The Role of Pause Cues in Language Learning: The Emergence of Event-related Potentials Related to Sequence Processing

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Abstract

■ Humans can derive sequential dependencies from unfamiliar artificial speech within several of minutes of exposure. However, there is an ongoing debate about the nature of the underlying learning processes. In a widely discussed study Peña et al. [Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. Signal-driven computations in speech processing. *Science, 298,* 604–607, 2002] argued for the importance of subtle acoustic cues in the signal, such as pauses, in order to switch between two computational mechanisms, which are conceptualized as rule-based versus statistical. The present study was aimed to approach this problem by recording event-related potentials in response to correct and incorrect phrases consisting of bisyllabics after short exposure to either rule-based or random artificial speech streams. Rule-based streams contained dependencies of the form AXC, whereby A elements reliably predicted the C elements and X elements were variable. Participants were exposed to four input and test phases. Two of the input streams were rule-based and contained either only probabilistic information related to the distribution of the AXC stimuli or an additional acoustic cue indicating the boundaries of relevant units. The other two streams were random variations of the rule-based streams. During the test phase in the condition with pause cues, an early negativity and a later positivity emerged for correct and incorrect items in comparison to their acoustically identical counterparts, which were presented after the random control condition. In the noncued condition, only negativities were seen. The timing and the scalp distribution of the negativities were different for correct and incorrect sequences in both the cued and the noncued conditions. The results are interpreted in support of a view of grammatical learning in which both distributional and acoustic cues may contribute to different aspects of syntactic learning. ■

INTRODUCTION

It is almost a truism to state that human language must be structured such that the human cognitive system will be able to acquire it without explicit instruction. As a matter of fact, this is proven to us every single day by millions of kids who start communicating without being told how to. However, the neurocognitive mechanisms by which humans achieve this feat are just beginning to be explored. The information contained in language itself (i.e., syntax, semantics, phonetics, prosody) and in the sociocultural environment is manifold, so that different and probably redundant cues may trigger learning of different aspects of language. Moreover, internal constraints of the learner's cognitive system, such as perceptual sensitivities, influence how the information of each domain is used for a specific purpose. The present study aims to investigate learning related changes in neural activity afforded by two properties of language which have been suggested to be important for learning, namely, the distributional information contained in language (Newport & Aslin, 2004; Saffran, 2001, 2002) and phonological cues (Onnis, Monaghan, Richmond, & Chater, 2005; Hirsh-Pasek & Golinkoff, 1996; Morgan, Meier, & Newport, 1987).

One way to explore if a specific portion of the language signal may contribute to language learning is the experimental isolation of this aspect of interest. This can be achieved by using artificial languages which consist just of those aspects which are the target of investigation. The usual procedure in artificial language studies comprises input phases, during which either a regular or a random input stream is presented, and test phases, during which participants complete a two-alternative forced-choice task or a grammaticality judgment. Using such a reductionist approach, artificial grammar experiments have shed light on the powerful learning mechanisms which are available to humans to segment relevant units and detect relationships between those (cf. Gomez, 2006, for a review).

In a seminal study, Saffran, Aslin, and Newport (1996) reported that 8-month-old infants were able to use transitional probabilities between syllables for word segmentation, a mechanism which has been labeled statistical learning. In their experiment, the participants were exposed to a continuous syllable stream consisting

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of four trisyllabic words which solely were defined by higher transitional probabilities of syllables within words compared to syllables between words. After only 2 min of exposure, infants could discriminate words from part-words as probed in a familiarization-preference procedure. Using similar paradigms, statistical learning of word segmentation has been shown in many studies for learners of different age groups (Cunillera, Toro, Sebastian-Galles, & Rodriguez-Fornells, 2006; Toro, Sinnett, & Soto-Faraco, 2005; Thiessen & Saffran, 2003; Aslin, Saffran, & Newport, 1998; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). Moreover, even higher-order dependencies, such as simple phrase structure rules or dependencies between nonadjacent elements, seem to be learnable via distributional cues (Saffran & Wilson, 2003; Gomez, 2002; Saffran, 2002; Gomez & Gerken, 1999).

Similarly to the statistical learning paradigm, artificial languages have also been used to demonstrate that humans can infer abstract rules from auditory input using a different process which has been conceptualized as rule extraction (Endress, Scholl, & Mehler, 2005; Peña, Bonatti, Nespor, & Mehler, 2002; Marcus, Vijayan, Bandi Rao, & Vishton, 1999). In these studies, participants learned to generalize the structure of a syllable sequence to sequences they have not been exposed to before. For example, in a widely recognized study by Peña and colleagues, participants were exposed to a stream of nine trisyllabics with the structure AXC in which one of three A elements perfectly predicted one of three C elements, whereas X elements could vary among three syllables. When participants listened to an unsegmented syllable stream, they were able to learn to segment the critical trisyllabics but not to generalize the underlying A–C dependency to items with a novel middle element X. However, when participants were presented with a syllable stream which contained additional acoustic cues at phrase boundaries (pauses of 25 msec), which marked the to-be-analyzed units, the A–C pattern was generalized. The authors take this finding to suggest that dual mechanisms may be used to analyze speech strings, namely, a statistical one which serves the purpose of word segmentation and a rule-based one, serving the purpose of detecting syntactic regularities. Importantly, the authors suggested that the rule-based learning mechanism may be triggered by specific acoustic properties of the speech signal, as for example the presence of pauses (Peña et al., 2002). This claim, however, has not remained unchallenged. Advocates of one uniform associative learning mechanism have criticized this account on a methodological and a theoretical basis (e.g., Perruchet, Tyler, Galland, & Peereman, 2004; Seidenberg, MacDonald, & Saffran, 2002). In their notion, the acoustic cues may simply modify the type of statistics which are calculated without altering the learning mechanism as such.

The present study is an attempt to specify the neurocognitive mechanisms involved in the processing of nonadjacent dependencies between words and the influence of pause cues by using event-related potentials (ERPs) as a direct and multidimensional measure of neural activity. ERPs have previously been used to distinguish different phases of auditory and linguistic processing. Obligatory components such as the N1 (negativity around 100 msec after stimulus onset) and P2 (first positive peak after the N1 between 150 and 275 msec) are modulated by acoustic features as well as selective and attentional processing. Later, cognitive components have been shown to distinguish different types of linguistic processes. Lexical–semantic processes are reflected in the N400 component, a negativity peaking at around 400 msec. Syntactic processing correlates with two different component families, which are early anterior negativities (E/LANs) and late positivities (P600s). Left dominant anterior negativities are frequently seen as indicating automatic syntactic processes such as local phrase structure processing (ELAN: 100–300 msec) and morphosyntactic processing (LAN: 300–500 msec). The P600, in contrast, has been interpreted as index for processing of syntactic complexity, syntactic integration, and syntactic repair (see Key, Dove, & Maguire, 2005; Friederici, 2002 for recent reviews).

Previous studies provided evidence that language-like artificial grammars can elicit syntax-related ERP components such as the E/LANs and the P600, suggesting that similar mechanisms play a role in natural as in artificial grammar processing (Friederici, Steinhauer, & Pfeifer, 2002; Hoen & Dominey, 2000). In contrast, artificial grammar studies using nonlinguistic structures reported modifications of the P3b component, which is a positivity in response to processing of an infrequent unexpected target independent of the cognitive domain (e.g., Baldwin & Kutas, 1997). Using established functional distinctions between ERP components, we hope to draw conclusions about the timing and type of the different processes related to nonadjacent dependency processing under different learning conditions. Before turning to the present experimental design, we like to provide a selective overview of relevant previous ERP studies using artificial languages.

Two studies in adults used sequences of synthetic speech syllables to test which ERP components indicate processes of word segmentation. Sanders, Newport, and Neville (2002) showed that the N1 component can indicate word segmentation. In that study, ERP responses to nonsense words, which were presented in a continuous syllable stream, were measured before and after participants had been familiarized with the individual words. After training, good learners showed an enhanced N1 component for word onsets, which the authors interpret as an on-line index for word segmentation independent of particular acoustic cues. Additionally, the authors report an increased N400 after training which they relate to lexical–semantic processes (Sanders et al., 2002). In a related study, Cunillera et al. (2006) investigated the acquisition of word segmentation. In contrast to the Sanders et al. (2002) study, they used a statistical learning paradigm with no explicit instruction. Moreover, they tested the impact of stress cues marking word boundaries on the emerging ERP components. When comparing a statistical learning condition to a random condition, they did not find an increased N1 component for word onsets. Instead, they report an increased positivity (P2) when words were marked by an artificial stress on the first syllable and an N400 when words were indicated only by distributional cues.

More relevant for our research question are studies which tested the processing of structural regularities within simple phrases. All artificial language studies which we know that tested syntactic processing either used explicit instruction about the underlying rule or feedback-based learning procedures during training. In the visual domain, Hoen and Dominey (2000) reported a left anterior negativity (LAN) for the processing of a syntactic transformation within a letter sequence. The authors interpret it as an indication of morphosyntactic processing in analogy to the LAN in language studies. Another visual study which tested the processing of linear versus hierarchically structured syllable sequences reported a positive ERP component in response to violations of either structure (Bahlmann, Gunter, & Friederici, 2006). The positivity was seen as being related to the degree of difficulty of integration in the two structurally different artificial grammar tasks.

There are few studies in which the emergence of syntax-related ERP components was investigated in the auditory domain (Mueller, 2006; Mueller, Hahne, Fujii, & Friederici, 2005; Friederici, Steinhauer, et al., 2002). Importantly, in these studies participants learned not only structural properties of the languages, but also the meaning of words. Friederici, Steinhauer, et al. (2002) used an artificial phrase structure grammar consisting of mono- or bisyllabic words. After intensive training of the artificial grammar, syntactic violations elicited an anterior negativity and a subsequent P600-like positivity. Mueller et al. (2005) used a miniature version of a real language (Japanese) to measure ERPs in response to syntactic and thematic violations before and after training. In this study, a P600 emerged after training together with different kinds of negativities for different violation types. Local phrase structure violations led to a broadly distributed negativity, which was interpreted as related to prosodic expectations, whereas case violations led to an N400-like component which, following previous work on thematic role assignment in natural languages (Frisch & Schlesewsky, 2001), was seen as indexing a conflict in the thematic hierarchy. Together, the studies show that with explicit training, language-like biphasic ERP components in response to syntactic violations can develop after a relatively short learning period.

The Present Study

In our study, we investigated the question whether and which language-related ERP responses would emerge in an untutored artificial grammar learning study in which the only cues to the underlying structure are those contained in the signal. Specifically, we were interested to determine the impact of distributional and prosodic cues on the learning outcome. The distributional cue was to be instantiated by the sequential order of the syllables and the prosodic cue by a pause between the to-be-analyzed units. We chose pauses as prosodic cues because they are among those acoustic parameters that frequently co-occur with major syntactic boundaries in natural language (Shattuck Hufnagel & Turk, 1996), influence syntactic phrasing (Steinhauer, Alter, & Friederici, 1999; Warren, Grabe, & Nolan, 1995), and allow us to keep the acoustic properties of the to-be-compared units of interest constant.

There are several reasons for which the investigation of learning with ERPs is challenging. It has to be considered that learning during a long exposure period can be an erratic and changeable process. Yet, ERPs require the averaging of many time epochs with events of the same type. Dynamic changes in the learning process may thereby remain undetected. A similar problem applies to the test phase. Gomez (2006) has suggested that activated memories during language learning may be in a fragile state and easily overwritten. This means that the presentation of too many incorrect examples in test phases could lead to an extinction of the learning effect. Also, the task has to be carefully considered. The frequently applied two-alternative, forced-choice task (e.g., Peña et al., 2002; Saffran, Newport, & Aslin, 1996) seems not apt to be used with ERPs because of the additional working memory demands it affords. Therefore, we combined the statistical learning paradigm with a standard ERP violation paradigm with a minimal number of trials. During learning phases, we presented random- and rule-based input streams, varying with respect to prosodic cues. In one condition, only distributional cues were present, whereas in the other condition, a pause cue was inserted, providing a salient marker for the to-be-analyzed units. The structures contained in the rule-based streams corresponded to the rule investigated by Peña and colleagues and was an AXC rule in which a specific A element predicted a specific C element while X elements were variable (cf. Figure 1). In contrast to the Peña et al. study, we used eight instead of three variable X elements for each language. This was done as high variability of the middle element has been shown to assist acquisition of nonadjacent dependencies (Gomez, 2002).

The units between which the relevant AXC dependency was established were bisyllabic sequences (cf. Figure 1). We chose to use bisyllabics instead of monosyllabics as in the Peña et al. study for several reasons. First, we wanted to ensure that the AXC structures as a whole are processed as phrases and not as words. Second, pause cues, together with other acoustic modulations, play a prominent role in sentential processing where they can indicate intonational phrase boundaries.

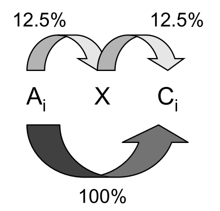
RULE		Language 1	Language 2	Language 3	Language 4
	A	tile$_1$, mide$_2$, gise$_3$	rine$_1$, degi$_2$, seti$_3$	nemi$_1$, rise$_2$, gide$_3$	deti$_1$, tise$_2$, neri$_3$
	X	puwo, moku, tufo, fogu, kumo, boku, wofu, guwo	kubo, mogu, fopu, tumo, pubo, bopu, wotu, gufo	gubo, tuwo, motu, bogu, fotu, kuwo, wogu, pufo	wopu, pumo, foku, botu, tubo, gumo, mopu, kufo
	C	semi$_1$, deri$_2$, legi$_3$	negi$_1$, ride$_2$, leti$_3$	gile$_1$, demi$_2$, segi$_3$	gine$_1$, seri$_2$, mise$_3$

Figure 1. Illustration of rule and lexicon of the four languages that were used in the experiment. Subscript numbers indicate which A and C elements build the rule-based frames.

For word boundaries, this is not the case. Rather, it has been a long and puzzling issue how humans segment words from speech without explicit markers such as pauses (e.g., Norris, McQueen, & Cutler, 1995). Sentential prosody has been suggested to play a prominent role for the acquisition of language (Soderstrom, Seidl, Kemler Nelson, & Jusczyk, 2003; Morgan, 1996; Morgan et al., 1987), and thus, if there is a syntactic learning mechanism in language which can be triggered by prosodic cues, it should be even more present during processing of phrase-like units compared to word-like units. The test phases were composed of an equal number of regular phrases (following the AXC rule) and phrases which contained a local violation, in which an X element occurred at an unlicensed position (incorrect category on the last element: AXX). Thereby we aimed to mimic phrase structure violations which have been used as test cases for automatic syntactic processing mechanisms by numerous previous studies (Friederici, Pfeifer, & Hahne, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991). We used random control conditions for two reasons. First, it provides a control for learning effects which may be due to exposure to a speech stream, with the particular elements independent of the inherent rule. Second, it provides us with a baseline for the independent evaluation of ERPs related to processing of correct sequences versus those related to the processing of incorrect sequences. By this procedure, we hope to specify not only violation-related deviance detection and processing mechanisms but, more interestingly, also normal sequential processing in the comparison of processing after rule input versus after random input.

Previous electrophysiological studies using artificial grammars let us to expect several ERP components, which may appear after one or both of the learning conditions for correct or incorrect items and may vary depending on the similarity or difference of the cognitive operations acquired during the exposure phase. Similar to the artificial grammar studies described above, anterior negativities could appear in response to local violations. Additionally, a P600 component was expected as indicating more controlled syntactic processing mechanisms. As both components have been shown to vary with proficiency (Friederici, Steinhauer, et al., 2002; Hahne, 2001), we expected that these components, if present at all, could vary depending on behavioral performance. But what to expect for the processing of correct sequences after learning? The learning studies, in which correct sequences were compared in learning and random conditions, were related to word segmentation and not to phrasal syntactic processing. The study by Sanders et al. (2002) reported a modulation of the N1 component as index of word segmentation. However, if the N1 effect was related to a less specific process as, for example, enhanced stimulus processing due to selective attention, a similar effect could well be expected for processing of our phrase-like units. Another prediction can be derived from studies using natural language stimuli with varying syntactic complexity. It was shown that the P600 is not restricted to incorrect sentences. It rather appears to be increased in amplitude when syntactic analysis becomes demanding (Friederici, Hahne, & Saddy, 2002; Kaan, Harris, Gibson, & Holcomb, 2000). Thus, we could expect a difference in the P600 time window even for correct sentences after a rule-based stream in comparison to their counterparts after the random stream, as it can be assumed that, after learning, participants would engage in some sort of syntactic operation which may be totally absent in the random condition.

METHODS

Participants

In the study, 27 right-handed, native German speakers with normal hearing volunteered. Seven participants had to be excluded due to a high number of artifacts in their electroencephalogram data or due to total absence of any learning effect. Mean age of the remaining 20 participants (of which 13 were women) was 25.9 years ($SD = 2.8$).

Stimuli and Procedure

For the experiment, four different made-up languages were created. A language consisted of 14 different words, namely, three Category A words, three Category C words, and eight Category X words. Words were CVCV sequences which were build from German syllables with medium frequency of occurrence. To control for unwanted acoustic modulations, the speech streams were produced using the voice de3 of the MBROLA diphone speech synthesizer (Dutoit, Bataille, Pagel, Pierret, & Van der Vreken, 1996). To indicate word boundaries, the first syllable of each bisyllabic was stressed as indicated by a lengthening of 70 msec and slightly higher pitch. In total, each word was exactly 536 msec long. For the rule-based exposure phases, the AXC sequences of each language were ordered randomly with the constraint that there were no adjacent repetitions of identical A–X structures. Random streams contained the identical tokens as rule-based streams in pseudo-randomized order, which was such that there was a minimal gap of three tokens between identical words. The rule-based and the random-input streams were synthesized once as a continuous stream and once with a 500-msec pause between triplets of words. Thus, each language was synthesized four times according to the four exposure conditions (rule-based with pause, rule-based without pause, random with pause, random without pause). Each exposure stream contained 198 triplets, which amounted to a stream length of 416 sec for streams with pause cues and 317 sec for streams without pause cues.

In test phases, 24 correct and 24 incorrect triplets were presented. Incorrect triplets were AXX sequences which were constructed with the constraint that the two X words were not identical. Each triplet was synthesized separately.

During the experiment, each participant was exposed to four experimental blocks consisting of an exposure and a subsequent test phase. For each participant, each language and each condition occurred once, however, in different language–condition pairings across participants. Thus, identical test items occurred for the different exposure conditions across participants. The order in which participants were presented the different exposure conditions was counterbalanced for the purpose of controlling for possible strategies such as looking for patterns that occurred in the previous input stream.

At the beginning of the experiment, participants were instructed in written and oral form to listen attentively to four alien languages during exposure phases in order to complete a grammaticality judgment during test phases. They were told that some of the languages may not be comprehensible to terrestrials. The electroencephalogram was recorded from 59 Ag/AgCl electrodes fixed in an elastic cap (Electro Cap International, Eaton, OH). Vertical and horizontal eye movements were recorded from electrode pairs which were placed above and below the right eye and from the outer canthi of the eyes. The sampling rate was 500 Hz and the recordings were on-line referenced to the left mastoid. Electrode impedances were below 5 kΩ. During the experiment, the participants sat in a sound-attenuated booth on a comfortable chair 1.3 m in front of a computer screen. The acoustic stimuli were presented via loudspeakers. Participants listened to four blocks of exposure and test phases which were indicated as such. While they were listening, participants saw a picture in cartoon style showing a robot face on the screen. Test phases followed immediately after exposure phases. During test phases, participants were presented a phrase 300 msec after a fixation cross appeared on the screen. At 1300 msec after the end of the sound, a picture appeared on the screen indicating that a button should be pressed. A smiling and a sad face indicated which side of the button box had to be pressed to indicate correct and incorrect phrases. Button configuration (left vs. right button for correct phrases) was reversed for half of the participants. After each block of an exposure and test phase, participants could take a rest.

Data Analysis

All statistics were computed using the SAS 8.2 software package. Behavioral responses were analyzed in a 4 × 2 analysis of variance with exposure (random, random with pause, rule-based, rule-based with pause) and answer type (number of correct answers vs. number of incorrect answers) as independent variables. ERPs were averaged in the time window from −200 to 1000 msec relative to the onset of the critical (last) bisyllabic in the test phases. Trials containing artifacts due to eye movements, amplifier saturation, or EMG were excluded from averaging. Twelve percent of the trials were rejected due to artifacts. For statistical evaluation of topographical differences, the electrodes were subsumed in four regions of interest (ROIs) with 11 electrodes: left anterior: FP1, AF7, AF3, F7, F5, F3, FT7, FC5, FC3, F9, FT9; right anterior: FP2, AF8, AF4, F8, F6, F4, FT8, FC6, FC4, F10, FT10; left posterior: TP7, CP5, CP3, P7, P5, P3, PO7, PO3, P9, PT9, O1; right posterior: TP8, CP6, CP4, P8, P6, P4, PO8, PO4, P10, TP10, O2. As we had no specific expectations about timing of our effects, we chose the time windows after visual inspection of the waveforms. Thus, the mean amplitude differences were analyzed in four subsequent time windows with a 2 × 2 × 2 × 2 repeated-measures ANOVA for AXC and AXX triplets separately. The four 2-level factors were hemi (left vs. right hemisphere), reg (anterior vs. posterior electrode sites), rule (rule-based input vs. random input), and pause (input with pauses vs. input without pauses). With the first three adjacent time windows, we tested for early ERP effects (25–125 msec, 125–225 msec, 225–325 msec), whereas later, slower changes were tested in the last time window from 350 to 750 msec. All effects which reached at least marginal significance at the $p < .10$ level are reported in the Results section.

RESULTS

Behavioral Results

Accuracy rates were 97% (SD = 6) for the rule-based condition with pauses, 67% (SD = 20) for the rule-based condition without pauses, 57% (SD = 16) for the random condition with pauses, and 56% (SD = 17) for the random condition without pauses. A significant interaction of exposure condition by correctness [$F(3, 57) = 24.50$, $p < .0001$] confirmed the differential distribution of correct and incorrect answers across exposure conditions. Further analyses revealed that only in the rule-based conditions did participants provide significantly more correct than incorrect answers [rule-based with pauses: $F(1, 19) = 271.93$, $p < .0001$; rule-based with no pauses: $F(1, 19) = 14.65$, $p < .001$] (Figure 2).

ERP Results

ERPs for Correct Phrases

When inspecting the ERP responses for correct C elements in the last position, an early, centro-parietally distributed negativity was seen for both rule-based conditions and an additional positivity was visible only in the rule-based condition with pauses (cf. Figures 3 and 5).

From 25 to 125 msec after stimulus onset, the repeated-measures ANOVA for correct (ACX) phrases revealed a significant main effect of rule [$F(1, 19) = 8.14$, $p < .01$]. In the following time window (125–225 msec), the same main effect was found [$F(1, 19) = 6.06$, $p < .024$]. In the time window from 225 to 325 msec, however, the main effect of rule reached only marginal significance [$F(1, 19) = 3.35$, $p < .083$]. Between 350 and 750 msec after stimulus onset, there was a significant three-way interaction of Reg by Pause by Rule [$F(1, 19) = 4.88$, $p < .04$]. Further analyses for each level of reg and of pause revealed a significant simple main effect of rule only for posterior electrode sites in the condition with pauses [$F(1, 19) = 6.51$, $p < .02$].

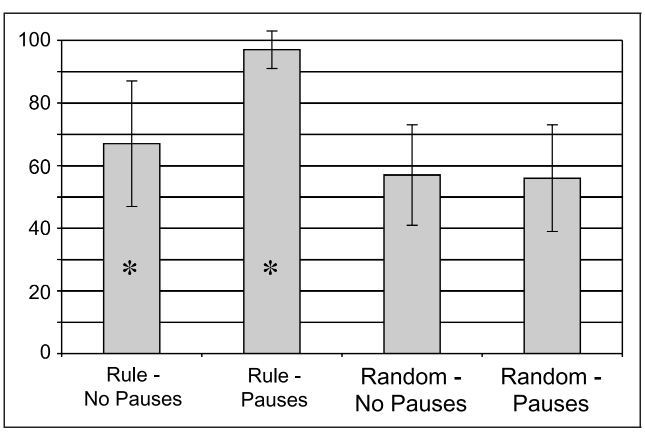


Figure 2. Accuracy rates in the grammaticality judgment task for each condition (* indicates significant difference from chance level).

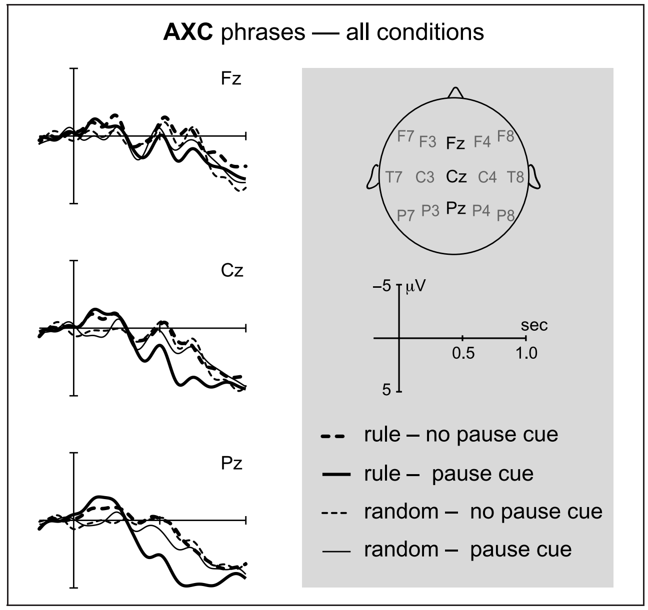


Figure 3. ERP responses time-locked to the last element of AXC phrases in the test phases. Dotted lines indicate ERPs for the conditions without pauses, whereas solid lines indicate the conditions with pauses. ERPs measured after rule exposure are plotted with thick lines and ERPs measured after random exposure are plotted with thin lines.

In sum, a broadly distributed negativity between 25 and 225 msec was confirmed for both rule-based conditions (condition with pauses and condition with no pauses). A subsequent posterior positivity was confirmed only for the condition with pauses.

ERPs for Incorrect Phrases

Visual inspection of the ERP responses for incorrect X elements in the last position of the sequences of the test phase indicated an early anterior negativity for both rule-based conditions and an additional positivity for the rule-based condition with pauses (cf. Figures 4 and 6).

Between 25 and 125 msec after stimulus onset, the repeated measures ANOVA Reg (anterior vs. posterior electrode sites) by Hemi (left vs. right electrode sites) by Pause (condition with pauses vs. condition with no pauses) by Rule (rule-based stream vs. random stream) for incorrect (AXX) phrases revealed a main effect of rule [$F(1, 19) = 4.47$, $p < .049$], a marginally significant interaction of Hemi by Rule [$F(1, 19) = 3.05$, $p < .097$], and a significant interaction of Reg by Rule by Pause [$F(1, 19) = 5.01$, $p < .037$]. Further analyses for each level of hemi revealed a simple main effect of rule over left hemispheric sites [$F(1, 19) = 7.58$, $p < .013$] and no significant effect over right hemispheric sites. The three-way interaction was due to a significant simple main effect of rule [$F(1, 19) = 5.36$, $p < .032$] for anterior electrode sites in the condition without pauses only. All other simple main effects were not significant.

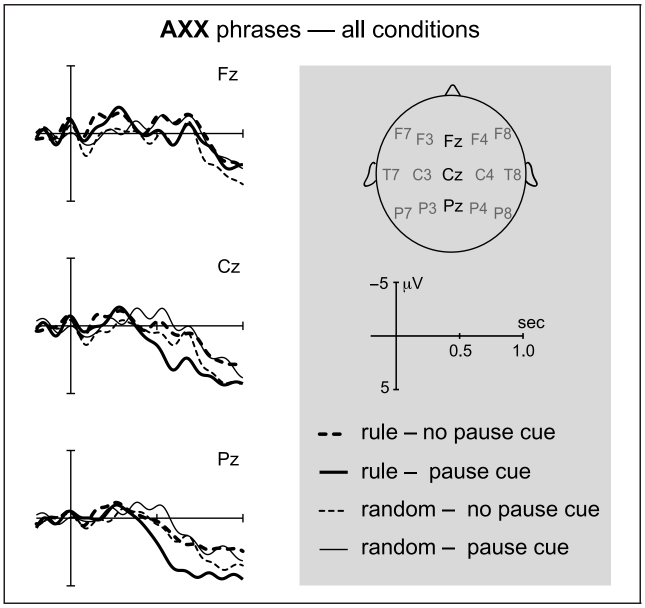


Figure 4. ERP responses time-locked to the last element of AXX phrases in the test phases. Dotted lines indicate ERPs for the conditions without pauses, and solid lines indicate the conditions with pauses. ERPs measured after rule exposure are plotted with thick lines and ERPs measured after random exposure are plotted with thin lines.

Between 125 and 225 msec, a main effect of rule was found [$F(1, 19) = 4.77, p < .042$] as well as an interaction of Hemi by Rule [$F(1, 19) = 4.02, p < .059$]. Further analyses for each level of hemi revealed a simple main effect of rule over left hemispheric sites [$F(1, 19) = 9.09, p < .007$] and no significant effect over right hemispheric sites.

Between 225 and 325 msec, a main effect of rule [$F(1, 19) = 4.63, p < .045$] and a marginally significant four-way interaction of Hemi by Reg by Rule by Pause [$F(1, 19) = 3.43, p < .080$] were confirmed. Separate analyses for each effect of rule were conducted for each region of interest and each level of pause separately. Results revealed simple main effects of rule only for left [$F(1, 19) = 3.97, p < .061$] and right [$F(1, 19) = 4.22, p < .054$] anterior sites in the condition with pause cues.

Between 350 and 750 msec, the two-way interactions of Reg by Rule [$F(1, 19) = 4.20, p < .054$] and of Rule by Pause [$F(1, 19) = 4.41, p < .049$] reached significance. When testing the effects of rule for each level of reg separately, there was a marginally significant effect over posterior electrode sites [$F(1, 19) = 3.92, p < .062$]. In the analyses for each level of pause, a significant effect of rule was confirmed only for the condition with pause cues [$F(1, 19) = 4.93, p < .039$].

In sum, the statistical analyses confirmed an early left-lateralized negativity for both the condition with pauses and the condition without pauses. An anterior negativity in this time window was seen only for the condition without pauses. However, in a later time window (225–325), an anterior negativity was seen for the condition with pauses, but not for the condition without pauses. A late positivity was seen only for the condition with pauses (Figures 3, 4, 5, and 6).

DISCUSSION

In the current study, we report behavioral and ERP results related to processing of nonadjacent dependencies of the form AXC between word-like bisyllabics after different exposure conditions. Processing of sequences after exposure to rule-based streams was compared to processing of sequences after exposure to random streams. To test the impact of an additional segmentation cue on learning success and processing, the rule-based and the random exposure streams were presented once with a 500-msec pause between phrases and once in a continuous manner.

Learning Success

The behavioral data suggest that the bracketing of a continuous language stream with inserted pauses helps in the acquisition of the hidden regularity. This was expected based on reports from previous behavioral artificial grammar learning studies (Peña et al., 2002; Morgan et al., 1987). However, learning was not totally absent when pause cues were lacking as it was in the study of Peña et al. (2002). This may be due to the different test conditions used. Our test conditions do not allow to decide if participants really used the nonadjacent dependency relationship for predicting the last element of the triplet or if they relied merely on transitional frequencies between adjacent elements (i.e., the final and the prefinal elements). Our violation condition was a local violation which we used in order to test for ERP correlates of local phrase structure processing. An ultimative test for the processing of nonadjacent dependency processing would require to test violations of the type AXC*, whereby the specific element C* is incorrect although belonging to the right category (cf. Perruchet et al., 2004). However, even if participants did not use the nonadjacent relation directly to parse the sequences, the difference between the condition with and the condition without pauses indicates that pauses improved performance in the detection of a structural violation. This adds to previous evidence which suggested that prosody may have a scaffolding function during language learning by restricting possible analyses to relevant units (Soderstrom et al., 2003; Morgan, 1996; Kemler Nelson, Hirsh-Pasek, Jusczyk, & Cassidy, 1989). In our case, the relevant units are two words, which are highlighted by prosody as instantiated by pauses. Both the concept of frequent frames (Mintz, 2002, 2003) as well as the suggested saliency of the edge position (Endress et al., 2005) during artificial language learning may elucidate how pauses may highlight A–C dependencies. Mintz (2002,

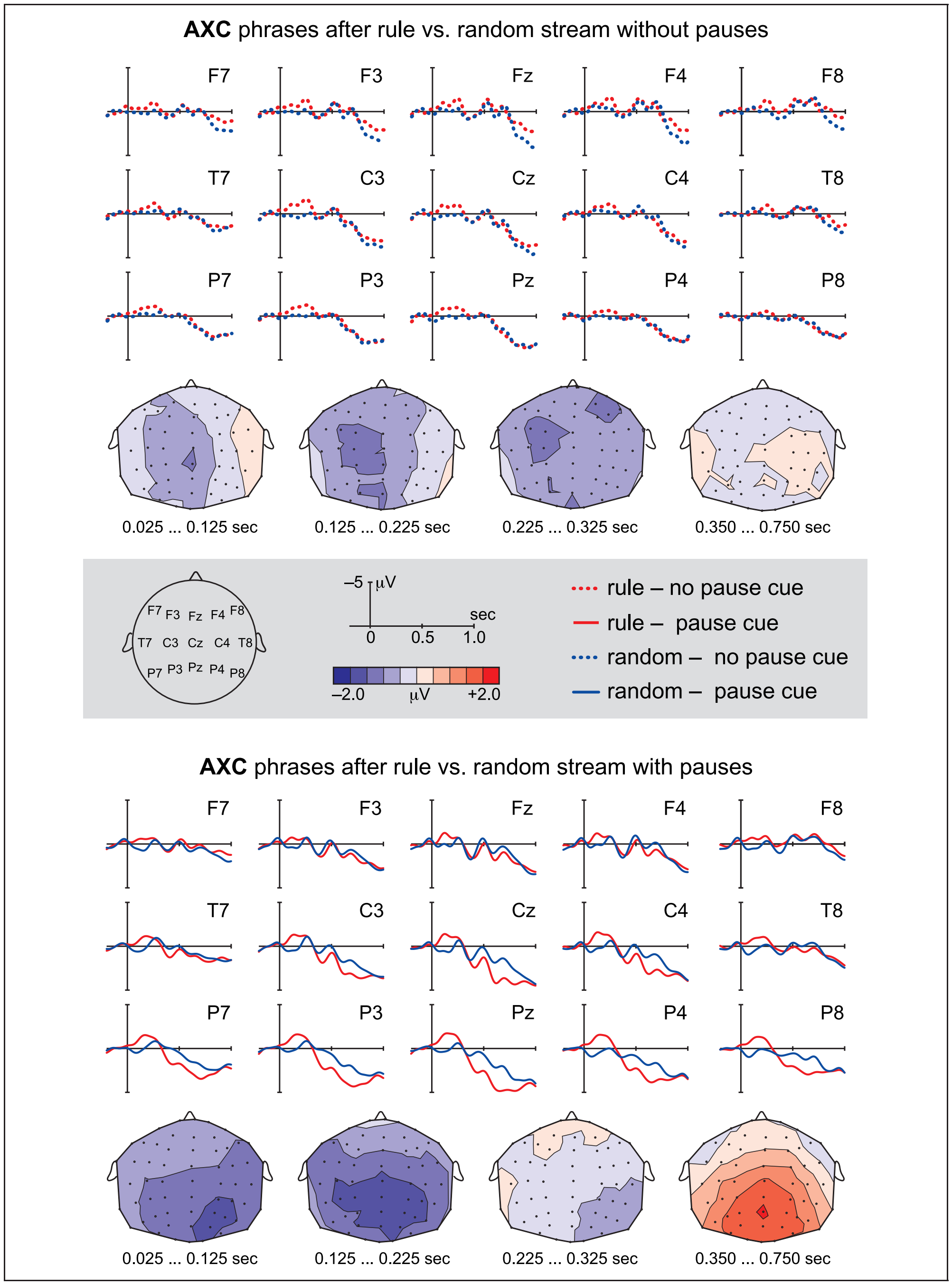


Figure 5. ERP responses and corresponding isovoltage difference maps during listening to AXC (correct) phrases separated for the condition with pauses and the condition without pauses. ERPs are time-locked to the onset of C.

2003) suggested that the distributional information provided by frequent frames, which are defined by two co-occurring words with exactly one (variable) intervening word in the middle, can assist the acquisition of word categories. The author used corpus analyses (Mintz, 2003) as well as an artificial language study (Mintz, 2002) to test this hypothesis. The role of prosody, however, remains unclear from these studies, as naturally spoken language, including prosodic cues, was used as stimulus material. If we conceptualize A–C structures as frequent frames, pauses exactly highlight those units which assist learning. In a different, but related paradigm, Endress et al. (2005) studied the role of edge positions for rule-learning. They found that a repetition structure contained in a syllable string was only acquired when it occurred at edges, which thus appear to be specifically relevant for learning. In our study, the A–C dependencies became dependencies between two edge positions only by the insertion of pause cues. This may explain the behavioral differences between stimulus conditions. Whether there is a fundamental difference in processing mechanisms in the condition with and without pauses cannot be concluded from behavioral data alone. We will therefore now turn to the ERPs measured

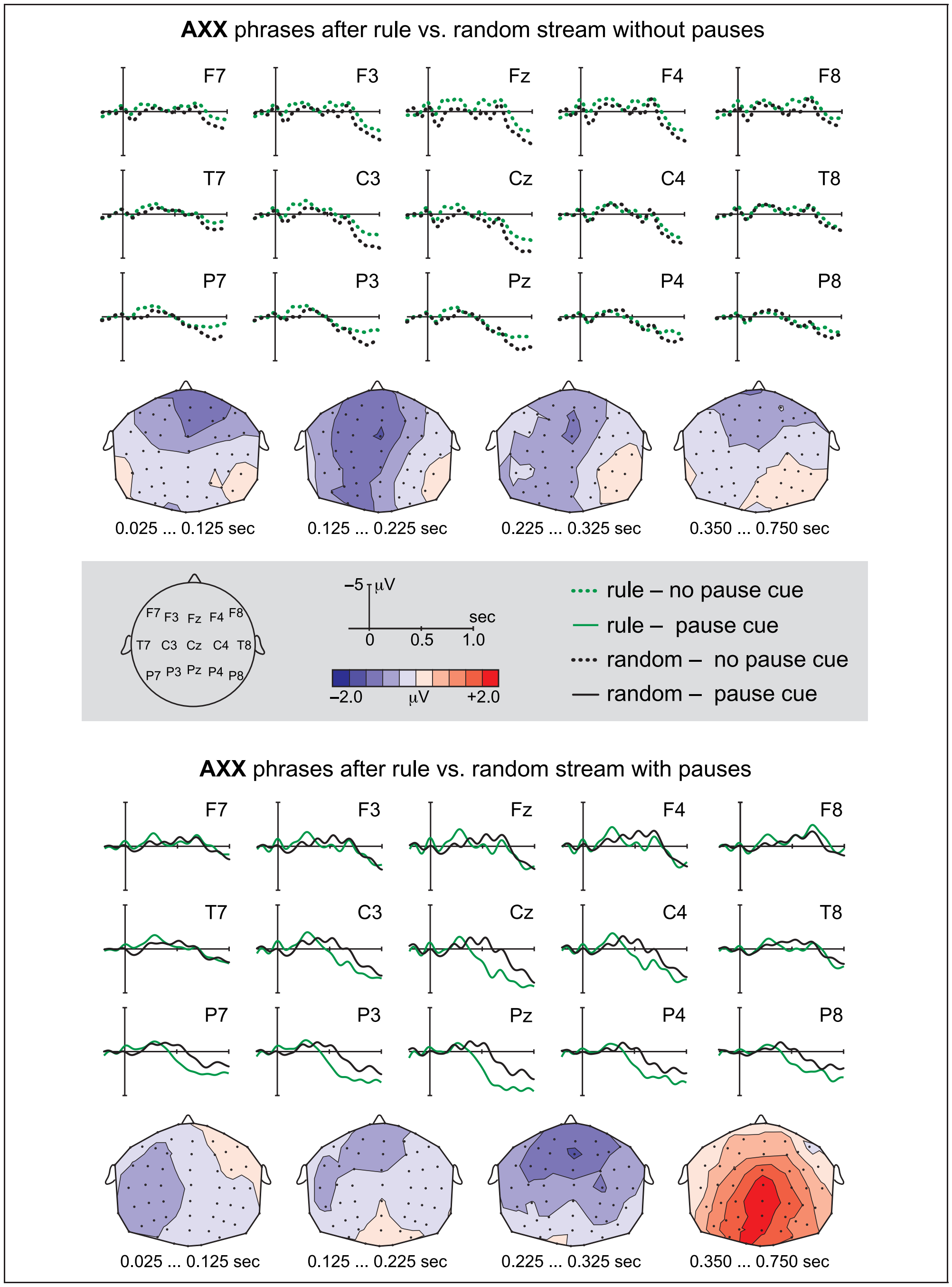


Figure 6. ERP responses and corresponding isovoltage difference maps during listening to AXX (incorrect) phrases separated for the condition with pauses and the condition without pauses. ERPs are time-locked to the onset of X.

during the processing of correct and incorrect triplets in the test phase.

Processing of Correct Items

For the conditions with and without pause cues, there was a broadly distributed negativity starting as early as 25 msec after stimulus onset. Due to the early latency, we concluded that the effect must be related to a processing stage which is temporally at or close to sensory processing levels, despite a potential underestimation of the real latency due to coarticulation effects which could be present to a certain degree in diphone-synthesized speech.[1] As the effect occurs for the identical stimuli as a function of different exposure conditions, it must reflect some top–down influence, however. Endogenous influences on early auditory ERP components, such as the N100, have frequently been reported and have often been related to sensory gating processes or cognitive processes triggered by selective attention (Sanders, Stevens, Coch, & Neville, 2006; Hansen & Hillyard, 1980; Hillyard, Hink, Schwent, & Picton, 1973). Näätänen (1982, 1990) proposed a very specific interpretation of such early attention-related ERP modulations in response to target stimuli, which he subsumed as processing negativity (PN), which is a negative deflection indexing a selective sensory state due to rehearsal of relevant stimulus features. In a word-learning experiment in which word segmentation was at issue, Sanders et al. (2002) reported an amplitude enhancement of the N100 component after participants had received extensive training on a small set of lexical items and were able to segment words from a continuous syllable string. The authors see the enhanced N100 as an early index for word segmentation. However, a less specific explanation of the observed N100 modulation seems conceivable, namely, that it indexes the allocation of attentional resources to a specific target syllable (marking word onset) rather than word segmentation per se. In any case, the result shows that the N100 response can be modified as a result of language training.

In some way or another, it reflects experience-dependent cognitive processing. We like to see the early negativity in our study as similar to the above-described effects, although not identical, as the topography and the shape of the negativity do not correspond to a typical N100. The findings of the attention-related N100 and processing negativity were obtained in tasks which were specifically designed to manipulate selective attention toward a specific set of stimuli while others had to be ignored (Sanders et al., 2006; Hansen & Hillyard, 1980; Hillyard et al., 1973). In our task, however, participants' focus of attention was at their free disposal so to say. It is conceivable, though, that learning, which obviously occurred only in the rule-based conditions, resulted in a specific attentional bias. If participants had acquired some kind of representation or sensitivity toward the rule-based A–C frame and held this actively in memory, this could have resulted in an enhanced processing of the A and the C elements, as X elements could be classified as not important. In our task, the element that is crucial for the grammaticality judgment is the C element, and thus, participants had every reason to pay specific attention to the position of element C. In the case of the occurrence of a correct C element, participants could rapidly match the incoming signal with the anticipated template and pass it on to further processing. Which process exactly is reflected in the early negativity, whether it is mere sensory enhancement, template access, or template matching, cannot be concluded from the present analysis. The question remains: What exactly was the template that participants held in memory? As the negativity occurred so early, it is improbable that it was a representation of a whole CVCV word. Our contention is that participants may have classified stimuli using a very simple as well as salient phonological feature, namely, the distinction between light vowels e and i and dark vowels o and u, which can be distinguished by place of articulation. If participants relied on this distinction, it is not necessary to wait for the whole CVCV sequence to recognize correctness or violation of a phrase. The judgment can be given based on a simple mapping of the expected vowel category (light vowel) with the actual vowel category. From a questionnaire that participants filled in after the experiment, we could obtain evidence that participants used such a strategy. Without having explicitly been asked for functions of light and dark vowels in the ACX structures, 13 of 20 participants reported that they had discovered rules related to the sequence of light and dark vowels. In the random conditions, such an expectation could not be build.

Interestingly, the early negativity was seen independently of the presence of an additional acoustic segmentation cue. This indicates that the respective expectations or selective attentional state could be built from exposure to distributional properties of the words alone. Moreover, the negativity does not go together with good behavioral performance. Thus, it seems that the process it reflects is contributing very little, if at all, to the conscious decision process.

We will now turn to the discussion of the additional positivity, which we found after exposure to the rule-based stream with pauses. In line with results from earlier natural language and artificial grammar studies, we interpret this positivity to reflect controlled syntactic processes (Bahlmann et al., 2006; Mueller et al., 2005; Friederici, Steinhauer, et al., 2002; Lelekov, Dominey, & Garcia-Larrea, 2000). The fact that it occurs not only for incorrect but also for correct items does not come as a surprise. Rather, this may indicate that participants are still at a stage in which even the processing of correct sequences is a demanding structural processing task. Correct, but difficult, syntactic structures have shown to elicit P600 effects in language experiments previously (Kaan & Swaab, 2003; Friederici, Hahne, et al., 2002; Kaan et al., 2000). Moreover, in the context of second-language learning, it has been shown that the P600, in response to correct sentences and to incorrect sentences, can be of similar amplitude (Hahne & Friederici, 2001). Thus, participants may have applied quite effortful syntactic integration mechanisms independently of the sentences' correctness in order to reanalyze and revalidate their syntactic judgment to ensure a correct answer. In the noncued condition, participants may not have had a representational basis (i.e., rule-knowledge) for such a validation process, and thus, did not display the positivity. One might be tempted to argue that the positivity may be related to task difficulty instead of the acquisition of different processes. In principle, it may be possible, that the emergence of the positivity negatively correlates with the experienced task difficulty as difficult syntactic structures can lead to enhanced P600 effects. However, the relationship between amplitude and difficulty goes in the opposite direction as would be normally expected. In the present case, the positivity was larger for the easier condition, thus, we therefore argue that the process reflected in the difference may rather be the emergence of rule-integration processes.

In sum, the mechanisms related to the processing of correct sequences after exposure to rule-based input with and without pause cues seem to be similar at an early point in time but different at a later processing stage. With respect to the learning mechanisms operating during exposure for sequences with and without pauses, this could mean that part of the processes on which the acquired representation is based is comparable (template matching of vowel sequence) while other parts emerged only when pause cues were present (later rule-integration processes). Thus, it does not seem to be the case that completely different aspects are learned depending on the presence of acoustic cues; rather, cues provide the basis for additional, complementary processes which, nonetheless, may be necessary for full rule acquisition.

Processing of Incorrect Items

We found anteriorly focused negativities in response to incorrect word categories (AXX instead of AXC structures) in both rule-based exposure conditions, and a late positivity only for the condition with pause cues. Moreover, there were intriguing differences with respect to timing of the negativity among the condition with pause cues and the condition without pause cues. Despite lower behavioral performance, the negativity for the condition without pause cues occurred earlier. If the anterior negativity, as proposed, for example, by the artificial language learning study by Friederici (2002), is interpreted as an indication for automatic syntactic processes, it is surprising that we find the negativity to occur earlier in the condition which is behaviorally the more difficult one. This seems quite implausible at first sight, as one might think that, during early stages of learning, automatic processes, which are not subject to voluntary control, are installed first and before the more controlled ones come into play. This, however, does not seem to be the case. During first-language acquisition, the P600, in response to syntactic violations, is present earlier (at 24 months of age; Oberecker & Friederici, 2006) than the early negativity which only develops some months later (at 32.5 months of age; Oberecker, Friedrich, & Friederici, 2005). This also holds for adult learners of a second language for whom the (early) anterior negativities are almost never observed, whereas positivities (P600) already emerge at lower proficiency stages (cf. Mueller, 2005, for a review). Thus, the P600 seems to be present earlier during language acquisition compared to the anterior negativity. Based on these findings, we might conclude that the biphasic pattern (negativity between 225 and 325 msec and late positivity) for the condition with pause cues reflects a more developed processing stage (rule-based) than the very early negativity, starting at 25 msec. We already discussed the possibility that this very early negativity might reflect local prediction based on sensory information. Another potential source for the early timing of the negativity in the condition without pauses could lie in the content of learning itself. In the condition without pauses, the only cue to phrase structure information was distributional. It is possible that participants in this condition only processed local transitional information and no nonadjacent dependencies. Such learning would have been sufficient to diagnose AXX triplets as incorrect, as during learning, two X elements never occurred in a sequence. In natural language processing, the earliest syntactic ERP component, the ELAN, has been claimed to reflect the processing of local syntactic dependencies between word categories (Friederici, 2002). Therefore, it is conceivable that, specifically, the condition in which only local transitional information was available triggered an early anterior negativity which may reflect the violation of a local expectancy without positing a long-distance relation between the first element and the last.

For the condition with an additional pause cue, an anterior negativity was present in a later time window (225–325 msec). It remains open whether this reflects just the delayed recruitment of the same processing resources as in the condition without pause cues or if it reflects a qualitatively different process. Based on previous experiments on rule processing in language, it could well reflect syntactic processes similar to those reflected in LAN components. LANs are often seen as indication for morphosyntactic processes and agreement processing, including nonlocal syntactic dependencies such as subject–verb agreement (Friederici, 2002). For example, in the study of Coulson, King, and Kutas (1998), participants were presented with a verb agreement violation instantiated in an incorrect third-person singular –s (**They suns themselves on the beach*.). In this case, the syntactic violation becomes evident only when the relationship between the suffix and the preceding pronoun is processed (they. . .–s) as the verb stem (sun), as such is, of course, a correct grammatical form. If the pauses, in our case, highlighted the rule-based dependency between the A and the C elements, the negativity in response to the incorrect X element could reflect the processing of the nonadjacent violation (A. . .X instead of A. . .C), which possibly affords more time compared to the computation of local phrase structure.

Similar to the correct condition, a subsequent positivity was seen for the incorrect condition after rule-based exposure with pause cues. We interpret the effect likewise as a correlate of syntactic integration mechanisms. As this effect was observed in the correct as well as in the incorrect conditions, we assume that the underlying process is related to the attempt to integrate independently of its successful outcome. The process reflected in the positivity may well be functionally related to the grammaticality judgment at the behavioral level.

The results from the incorrect conditions seem to indicate greater differences between input conditions with and without pauses compared to those from the correct condition. Although earlier processes were comparable in the correct conditions with and without pauses, this is not the case for the incorrect conditions.

Theoretical Implications

At the outset, our study was motivated by the debate about the underlying processes in statistical and rule-learning. Specifically, we liked to address the hypothesis, raised by Peña and colleagues, that acoustic cues can trigger rule-learning processes which are conceptualized as fundamentally different to statistical learning processes. Although the ERP data recorded in our experiment were not directly taken from the learning phase, we may draw conclusions about learning by looking at its outcome. In addition to behavioral data, ERPs allow us to specify at what time point processing of learned items differed from processing of unlearned items and what type of cognitive process it may be. For both correct and incorrect items, we found differences and similarities between the input conditions with and without pauses, which we discussed in detail above. Indications for rule integration and for the processing of a nonadjacent morphosyntactic dependencies were seen only for the condition with pauses. The former were concluded from the finding of a P600-like positivity and the latter from the observation of a LAN-like negative component for the condition with pause cues. For the condition without pauses ERPs, the presence of an early centrally distributed negativity suggested that processes of selective attention and local expectancies for a specific stimulus category may have taken place. Thus, our results are consistent with the notion that some presegmentation is necessary for the full acquisition of nonadjacent rules. This seems to be accompanied by ERP changes during the processing of the respective items. Unfortunately, the present data do not allow us to specify the dynamics of the learning process itself, namely, if it is a gradual or a discrete process of rule extraction. The different end-products of learning, however, suggest that the condition with pauses led to qualitative changes in neural processing in addition to quantitative changes in behavioral performance.

Conclusion

To our knowledge, this is the first ERP study which tested nonadjacent dependency processing in phrase-like units of auditory language after untutored learning by mere exposure to a rule-based input. Participants successfully acquired a representation of the phrases and, depending on stimulus-based cognitive requirements (processing of correct vs. processing of incorrect items), different cognitive operations seem to be involved in solving the task. When pauses were present in the learning input, qualitative changes with respect to ERP components emerged, suggesting that different cognitive and neural processes were enabled by listening to a presegmented learning stream. This finding is consistent with the proposal that acoustic cues, such as pauses, may trigger the extraction of syntactic regularities (Peña et al., 2002). However, a very early ERP component (early negativity for correct items) occurred independently of the presence of a pause cue, indicating that at least one, relative early process (possibly template matching) is shared independent of the presence of an additional pause cue. Thus, our results support a multidimensional view of learning, whereby all possible sources of information, in our case, distributional and prosodic, can be and are used to build a stimulus representation.

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Note

1. Diphone synthesizers concatenate pieces of speech which contain a boundary between two phonemes which makes them sound relatively natural without losing the power of control for acoustic properties.

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