Detection of pattern repetitions in continuous acoustic sequences is robust against inattention and temporal irregularity

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Detection of repeating patterns within continuous sound streams is critical for efficient auditory perception. Previous research demonstrated that the human auditory system is remarkably sensitive to periodic pattern repetitions even in randomly generated sounds that do not carry semantic content, such as white noise or sequences of tone pips. Listeners are well able to rapidly respond to repetitions in active behavioural repetition detection tasks, and successful repetition detection was reflected in different neural markers: Compared to random sequences without repetitions, repetitions of a certain sound pattern within a sequence led to an increase in sustained activity relative to the first pattern repetition onset, a characteristic positivity-negativity complex in the event-related potential (ERP) time-locked to repeating pattern onsets within the sequence, and enhanced inter-trial phase coherence (ITPC) of low-frequency neural oscillations. These different markers were partly attributed to dissociable functions. There is evidence that neither a strict temporal regularity of pattern repetitions nor attention towards the sounds is an indispensable prerequisite for repetition detection. However, it remains less clear whether and how attention and regularity modulate repetition detection. The present EEG study aimed to scrutinise the modulatory role of attention and regularity on pattern repetition detection in continuous acoustic sequences, and how this is reflected in different EEG markers.

To address this question, 29 young, healthy participants with normal hearing listened to sound sequences with and without repetitions of a certain sound pattern, while their EEG was recorded in two separate sessions. The sequences were 3500 ms long and consisted of “correlated noise”. Correlated noise refers to randomly generated white noise sequences that were transformed by means of a generative model such that they match statistical properties, i.e., the correlative structure, of natural sounds. Half of the sequences contained repetitions of a certain 200-ms sound segment (six presentations in total per sequence), whereas the other half consisted of random correlated noise without pattern repetitions. Pattern repetitions either occurred with a fixed interval of 300 ms between patterns (regular) or with variable intervals between 50 and 550 ms (jittered). Regular and jittered sequences were presented in separate blocks within each session. In the first session, listeners’ attention was directed away from the auditory stimulation by means of a demanding visual distractor task (no-attention), while in the second session, they attended to the sounds and were asked to detect repetitions therein (attention). We analysed different EEG signatures of repetition detection in sounds: sustained activity throughout the sequence, ERPs relative to repeating pattern onsets, and ITPC. For ERP and ITPC analysis, signals were re-referenced to the mean of both mastoids and averaged across a fronto-central electrode cluster (F1, F2, Fz, FC1, FC2, FCz, C1, C2, Cz). Mean ERP amplitudes were extracted for two time windows of interest, which ranged from 0 to 160 ms (early positivity) and from 190 to 380 ms (later negativity) relative to the onset of single pattern repetitions (i.e., 2^{nd} to 6^{th} pattern occurrence per sequence). ITPC was computed from the results of a convolution of single epochs (again corresponding to single pattern repetitions) with Morlet wavelets, and mean ITPC at frequencies from 1 to 4 Hz were extracted for a time window ranging from 0 to 500 ms relative to pattern onset. For the analysis of the sustained response, we computed global field power (GFP) as the root mean square of the signal across all 64 average-referenced scalp electrodes. Mean GFP was extracted from 500 to 3000 ms relative to the first pattern onset per sequence (i.e., from the first pattern repetition onset to the end of the sequence).

Successful repetition detection was reflected consistently in all three EEG markers under investigation: Across all attention and regularity conditions, pattern repetitions led to increased sustained response amplitudes throughout the whole sequence, evoked a characteristic positivity-negativity complex in the ERP relative to pattern onset, and enhanced inter-trial phase coherence of low-frequency oscillations. More specifically, GFP was larger for sequences with repetitions compared with random sequences during the sustained phase that followed a relatively sharp increase after sequence onset (from 500 ms to 3000 ms relative to the first pattern onset). In the ERP, the positivity-negativity complex was evoked relative to repeating pattern onsets across both regular and jittered sequences during both attention and inattention. We observed (descriptive) forward shift of the onset of the early positivity in regular sequences, which likely reflects anticipation of predictable upcoming pattern onsets. Repetition-related amplitude changes were analogous for both positive (0 to 160 ms) and negative (190 to 380 ms) components of the ERP: In sequences that contained pattern repetitions, mean amplitudes were larger (i.e., more positive, or negative, respectively) than in random sequences without repetitions. Finally, ITPC at low frequencies between 1 and 4 Hz was stronger in sequences with than in sequences without repetitions in a time range from 0 to 500 ms relative to single patterns. In the attention session, listeners were also able to detect pattern repetitions behaviourally well above chance across both regular and jittered blocks (with no significant difference between the two). While repetition effects in the EEG were significant across all attention and regularity conditions, we found evidence for a significant modulation by attention for all three neural markers: The amplitude increase of the sustained response, amplitudes of the ERPs relative to repeating pattern onsets, and the change in ITPC were larger when listeners attended to the sounds compared to when they performed a visual distractor task and ignored the sounds. In contrast, there was no evidence for a modulation of the repetition effect by the temporal regularity of a sequence in sustained activity and ERPs to repeating pattern onsets, and only a trend towards a larger repetition effect for regular compared with jittered sequences in ITPC.

Overall, we replicate findings of earlier studies that had shown that listeners automatically detect pattern repetitions within continuous acoustic sequences. Importantly, we demonstrate that repetitions were detected automatically even when they were unpredictable in the absence of a strict temporal regularity that could have served as a cue for upcoming pattern onsets. Thus, the current study expands findings of previous studies, which had shown pre-attentive tracking of pattern repetitions only for strictly periodic sequences. Moreover, while earlier studies had shown automatic processing of pattern repetitions in the absence of attention, the current study is the first one to show that an attentional focus on the auditory sequences (and the repetitions therein) significantly enhances repetition detection in a within-subject design with a strict attention control. It is plausible to assume that attention to the sounds enhances perceptual representations, which in turn facilitates repetition detection and may also pave the way for longer-term memory formation for patterns that recur across multiple trials. Unlike a previous study, we found an advantage in repetition detection through attention across all three EEG markers, which does not support the idea that they might reflect functionally dissociable processes (e.g., pre-attentive sensory tracking of repetitions vs. more abstract sound structure representation that requires attention). Instead, our data suggest that all processes that contribute to repetition detection as reflected in different EEG markers are enhanced through attention, although we would still not exclude that they may be functionally nuanced. In contrast to attention, temporal regularity did not appear to play a strong modulatory role for repetition detection. Whereas the early positive component of the ERP relative to repeating pattern onsets was only reported for regular, but not for jittered sequences previously, both positive and negative components were evoked irrespective of the regularity of a sequence in the current study. This suggests that, rather than reflecting tracking of stimulus periodicity, the positivity is part of a positivity-negativity complex, which as a whole is related to pattern repetition detection in both regular and jittered sequences. Nevertheless, the periodicity in regular sequences allowed for (additional) entrainment of neural oscillations to the rhythmic stimulation and anticipation of upcoming pattern onsets, which was reflected in (the trend towards) a larger repetition effect in ITPC and a (descriptive) forward shift of the early positivity in the ERP relative to pattern onset. Importantly however, a synchronisation of neural responses by repeating pattern onsets, possibly achieved via phase-reset of ongoing oscillations did not require strictly periodic pattern repetition, but occurred also in temporally irregular sequences.

Taken together, the current study suggests that pattern repetition detection in continuous sounds relies on a flexible mechanism that is robust across varying contextual demands, including inattention and temporal irregularity such as they often occur during naturalistic listening. Yet, repetition perception can be sharpened through an attentional focus to the auditory input.