite the fact that in actuality there were no anomalous sequences, indicated that they were vigilant in trying to detect anomalies.

Figure 1a illustrates the time course of activity at representative electrodes from each of the four regions in response to the critical element in position 4. In the 0–200 ms post-stimulus period the ERP profiles for the two conditions displayed a standard N1-P2 complex. Then, during the 200–400 ms window, for the function-symbol condition, the P2 component remained positive until the onset of a negative shift at around 400 ms. In contrast, in the control condition during this 200–400 ms period there was a negative-going component followed by the onset of a P300-like positivity. During the late (400–600 ms) period, activity for the function-symbol condition was characterized by a negative shift that appeared more pronounced for the left anterior *vs* right anterior electrodes. In contrast, during this 400–600 ms period, the control condition displays a symmetrical centroparietal positivity corresponding to the P300 effect.

Fig. 1b illustrates the spatial topography of the scalp voltage differences obtained by subtracting the control condition voltages from the function-symbol voltages at 500 ms post-stimulus. This subtraction clearly reveals the lateralization of the negative shift observed in the late (400–600 ms) period for the function-symbol *vs* control condition, with its central and left anterior predominance, similar to that of the syntactic LAN.

These observations were confirmed in the repeated-measures ANOVA. Main effects were significant for time period ($F(1,9) = 7.20$, $p < 0.05$), location ($F(3,27) = 7.6$, $p < 0.0001$) and electrodes ($F(4,36) = 5.38$ $p < 0.002$), but not for condition ($F(1,9) = 0.5$, $p > 0.5$). The significant time period × condition interaction ($F(1,9) = 13.8$, $p < 0.005$) confirms that the early and late effects are condition-dependant as observed. Likewise, the significant 3-way time period ×

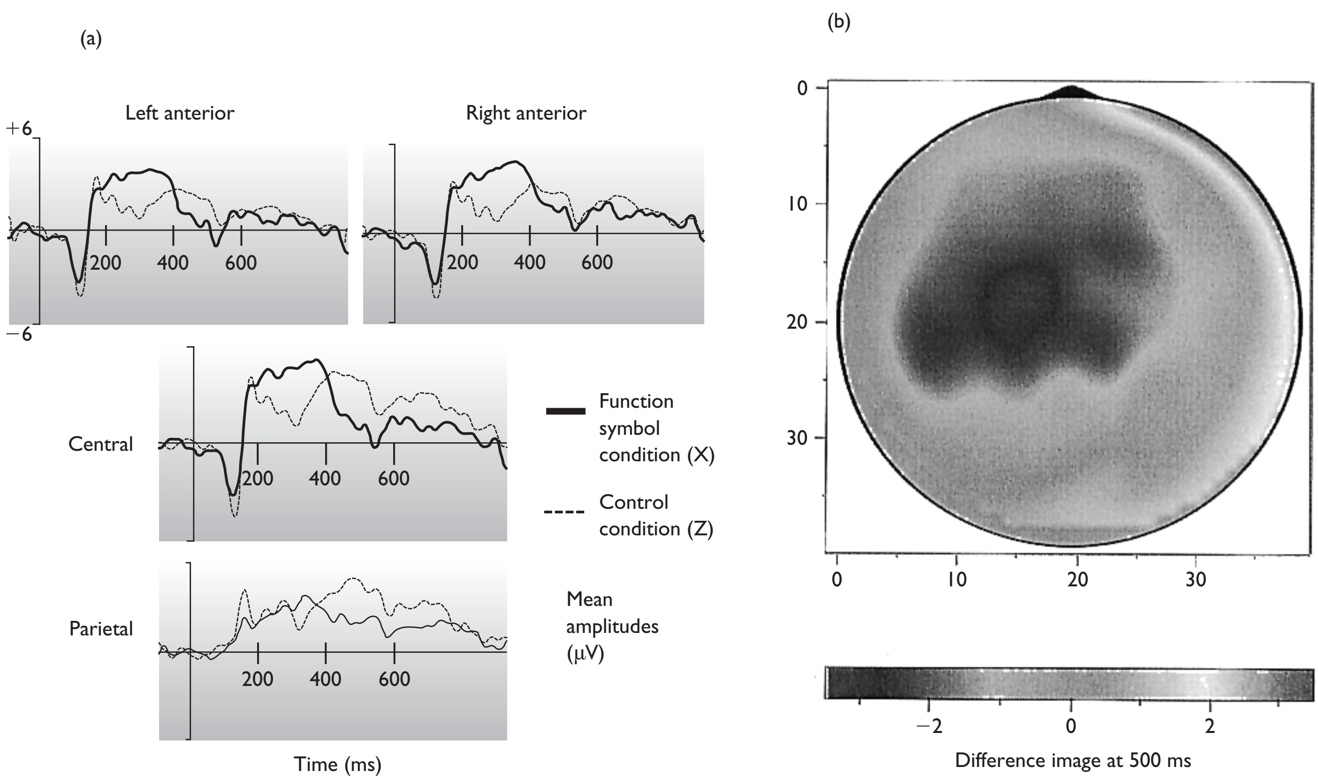

Fig. 1. (**a**) Grand averages for 10 subjects in the function-symbol *vs* control conditions for representative electrodes from the left anterior, right anterior, central and parietal sites. Voltage scale from +6 to −6 μV. Time scale in ms. (**b**) Subtraction image of function-symbol minus control conditions at 500 ms post stimulus. Note the left anterior distribution of the processing negativity.

location × condition interaction ($F(3,27) = 5.28$, $p < 0.01$) indicates that these effects are also dependant on the topographical scalp distribution.

Planned comparisons confirmed the maintained positivity in the early (200–400 ms) time period for the function-symbol *vs* the control condition at the four spatial sites ($p < 0.001$). More importantly, planned comparisons also confirmed that the LAN-like negative shift in the late (400–600 ms) time period for the function-symbol *vs* control condition is significant for left anterior, central and parietal sites ($p < 0.001$), but not the right anterior site ($p = 0.48$). Finally, the observation that in the later period (400–600 ms) the negative shift in the function-symbol condition was more pronounced for the left anterior than the right anterior region was confirmed by a *post hoc* (Scheffé) test ($p = 0.012$). In contrast, a *post hoc* (Scheffé) test revealed that there was no significant left anterior *vs* right anterior difference during this period for the control condition ($p = 0.96$). This indicates that the left asymmetry in the subtraction image (Fig. 1b) is due to the asymmetric negativity in the function-symbol condition.

DISCUSSION

The objective of the current study was to test the hypothesis that the left anterior negativity (LAN) observed for function words [5–10] could reflect the construction of a predictive representation of the subsequent sequential structure, guided by syntactically informative symbols (e.g. function words). While the LAN can also be evoked by syntactic anomalies [21], we focus here on the LAN effects associated with structural complexity and transformation processing. In particular our hypothesis predicted that under appropriate conditions, this effect could be elicited in a non-linguistic sequence processing context.

To accomplish this we developed a non-linguistic sequencing task with two conditions: in the function-symbol condition, presentation of the letter X at sequence position 4 is associated with a structural transformation that when applied to elements 1–3 will predict elements 5–7. In contrast, in the control condition, presentation of the letter Z in position 4 is associated with a requirement to verify that Z also appears in position 8, involving no transformation processing and no relationship between elements 1–3 and 5–7. We observed that in the function-symbol *vs* control condition, the critical fourth element elicits a lateralized negative shift with temporal and spatial distribution quite similar to that of the LAN observed in syntactic processing of structural complexity, including that associated with function words, supporting our hypothesis.

While this lateralized negative-going potential is similar for function words and non-linguistic function symbols, it is noteworthy that we can observe differences between ERP responses to function symbols *vs* those for function words in natural language. In particular, the function symbol is associated with a prolongation of the P2 component that remains positive until ~400 ms when the negative shift begins. A similar effect has been observed in an artificial grammar learning task [22], where the processing of non-linguistic sequence elements that were consistent with the learned grammar elicited an enhanced positive going effect between 200 and 500 ms, quite similar to the effect seen in our experiment. This effect was considered to reflect the confirmation of a learned sequential expectancy [22]. From this perspective, in our task, as contrasted with language processing tasks, subjects will have enhanced expectation that the fourth element will be either the function symbol, or the control cue. Thus, confirmed expectation of the function symbol in the context of the learned transformation would then yield the extended P2 effect, as observed for grammatical targets in Baldwin and Kutas's [22] sequencing task.

These results support (but do not confirm) the proposal that structural processing associated with the left anterior negativity is not specific to language, but is rather a more general neurocomputational capability for treating structural complexity in rule-governed sequences. This is consistent with recent simulation studies that suggest that a common neural mechanism could be responsible for rule-based processing of linguistic and non-linguistic sequences [16–18]. Indeed, based on this shared mechanism, these simulation studies correctly predicted that impairments in linguistic and non-linguistic rule-governed transformation processing should be correlated in neurological patients [19,20]. While the results reported here support our hypothesis, they do not confirm it, and the question remains open for further investigation.

CONCLUSION

Complex cognitive functions including language can likely be decomposed into component processes, but it is not clear to what extent these component processes are specific to language. Words that drive syntactic structural transformations generate an ERP left anterior negativity (LAN) at around 400 ms that is not present for words that do not trigger such transformation processing [5–10]. We tested the hypothesis that this ERP profile would also be observed in a non-linguistic sequencing task for function symbols that direct subsequent structural transformations. Our discovery of a negative shift in the 400–600 ms time frame that is significantly lateralized to the left anterior cortex in such a non-linguistic task supports our hypothesis. This observation argues that at least some components of language processing can be expressed and studied in isolation from the complexity of the complete language faculty, and are thus not language specific [16–18]. This argument is supported by our recent observation that the degree of agrammatic comprehension in aphasic patients is predicted by their impairment in a non-linguistic cognitive sequence transformation task similar to that employed here [19,20]. The cautious exploration of these cognitive processes that can be expressed in linguistic and non-linguistic sequences should have important implications for the more precise computational and neurophysiological characterization of human cognition, including the language faculty.

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