Neuropsychologia 95 (2017) 1–10

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Statistical learning of an auditory sequence and reorganization of acquired knowledge: A time course of word segmentation and ordering

Tatsuya Daikoku, Yutaka Yatomi, Masato Yumoto*

Department of Clinical Laboratory, Graduate School of Medicine, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8655, Japan

ARTICLE INFO

Keywords:
Word segmentation
Word ordering
Statistical learning
Markov process
Magnetoencephalography

ABSTRACT

Previous neural studies have supported the hypothesis that statistical learning mechanisms are used broadly across different domains such as language and music. However, these studies have only investigated a single aspect of statistical learning at a time, such as recognizing word boundaries or learning word order patterns. In this study, we neutrally investigated how the two levels of statistical learning for recognizing word boundaries and word ordering could be reflected in neuromagnetic responses and how acquired statistical knowledge is reorganised when the syntactic rules are revised. Neuromagnetic responses to the Japanese-vowel sequence (*a*, *e*, *i*, *o*, and *u*), presented every .45 s, were recorded from 14 right-handed Japanese participants. The vowel order was constrained by a Markov stochastic model such that five nonsense words (*aue, eao, iea, oiu,* and *uoi*) were chained with an either-or rule: the probability of the forthcoming word was statistically defined (80% for one word; 20% for the other word) by the most recent two words. All of the word transition probabilities (80% and 20%) were switched in the middle of the sequence. In the first and second quarters of the sequence, the neuromagnetic responses to the words that appeared with higher transitional probability were significantly reduced compared with those that appeared with a lower transitional probability. After switching the word transition probabilities, the response reduction was replicated in the last quarter of the sequence. The responses to the final vowels in the words were significantly reduced compared with those to the initial vowels in the last quarter of the sequence. The results suggest that both within-word and between-word statistical learning are reflected in neural responses. The present study supports the hypothesis that listeners learn larger structures such as phrases first, and they subsequently extract smaller structures, such as words, from the learned phrases. The present study provides the first neurophysiological evidence that the correction of statistical knowledge requires more time than the acquisition of new statistical knowledge.

1. Introduction

1.1. Statistical learning in language acquisition

How do humans learn a novel structure without explicit knowledge? It is well known that the mother language is acquired without explicit instruction of grammatical categories. Several earlier studies have suggested that learners can extract statistical regularities embedded in speech sequences, a phenomenon called statistical learning (Saffran et al., 1996; Saffran, 2003). Even awake and sleeping neonates and infants can extract words from speech sequences using the statistical learning strategy of word segmentation after only two minutes of listening experience, implying that the general ability of statistical learning may be innate in humans (Saffran et al., 1996; Teinonen et al., 2009; Kudo et al., 2011). Statistical learning used for locating word boundaries can also be used to acquire syntax (Saffran, 2001, 2002; Thompson and Newport, 2007). Furthermore, a behavioural study demonstrated two aspects of linguistic statistical learning of word segmentation and word order (Frost and Monaghan, 2016). This implies that statistical learning is broadly used across different tasks in language acquisition (Morgan and Newport, 1981; Mintz et al., 2002). However, how/when statistical learning contributes to language acquisition and how learning effects are reflected in neurophysiological responses remains an open question. One of the problems is that most previous studies have investigated only a single aspect of language learning at a time, such as the acquisition of words (Abla et al., 2008; Paraskevopoulos et al., 2012) or grammatical structure (Furl et al., 2011; Daikoku et al., 2014, 2015). In our real-world learning environments, when humans listen to language sequences, they are exposed to linguistic traits of word boundaries and word order patterns. Therefore, to understand the statistical learning mechanism in our real-world language learning environments and how/when statistical learning

* Corresponding author.
E-mail address: yumoto-tky@umin.ac.jp (M. Yumoto).

http://dx.doi.org/10.1016/j.neuropsychologia.2016.12.006
Received 25 June 2015; Received in revised form 23 November 2016; Accepted 5 December 2016
Available online 06 December 2016

contributes to language acquisition, it is necessary to investigate how these two levels of statistical learning of speech-tone sequences embedding both words and patterns from the word order can be reflected in neuromagnetic responses.

According to recent studies, the strategies for language acquisition can be shifted from domain-general statistical learning to domain-specific native-language perception between 6 and 12 months, a critical period for language acquisition (Hauser et al., 2002; Kuhl, 2011; Peña et al., 2012). A young infant (birth from 37 weeks to 8 months) uses a statistical learning strategy to recognize boundaries between words in speech sequences (Saffran et al., 1996; Teinonen et al., 2009; Kudo et al., 2011). As they grow, they begin to show a narrowing in their language perception by at least by 12 months of age. For example, using oddball paradigms, Bosseler et al. (2013) demonstrated that in 6-month-old infants, brain oscillations in the theta band (4–8 Hz), which can reflect increases in attention and cognitive effort, increased when exposed to both native and non-native language stimuli that appeared in the experiment at higher probabilities compared to those appearing at lower probabilities, suggesting a capability to perform statistical learning for language acquisition, regardless of language status (native or non-native). In contrast, adults showed increased brain oscillations in the theta band specifically for non-native language stimuli, regardless of the probability of appearance during the experiment. The 12-month-old infants showed increased brain oscillations in the theta band specifically for native language regardless of the probability of appearance during the experiment, whereas adults showed increased theta to non-native language. The author suggested that 12-month-old infants attend to the detailed characteristics of native language to develop representations in knowledge, implying a pattern in the transition of learning strategies from 6-month-old infants to adults. These results may be consistent with the fact that the perceptual narrowing occurs by 12 months of age. Importantly, this shift in learning strategy may be particularly related to statistical learning for language, rather than statistical learning in general. These studies suggested that the language learning strategies could inevitably be shifted from domain-general statistical learning to domain-specific native-language perception because there is a critical period for language acquisition. This notion may, on the other hand, raise the question of whether adults retain the ability for statistical learning even after they have shifted to domain-specific native-language perception such as syntax and words. Regarding this question, the previous studies demonstrated that adults who had acquired native language also performed statistical learning when they tried to learn an unknown language (Saffran et al., 1999; Gómez, 2002; Peña et al., 2002; Daikoku et al., 2015): adults can extract statistical regularities such as transitional probabilities included in speech sequences and can recognize both word boundaries and word order in speech sequences (i.e., word segmentation and syntax, respectively) (Frost and Monaghan, 2016). However, previous studies have suggested that learners had difficulty in extracting grammatical-like regularity based on non-adjacent dependency included in speech sequences, and the discovery of the grammatical system appears to require a different type of computation as well as transitional probability (Gomez, 2002; Peña et al., 2002). Taken together, recent studies suggest that adults perform statistical learning to acquire words and simple syntax when they try to learn an unknown language, while different types of learning strategies are additionally required to acquire the grammatical system.

One of the most essential abilities in learning is to constantly modify and update the acquired knowledge. The neural mechanisms underlying the modification of motor memories have been examined in earlier studies (Birbaumer, 2010; Censor et al., 2010). In a behavioural study, Gebhart et al. (2009) investigated how changes in statistical information affected learning when learners were presented with speech sequences with an embedded statistical structure. They demonstrated that past statistical knowledge blocked statistical learning and that participants learned changed statistical structure when exposed to the changed structure for an extended duration vis-à-vis the duration of the first statistical structure. On the other hand, to the best of our knowledge, none of these studies investigated the neural representation underlying the modification of linguistic statistical learning. To generally understand how statistical learning contributes to language learning, the neural basis underlying the modification of statistical knowledge needs to be examined. In the present study, using magnetoencephalography (MEG), we verified how the modification of acquired statistical knowledge as well as statistical learning is reflected in neural responses.

1.2. Neurophysiological markers of statistical learning

Previous studies on auditory statistical learning, using a second-order Markov chain (Markov, 1971, reprinted in 1971; Furl et al., 2011; Daikoku et al., 2014, 2015) or a word segmentation task (Abla et al., 2008; Paraskevopoulos et al., 2012), have shown that auditory statistical learning can be reflected in neural responses. Previous studies using two different experimental paradigms have shown similar results: neural responses to tones that appear frequently in reference to the most recent tones are more rapidly reduced than responses to tones that appear infrequently. In addition, these statistical learning effects reflected in neural responses could be observed in both the ERPs and the magnetic counterparts of ERPs. This neural effect could be observed in the responses at approximately 50 ms (i.e., P1/P1m) (Paraskevopoulos et al., 2012; Daikoku et al., 2016), 100 ms (i.e., N1/N1m) (Abla et al., 2008; Furl et al., 2011; Daikoku et al., 2014, 2015; Koelsch et al., 2016), and 200 ms (i.e., P2/P2m) (Furl et al., 2011) after stimulus onset.

A previous study on learning reported that adaptation effects on the N1m and P2m responses to repeated stimuli were detected at different time scales and polarities. In that study, the participants attended two experimental sessions on different days. The N1m amplitudes were attenuated during each session and were recovered between the two sessions. In contrast, the P2m amplitudes were fairly constant within a session but increased from the first to the second session (Ross and Tremblay, 2009). This suggests that the P2 response resists adaptation more than the N1 response. Due to this long time constant of P2 response modification, in our previous study, when participants listened to auditory sequences for 5 min, statistical learning effects were reflected in the N1 but not the P2 responses (Daikoku et al., 2014, 2015). By training for voice-onset-time perception, the N1-P2 peak-to-peak amplitude increased over a long time scale of 10 days, whereas the P1-N1 peak-to-peak amplitude had no significant difference at any time scale (Tremblay et al., 2001). In these studies, the temporal dynamics of P1m, N1m, and P2m amplitudes could be interpreted as a reflection of neuroplastic changes along different time scales. The present study aimed to investigate how adults can extract statistical structure contained in words and syntax during short-term exposure to auditory sequences in which an original artificial grammar was embedded and how short-term statistical learning can modulate the early neuromagnetic components of P1m and N1m, reflecting the pre-attentive processing of short-term memory.

1.3. The purpose of the present study

How statistical learning contributes to language acquisition remains highly controversial. Previous neurophysiological studies have investigated only a single aspect of language learning at a time, such as the acquisition of words (Abla et al., 2008; Paraskevopoulos et al., 2012) or grammatical structure (Furl et al., 2011; Daikoku et al., 2014, 2015). In our real-world learning environments, when humans listen to language sequences, they are exposed to the linguistic traits of word boundary and word order patterns. Therefore, to understand the statistical learning mechanism in our real-world language learning environments, we investigated how these two levels of statistical