

# Dissociable ERP profiles for processing rules vs instances in a cognitive sequencing task

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A hotly debated question in cognitive neuroscience is whether individual instances of perceptual sequences, and the rules that describe them, are processed by the same brain mechanisms. We tested the hypothesis that such rules and instances are processed by dissociable brain mechanisms. We analyzed event-related brain potentials (ERPs) evoked during cognitive sequencing tasks that assessed surface (instance) vs abstract (rule) structure learning. Sequence instances ABCBAC and DEFEDF have different serial order or surface structure, but share the same rule or abstract structure, 123213. Nine healthy subjects were first trained to learn a set of surface and

abstract structures in sequences of visually presented stimuli. During the subsequent ERP recording, for surface and abstract structures, they then discriminated between acceptable and unacceptable sequences, based on the pre-learned regularities. Abstract structure processing evoked a late positivity around 500 ms, which was not seen in the surface structure processing, supporting our hypothesis of dissociable processes. We discuss implications for the rule vs instance debate, and similarities between this late positivity and the P600 observed in previous studies of syntactic processing. *NeuroReport* 11:1129–1132 © 2000 Lippincott Williams & Wilkins.

**Key words:** Abstract structure; P600; Sequence processing; Surface structure; Syntax

## INTRODUCTION

Among the most adaptively effective cognitive functions is the capacity to generate novel yet appropriate sensorimotor sequences in language, game playing, motor control etc., based on learned rules. The hotly debated question remains as to whether the same processes that are involved in learning a single instance of a sensorimotor sequence are also involved in the extraction and manipulation of generalized rules for generating new sequences [1–5]. This question has recently come to the forefront in the context of infant language processing where both instance [6] and rule [7] learning have been demonstrated. Indeed, the debate over shared vs distinct mechanisms continues and has important implications in the theory of learning and language acquisition [7–12].

In order to address this open issue, we have recently studied the instance vs rule distinction in the domain of sensorimotor sequence learning, where we introduce the following notions of surface and abstract sequential structure: In a temporal sequence of items, the surface structure is the sequence of items itself (i.e. their serial order), while the abstract structure is the underlying rule that permits the construction of this and other sequences of the same type. For example, the isomorphic sequence instances ABCBAC and DEFEDF have different serial orders or surface structures, but share the same rule or abstract

structure, 123213. This abstract structure can be used to generate an open set of new isomorphic sequences such as RAFARF, NZTZNT etc. We have recently argued, based on studies of simulation [12–14], experimental psychology [14] and neuropsychology [15,16] that the processing of surface and abstract sequential structure rely, at least in part, on dissociable neurophysiological processes.

Our simulation studies demonstrated that surface structure can be learned by a network model that uses recurrent connections to encode sequential structure, but that this model fails to learn abstract structure. In contrast, a modified version of this model that represents sequences in terms of their internal repetitive structure can learn abstract but not surface structure [13,14]. Indeed, only the abstract model was able to learn the rule-based regularities as demonstrated by the infants in Marcus *et al.* [7,12]. While this indicates from one theoretical perspective that surface and abstract structure are treated by dissociable processes, the debate is still open. Indeed, it is possible that alternative models may be able to perform the abstract task without modification, as recently suggested by Christiansen and Curtin [11], thus motivating further exploration of this issue.

In human studies, we demonstrated that the cognitive processes for treating surface structure appear to be active by default, in implicit conditions, even when subjects are

unaware that they are learning [14]. It is likely that these processes rely on the frontostriatal system, as they are impaired in parkinsonian patients [17,18]. In contrast, cognitive processes for the treatment of abstract structure appear to rely less on the frontostriatal system, as they are shown to be effective in Parkinson's patients [15,19]. In addition these processes appear to be linked to subjects' explicit awareness of the abstract structure [2,14–16], and such explicit awareness has now been demonstrated to involve neurophysiological processes that are dissociable from those for implicit processing [20].

These arguments for dissociable neurophysiological processes underlying surface and abstract structure would predict a corresponding difference in brain potentials evoked by the processing of these two types of sequential structure. A similar type of dissociation in syntactic *vs* semantic processing in language has been extensively demonstrated in ERP studies [21–23]. Such studies indicate that the processing of semantic anomalies is associated with an N400 response, a negative going potential around 400 ms [22,24–26]. In contrast, detection of syntactic anomalies has been associated with the P600, an enhanced centro-parietal positive going effect around 500–600 ms [21,22]. Syntactic processing is also associated with the lateral anterior negativity (LAN) an early negative going wave around 400 ms predominantly over the left anterior cortex, though this appears to be a more selective response that does not occur for all syntactic processing [21,22,27,28].

We previously observed that abstract sequential structure, as defined above, is similar to syntactic structure in that both are based on generalized rules governing the specification of sequential form, rather than content [13,29]. Given this similarity, if the treatment of surface and abstract structure rely on dissociable processes, we would predict that abstract structure would be accompanied by a late positivity (of the P600 type) that would not be observed for surface structure processing. To test this prediction we recorded ERPs while subjects performed sequence discrimination tasks that selectively required surface or abstract structure processing, and then compared the resulting ERP profiles.

## MATERIALS AND METHODS

Nine subjects, aged 21–35 years and free of neurological impairment entered the study. All subjects were advised of the details of the procedure and gave their informed consent to participate. Subjects were seated 50 cm in front of a 19 inch color video monitor to observe the presentation of sequences of colored geometrical forms at a fixation point on the screen. The sequences had to be categorized as acceptable or unacceptable with respect to a pre-learned surface or abstract structure.

Each subject was recorded during four sessions of ~15 min each, with a 5 min break between sessions. Two sessions tested the ability to categorize sequences as acceptable or unacceptable with respect to a pre-learned surface structure (surface task), and two sessions tested the ability to categorize sequences based on a pre-learned abstract structure (abstract task). The four sessions were administered in an ABBA permutation, with half of the subjects starting with the surface task, and half starting with the abstract task.

**Stimulus presentation and timing:** For both the surface and abstract tasks, each sequence consisted of six elements. Elements were presented for 200 ms with a stimulus onset asynchrony of 800 ms. The surface task used a single six-element reference surface structure for training and testing. Likewise, the abstract task used a single six-element reference abstract structure of the format 123423 for training and testing. The reference abstract structure was used to generate a set of 360 ( $6 \times 5 \times 4 \times 3$ ) isomorphic sequences such as ABCDBC, DEFCEF, etc., where each letter represents one of six possible geometrical figures. This set was divided into training and testing sets of 180 sequences each. For both tasks, on a randomly selected half of the trials (both for training and recording), the sequence was rendered unacceptable by changing the fifth element.

**Training:** During a training period just prior to the recording, subjects learned the reference surface and abstract structures. The reference surface and abstract structures were learned separately. During training for the reference surface structure, subjects were shown a figure indicating the six element sequence of geometrical forms corresponding to the reference surface structure, and were told that they would be asked to classify sequences of geometrical forms as acceptable or unacceptable with respect to this surface structure. Likewise, during separate training for the reference abstract structure, subjects were shown a figure indicating a six element sequence of geometrical forms with the abstract structure 123423 (in which the second and third elements are repeated in the fifth and sixth elements), and were told that they would be asked to classify sequences of geometrical forms as acceptable or unacceptable with respect to this abstract structure.

For both training conditions, on a random distribution of half of the training sequences, the fifth element of the sequence was modified to violate the reference structure, thus rendering the sequence unacceptable. Subjects were not aware of the distribution of unacceptable sequences, nor were they aware that the fifth element was the site of violation. During the training, feedback was provided. Learning was demonstrated by error-free classification of 10 successive sequences. For all subjects, this knowledge of the reference structure was expressed after 15–25 trials (sequences) for both the surface and abstract structure training conditions.

**Recording:** The subsequent ERP recording then took place in four permuted sessions as described above. Artifacts in recordings were rejected automatically, and recording proceeded until at least 20 acceptable and 20 unacceptable sequences were recorded for each session. Each recording session thus consisted of ~45–50 sequence presentations.

Brain activity was recorded with 20 electrodes attached to the scalp according to the international 10-20 system, and referenced to the nose. The electro-oculogram (EOG) was monitored by a silver/silver chloride cup electrode attached to the supero-lateral margin of the right superciliary arch, also referenced to the nose. A ground electrode was fixed to the forehead midway between the Fz and Fpz positions. Electrode/skin impedances were kept below 2 K $\Omega$ . Visual responses were amplified differentially 30 000

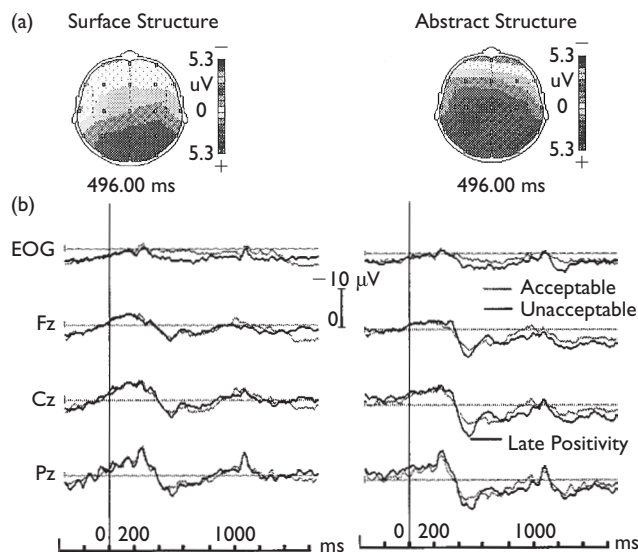
times (bandpass 0.3–30 Hz) and digitized at 250 Hz over an analysis time of 2048 ms, starting 400 ms prior to the presentation of the fifth stimulus, until the final stimulus. An automatic artifact rejection system excluded from the average any trial containing transients exceeding  $\pm 60 \mu\text{V}$  at any recording channel including the EOG. Topographical maps of the scalp distribution of ERP signals were obtained with a commercially available system (Brain Atlas, Biologic Sys Corp., Chicago, IL, USA); maps were first derived by linear interpolation and later by 2D spline functions.

**Data analysis:** Analyses were performed on the scalp electrode voltage differences (unacceptable minus acceptable conditions) during four temporal periods of interest expressed in milliseconds from the onset of the critical fifth element: (1) a reference period from 0 to 112 ms, (2) an early negativity (EN) period from 280 to 380 ms, (3) a late positivity (LP) period from 400 to 500 ms, and finally (4) a slow wave (SW) period from 600 to 700 ms. These data were analyzed in a three-way ANOVA on period (Ref, EN, LP, SW), electrode (Fz, F3, F4, F7, F8 Pz, P3, P4, Cz) and condition (surface, abstract). The dependent variable was the voltage difference in microvolts for responses to unacceptable sequences minus those for acceptable sequences. The voltages for responses to acceptable sequences and unacceptable sequences were calculated for each subject as the average of the 40 trials for the given condition, electrode and time period.

## RESULTS

The subjects were well trained to discriminate sequences based on the reference surface structure and reference abstract structure, with performance  $> 90\%$  correct in all cases. Two subjects were rejected for excessive eye blinks. Figure 1a illustrates the surface maps of electrical activity differences in microvolts, between responses to unacceptable sequences and those for acceptable sequences during the late positivity (LP) period. These difference maps indicate a positivity at 496 ms that appears more pronounced for the abstract than for the surface task. Figure 1b displays the responses at the fifth element for acceptable and unacceptable sequences for the two tasks, at the midline electrodes. For both tasks, there is a biphasic response with an early negativity, followed by a later positivity. Both the negative and particularly the positive responses were more pronounced for unacceptable sequences in the Abstract task with respect to the surface task (see Fig. 1b).

These observed differences between the ERP profiles for surface and abstract structure processing were confirmed in the condition  $\times$  period  $\times$  electrode ANOVA. The condition  $\times$  period interaction was reliable ( $F(3,216) = 7.1$ ,  $p < 0.0005$ ), verifying that period-specific processing differences between acceptable and unacceptable sequences varied depending on whether surface or abstract structure was being processed. Planned comparisons revealed a significant difference between these voltage difference values for the late positivity (LP) and the reference period in the abstract condition ( $p = 0.00001$ ), but not the surface condition ( $p = 0.35$ ). A subsequent analysis revealed that when electrodes were grouped in terms of anterior, central,



**Fig. 1.** Comparison of surface vs abstract processing conditions for the critical fifth stimulus. The surface maps of the difference in microvolts between potentials for unacceptable–acceptable sequences illustrate a late positivity around 500 ms that appears more pronounced and more posterior in the Abstract structure condition. In the grand-averaged traces for the acceptable and unacceptable sequence processing for the midline electrodes, the late positivity appears enhanced in the abstract processing condition.

and posterior scalp locations, the LP effect was more pronounced in the parietal electrodes ( $p = 0.0002$ ) than in the central ( $p = 0.011$ ) or anterior ( $p = 0.022$ ) regions.

## DISCUSSION

A given perceptual sequence can be described in terms of its specific surface structure or in terms of its more generalized abstract rule structure. Thus, the sequence ABCBAC contains a surface structure defined by the sequential order of its elements, and an abstract structure defined by the rule 123213 that describes the repetition relations between the triplets 213 and 123. In the current experiment we attempt to dissociate the processing of surface and abstract structure in two tasks. In each task a single reference structure provides the basis of classification. The surface task requires element-by-element comparison of the reference surface structure with the current sequence. The abstract task requires mapping the reference abstract structure onto the current sequence in order to compare repeating elements (i.e. that elements 2 and 3 are repeated in elements 5 and 6).

Our ERP analysis demonstrates significant processing differences associated with the treatment of surface vs abstract incongruities. This suggests that these two levels of treatment rely on distinct neural processes, in agreement with a growing line of evidence from studies of simulation [12–14], experimental psychology [14] and neuropsychology [15,16,19]. Given this difference in ERP profiles for surface vs abstract structure processing we might now ask if an analysis of these profiles can inform us of the nature of the underlying processing.

From this perspective we note that one of the principle

differences between surface and abstract structure is that a single abstract structure (e.g. 123213) can be used to generate an open set of new sequences (e.g. ABCBAC, DEFEDF, XRSRXS, etc.), whereas surface structure does not so transfer to new sequences. In this sense, abstract structure is similar to syntactic structure in that both can be used to generate or recognize new isomorphic sequences. We have proposed that there may be common neurophysiological processing for this aspect of the treatment of abstract and syntactic structure [13,14,29], and have indeed demonstrated a significant correlation between impairments in treating abstract structure and syntactic structure in agrammatic aphasic subjects [29]. Given these observations, one would expect to encounter similarities in the ERP profiles for these two types of processing. Interestingly, in several studies that contrast syntactic with other (e.g. semantic, lexical) aspects of language processing, the ERP profiles for syntactic processing share one major aspect of those that we have found for abstract structure processing. In particular, the presence of a late positivity similar to the one we observed in abstract but not surface processing has been repeatedly reported during the treatment of syntactic category violations [21,22,27]. In related studies this positivity is seen as a member of P300 component, often found following unexpected stimuli which require an updating of preceding information [30]. Recently a P600-like response has also been demonstrated in response to incongruities in the syntactic phrase structure of music in musically educated subjects [31]. This provides additional evidence that abstract structural organization for both linguistic and non-linguistic sequences may rely on partially overlapping neurophysiological processes.

It is noteworthy that in response to abstract structure violations, we did not observe a significant early left anterior negativity reported in certain syntactic violation studies [21,23,30]. This suggests that while there may be some common neurophysiological basis for syntactic and abstract sequence processing, syntactic processing may require additional neurophysiological process, including those left hemisphere structures responsible for the early lateralized negativity.

Completing the comparison with linguistic studies, we note that surface structure violations do not give rise to an N400-like response observed for semantic violations, and the more general lack of similarity between ERPs for surface structure incongruities and ERPs for semantic violations. Thus while the processing of abstract and syntactic structure might share some common neurophysiological basis, this appears not to be the case for the processing of surface and semantic structure.

## CONCLUSION

Are rules distinct from the instances they describe? Our primary objective here was to test the hypothesis that

surface structure (instances) and abstract structure (rules) rely on distinct neurophysiological processes that should be revealed by dissociable ERP profiles. The significant differences in cortical activity that we observed during processing of surface *vs* abstract structures, as revealed by the condition  $\times$  period interaction, support this hypothesis. Such evidence provides a critical argument in the ongoing debate concerning the separability of rules and instances, suggesting that indeed they are neurophysiologically dissociated. The similarity between the late positivity that was exclusive to abstract structure processing, and late positivities noted during syntactic and music phrase structure processing in previous studies suggests that these processes might share some common neurophysiological basis [14,29,31], an interesting possibility that remains open to further investigation.

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