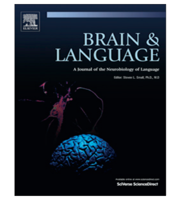
Brain & Language 148 (2015) 64–73

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l



Temporal dynamics of contingency extraction from tonal and verbal auditory sequences

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ARTICLE INFO

Article history:
Accepted 15 November 2014
Available online 12 December 2014

Keywords:
Predictive coding
Regularity
Deviance detection
Mismatch negativity (MMN)
Contingency learning
Event-related potential (ERP)
Brain activity
Speech
Language

ABSTRACT

Consecutive sound events are often to some degree predictive of each other. Here we investigated the brain's capacity to detect contingencies between consecutive sounds by means of electroencephalography (EEG) during passive listening. Contingencies were embedded either within tonal or verbal stimuli. Contingency extraction was measured indirectly via the elicitation of the mismatch negativity (MMN) component of the event-related potential (ERP) by contingency violations. MMN results indicate that structurally identical forms of predictability can be extracted from both tonal and verbal stimuli. We also found similar generators to underlie the processing of contingency violations across stimulus types, as well as similar performance in an active-listening follow-up test. However, the process of passive contingency extraction was considerably slower (twice as many rule exemplars were needed) for verbal than for tonal stimuli These results suggest caution in transferring findings on complex predictive regularity processing obtained with tonal stimuli directly to the speech domain.

1. Introduction

Speech comprehension requires auditory information processing in real-time because the acoustic input is ephemeral – it disappears right after it is encountered. The computationally intense real-time processing load is partly reduced by the fact that speech sounds usually do not follow each other randomly. Instead, upcoming words and phonemes within natural speech are often predictable at various processing levels such as high-level semantics (e.g., Federmeier, 2007) or low-level acoustics (e.g., Arnal & Giraud, 2012). In the present study, we investigated a particular type of predictability, namely contingent transitions between phonemes (e.g., *A can be followed by B but not C*). Such contingencies are relevant in phonotactic constraints (e.g., Steinberg, Truckenbrodt, & Jacobsen, 2010, 2011) and in learning words on the basis of consistent co-occurrence of a word's constituents. We specifically wanted to assess how quickly such contingencies can be newly acquired from initially arbitrary streams of syllables. Based on the rationale that picking up contingent co-occurrences of phonemes is important during language acquisition, we hypothesized that the healthy human brain should be able to extract such contingencies quickly and efficiently.

We capitalized on previous work on the extraction of feature contingencies from pure tone sequences (Bendixen, Prinz, Horváth, Trujillo-Barreto, & Schröger, 2008; Paavilainen, Arajärvi, & Takegata, 2007). These authors investigated the extraction of contingency rules of the type, *the duration of one sound predicts the frequency of the next sound* (whose duration then again predicts the frequency of the following sound in the sequence, and so on; cf. Fig. 1a). By means of event-related potential (ERP) components extracted from continuous electroencephalography (EEG) recordings, both studies compared the brain activity elicited by tones following the contingency rule with activity elicited by tones violating this rule. Processing differences between these events were taken to demonstrate the successful acquisition of the contingency rule. These processing differences took the form of a fronto-central negative displacement of the ERP for tones violating the contingency rule from 140 to 180 ms following violation onset, known as the so-called mismatch negativity (MMN) component

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http://dx.doi.org/10.1016/j.bandl.2014.11.009
0093-934X/

of the ERP (e.g., Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007). The MMN component is often observed in response to deviations from auditory sequential regularities, even when participants pay no attention to the tones. MMN is interpreted as an indirect indicator of the auditory system having picked up the regularity (Schröger, 2007; Winkler, 2007).

MMN results showed that it is possible for human listeners to extract the above-mentioned feature contingency (*the duration of one sound predicts the frequency of the next sound*) even when the tone sequences are presented outside of the focus of attention (Bendixen et al., 2008; Paavilainen et al., 2007). Furthermore, embedding the contingency rule into a dynamic stimulus protocol, in which contingencies kept emerging and vanishing, revealed that the process of contingency extraction happens very quickly: Just 15–20 exemplars of the contingency rule need to be encountered for the brain to pick up the contingent relations and detect subsequent contingency violations (Bendixen et al., 2008).

One may wonder why the auditory system should be able to extract such relatively arbitrary transition rules between the duration and frequency of consecutive tones in a sequence. In previous studies, this impressive capacity was interpreted with reference to its importance for language processing (Bendixen et al., 2008; Paavilainen et al., 2007). For instance, using the duration of one acoustic event to predict some characteristics of the next event would be relevant for learning phonotactic rules such as, *a long [a] is followed by consonant 1 while a short [a] is followed by consonant 2*. Yet though this analogy of tone and speech contingencies is suggestive, no study has yet attempted to transfer the tonal contingency extraction paradigm to speech material. It is, therefore, unclear whether the principles of contingency extraction revealed by pure-tone ERP studies indeed translate to the speech domain.

In the present study, we put this issue to a direct test by implementing strictly parallel manipulations of auditory feature contingencies based on tonal stimuli (closely following Bendixen et al., 2008) and based on verbal stimuli (designed to be conceptually identical to the tonal version). We hypothesized common principles of contingency extraction for both stimulus types, thus providing further evidence for the close relation between language and basic auditory temporal processing (Kotz & Schwartze, 2010). More specifically, we tested (1) how many contingent exemplars would be needed within either stimulus set before an auditory contingency would be extracted. We then compared (2) the generators of the involved auditory processes across stimulus types by means of EEG source localization (Michel et al., 2004; Trujillo-Barreto, Aubert-Vázquez, & Valdés-Sosa, 2004). Finally, we investigated (3) whether the contingencies extracted outside the focus of attention (as revealed by ERPs obtained during passive listening) would be accessible during active listening, when participants were asked to detect and overtly report contingency violations. In both previous studies (Bendixen et al., 2008; Paavilainen et al., 2007), active detection performance had been relatively poor, which may have been due to the relatively arbitrary association of basic tone features. We hypothesized that active contingency extraction would be easier within speech stimuli; a finding that would lend further credit to the importance of the investigated processes for everyday language processing.

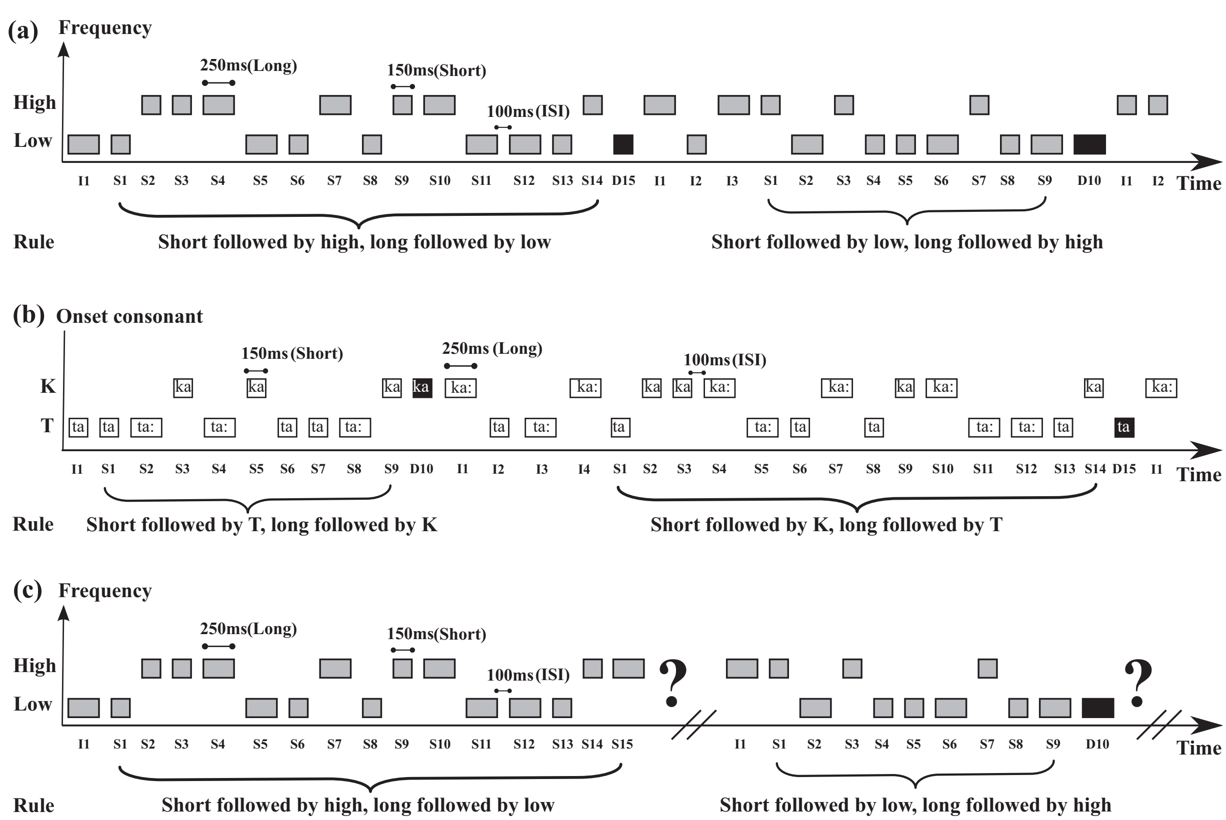

Fig. 1. Exemplary stimulus sequences. (a) Tonal stimuli as presented during passive listening. (b) Verbal stimuli as presented during passive listening. (c) Stimulus sequence during active listening (illustrated here with tonal stimuli, but following identical principles for verbal stimuli). Stimulus categories are abbreviated as follows: S = Standard, D = Deviant, I = Irregular stimulus (i.e., random sequences interspersed between consecutive regular sequences). Numbers indicate positions of the corresponding stimulus category. Question marks indicate positions after which the sequences were stopped during active listening to wait for the participant's judgment of the last tone as rule-conforming or rule-violating.