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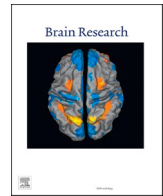
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# Attention modulates repetition effects in a context of low periodicity

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## ABSTRACT

Stimulus repetition can result in a reduction in neural responses (i.e., repetition suppression) in neuroimaging studies. Predictive coding models of perception postulate that this phenomenon largely reflects the top-down attenuation of prediction errors. Electroencephalography research further demonstrated that repetition effects consist of sequentially ordered attention-independent and attention-dependent components in a context of high periodicity. However, the statistical structure of our auditory environment is richer than that of a fixed pattern. It remains unclear if the attentional modulation of repetition effects can be generalised to a setting which better represents the nature of our auditory environment. Here we used electroencephalography to investigate whether the attention-independent and attention-dependent components of repetition effects previously described in the auditory modality remain in a context of low periodicity where temporary disruption might be absent/present. Participants were presented with repetition trains of various lengths, with/without temporary disruptions. We found attention-independent and attention-dependent repetition effects on, respectively, the P2 and P3a event-related potential components. This pattern of results is in line with previous research, confirming that the attenuation of prediction errors upon stimulus repetition is first registered regardless of attentional state before further attenuation of attended but not unattended prediction errors takes place. However, unlike previous reports, these effects manifested on later components. This divergence from previous studies is discussed in terms of the possible contribution of contextual factors.

## 1. Introduction

Stimulus repetition is known to elicit a reduction in neural responses (i.e., repetition suppression, RS) in neuroimaging studies. This phenomenon was initially believed to result from the bottom-up processing of perceptual information such as fatigue, sharpening, and facilitation of the neural activation in the sensory cortices (for a review see Grill-Spector et al., 2006). Later studies, however, found that RS can be modulated by the likelihood of stimulus repetition. That is, infrequent stimulus repetition could reduce the amplitude of RS. Such modulation was first demonstrated in the visual domain (Summerfield et al., 2008, 2011) and quickly replicated in the auditory system (Costa-Faidella et al., 2011; Todorovic et al., 2011; Wacongne et al., 2012; Andics et al., 2013; Emberson et al., 2019). It was therefore suggested that RS is a consequence of the correct prediction of the repeated stimulus. In other words, RS largely reflects the top-down attenuation of prediction errors

(PE) (Friston, 2005; Ewbank et al., 2011; Auzstulewicz & Friston, 2016).

In electroencephalography (EEG) research, a number of event-related potential (ERP) components, such as the N1, the P2, and the P3a, are known to be modulated by the repetition of auditory stimuli. Although the N1 and the P2 are often discussed together, it has been suggested that they are actually related to different processes (Crowley & Colrain, 2004). The N1 is considered to reflect the spontaneous detection of novel sensory inputs (Näätänen & Picton, 1987) which usually shows a pronounced amplitude decrease after the first presentation of a sound. From the point of view of predictive coding models of perception (Rao & Ballard, 1999; Friston, 2005), the N1 is widely regarded as a marker for PE, and its suppression in response to stimulus repetition is consequently interpreted as the reduction of PE to correctly predicted inputs (Auzstulewicz & Friston, 2016; Bendixen et al., 2012). Regarding the P2, there is little agreement about its functional

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interpretation (Horváth, 2015), but it has been proposed to reflect a neural process of comparison between sensory inputs and the internal prediction. Therefore, its amplitude modulations may also be interpreted as reflecting PE processing, arguably at a higher hierarchical level within a hypothetical auditory deviance detection system (Costa-Faidella et al., 2011). However, previous research provide contradictory results, with P2 amplitude decreasing (Hsu et al., 2014) or increasing (Haenschel et al., 2005) with stimulus repetition in the roving paradigm. The specifics about how PE processing is reflected on P2 differ depending on whether P2 amplitude was found to be suppressed (showing RS) or enhanced (showing repetition enhancement, RE). In the former case, P2 RS is considered to be the consequence of a match between the actual and the predicted inputs (Hsu et al., 2014; Timm et al., 2014), reflecting PE reduction in a similar way to the N1. Actually, in some of these studies N1 and P2 suppression are discussed jointly as part of the N1-P2 complex (Timm et al., 2014). In studies where P2 amplitude was enhanced, this RE has been explained as part of the phenomenon of repetition positivity, which is a positive deflection spanning between 50 and 250 ms at frontocentral electrodes in the ERPs to standard sounds. Its amplitude increases with increasing number of repetitions in the roving paradigm (Baldegweg et al., 1999, 2004). Supportive of the predictive coding models of perception, it could be considered as an index of PE attenuation during the formation of memory traces (Baldegweg, 2006, 2007). Finally, the frontocentral P3a component is often taken to reflect processes related to an involuntary attention switching towards a deviant stimulus (Horváth et al., 2008; Schröger & Wolff, 1998; Schröger et al., 2000; Polich, 2007). This attention switch would be triggered by the detection of PE (Schröger et al., 2015) in earlier processing stages, which would inform higher processing levels about the inaccuracy of predictions (Friston, 2005), resulting in the allocation of additional resources to process the unexpected stimulus and improve the predictive model. The P3a exhibits rapid habituation (for a review see Friedman et al., 2001), so that its amplitude decreases as the eliciting stimulus is repeated.

Despite increasing evidence that casts repetition effects as a consequence of attenuated PE, it remains unclear how these effects are modulated by attention, which weights PE with a measure of precision (Feldman & Friston, 2010; Jiang et al., 2013; Schröger et al., 2015). Using functional magnetic resonance imaging (fMRI), previous research yielded equivocal evidence on this issue, with some reporting repetition effects to be attention-independent (Bentley, 2003) and some reporting them to be attention-dependent (Eger, 2004; Yi & Chun, 2005; Yi et al., 2006; Henson & Mouchlianitis, 2007; Moore et al., 2013; Kikuchi et al., 2019). Taking advantage of the temporal resolution of EEG, our previous research showed that repetition effects consist of sequentially ordered attention-independent and attention-dependent components (Hsu et al., 2014). In that study we ran two experiments in which participants were presented with a roving stream (consisting of pairs of identical tones) interleaved with a filler stream (consisting of random tones without repetitions). When participants focused on the roving stream, attended repetition effects were measured. When participants focused on the filler stream, unattended repetition effects were measured. The results showed that repetition effects manifested as attention-independent RS on N1 and attention-dependent RS on P2. While repetition effects on N1 were significant regardless of attention, they were conspicuous on P2 only when there was a moderate level of attention. The results indicated that the attenuation of PE upon stimulus repetition is first registered regardless of attentional state before further attenuation of attended but not unattended PE takes place.

Notably, repetition effects were examined in a context of high periodicity in the aforementioned research. That is, in the roving stream, each tone was repeated once before the next random selection was made, so that participants could be (explicitly or implicitly) certain of when the alternation occurs. Such foreknowledge prevents exogenous orienting of attention to stimulus changes (Sussman et al., 2003; Max et al., 2015), leading to smaller responses in the brain. Animal research,

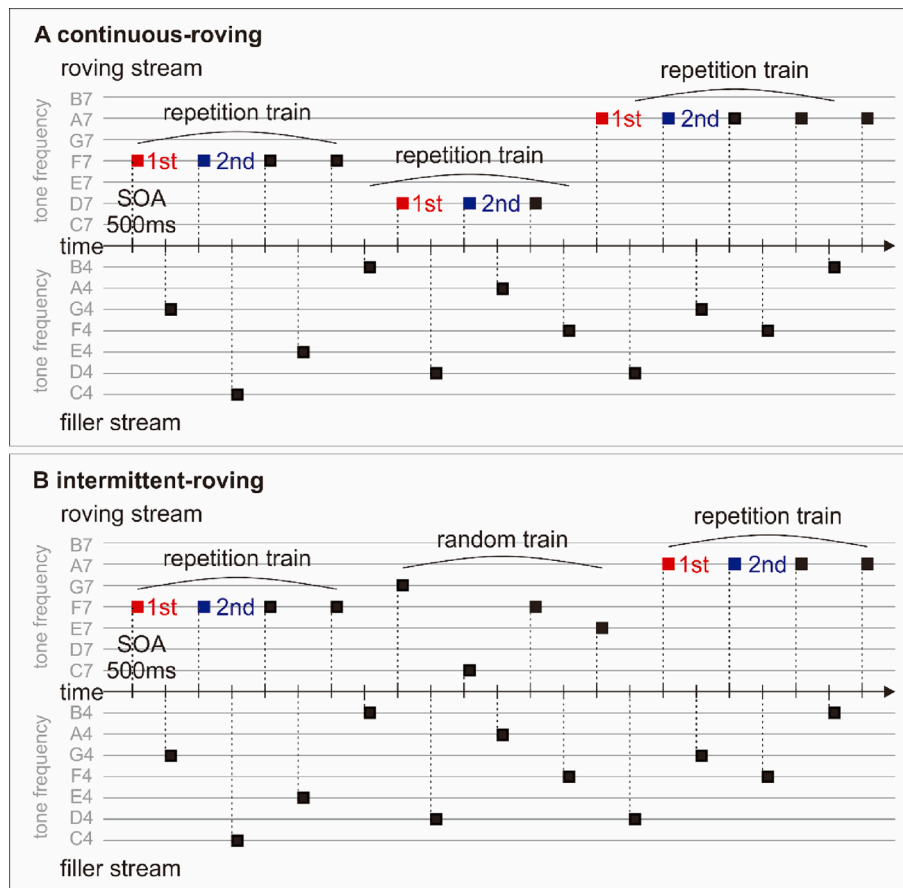
on one hand, documented that tones in periodic sequences relative to random sequences evoked smaller responses in the auditory cortex of anaesthetised rats (Yaron et al., 2012). Human research, on the other hand, demonstrated that the smaller responses to periodic stimulation more often appeared on later ERP components and neural oscillatory activities. For example, Volosin & Horváth (2014) showed that, while the N1/mismatch negativity (MMN) was unaffected by periodicity, the P3a was significantly reduced in periodic deviations relative to random deviations. Dürschmid et al. (2016) showed that, while the MMN did not discriminate periodic changes from random changes, frontal high gamma activity (80–150 Hz) showed no mismatch response to periodic deviations but a selective response to random deviations. Chang et al. (2018) also showed that pre-deviants beta power desynchronisation was larger to periodic deviations relative to random deviations. Furthermore, the deeper the pre-deviant beta power desynchronization, the smaller the post-deviant P3a. Overall, a context of high periodicity can be considered as a situation where stimulus changes trigger minimal PE.

However, the statistical structure of our auditory environment is richer than that of a fixed pattern. For example, music and language incorporate complex changes in statistical regularities. Moreover, such context of low periodicity inevitably contains temporary disruptions in everyday settings, where exogenous orienting of attention to stimulus changes is commonly observed. Can we still observe the sequentially ordered attention-independent and attention-dependent repetition effects in this case? The goal of the current research was to investigate whether the attention-independent and attention-dependent repetition effects observed in our previous research (Hsu et al., 2014) remain in a context of low periodicity where temporary disruption might be absent/present, which better represents the nature of our auditory environment. We presented participants with blocks of tone sequences containing a roving stream (composed of repetition trains of various lengths) interleaved with a filler stream (composed of random tones without repetitions). The tones in each stream were chosen from different frequency sets in order to make the roving and filler streams clearly distinguishable from each other. To further manipulate temporary disruption, each block contained one of two types of roving streams, i.e., continuous or intermittent (see Fig. 1). While the continuous-roving stream contained repetition trains alone (i.e., temporary disruption was absent), the intermittent-roving stream contained not only repetition trains but also random trains (i.e., temporary disruption was present). In each block, participants were instructed to focus on either the roving stream or the filler stream, so that we could respectively measure attended and unattended repetition effects in the roving conditions. A small number of stimuli (10%) in both attended and unattended streams were of attenuated loudness to serve as targets and distractors, respectively. Participants were required to press a key when they detect a softer tone in the attended stream, ignoring the stimulation in the unattended stream. This was made to ensure that participants focused on a given stream. To estimate repetition effects, we measured the amplitude of three ERP components (i.e., N1, P2, and P3a) in response to the 1st and the 2nd stimuli within each repetition train. If the way attention modulated the attenuation of PE upon stimulus repetition can be generalised to a setting which better represents the nature of our auditory environment, we should be able to replicate here the sequentially ordered attention-independent and attention-dependent repetition effects observed in our previous work (Hsu et al., 2014). Specifically, attention-independent effects should appear first, followed by attention-dependent effects, which would indicate that the attenuation of PE is pre-attentively registered in the auditory system before attended, but not unattended, PE are further attenuated.

## 2. Results

### 2.1. Behavioural data

Participant's behavioural performance in the target detection task



**Fig. 1.** Schematic illustration of the stimuli. Continuous series of tones were created with alternate tones from the roving and filler streams from different frequency sets.

was as follows (**false alarm rate**: range = 0.01–0.36, mean = 0.11, SD = 0.09; **hit rate**: range = 0.51–0.95, mean = 0.80, SD = 0.12; **RT**: range = 454.26–630.24, mean = 542.50, SD = 45.79). Overall, it is comparable to our previous experiments (mean false alarm rate: 0.03–0.11; mean hit rate: 0.92–0.70; mean RT: 555.40–500.23) (Hsu et al., 2014).

In addition, paired samples t-tests were performed to check whether participants' target detection performance differ between roving and filler streams. Note that behavioural performance to roving streams was obtained when stimulus repetition was attended and behavioural performance to filler streams was obtained when stimulus repetition was unattended. The results showed that participants' false alarm rate differed between roving and filler streams ( $t(22) = 3.75$ ,  $p \leq 0.001$ ), where participants made more false alarms in roving (mean = 0.18; SD = 0.17) than filler (mean = 0.05; SD = 0.05) streams. Since these false alarms could include responses to non-targets in the attended streams (due to changes in frequency in the repetition train, random train, or both) as well as responses to distractors in the unattended stream, it is difficult to interpret this difference. Meanwhile, there was no difference between roving and filler streams on participants' hit rate ( $t(22) = -1.48$ ,  $p = 0.15$ ) and RT ( $t(22) = 1.21$ ,  $p = 0.24$ ).

## 2.2. ERP data

Fig. 2A illustrates the grand average ERPs on three representative electrodes at midline (i.e., Fz, Cz, Pz), which shows N1 with a fronto-central distribution at around 100 ms, P2 with a central distribution slightly before 200 ms, and P3a with a central distribution slightly after 200 ms. Fig. 2B shows the component loadings of 24 components in the temporal PCA yielding components clearly corresponding to N1, P2, and P3a. Fig. 2C shows the N1, P2, and P3a component score topographic

maps in each condition.

Fig. 3 shows the N1, P2, and P3a component scores averaged across three electrodes showing the most negative/positive responses in each condition, which were submitted to a DISRUPTION (continuous/intermittent roving)  $\times$  ATTENTION (attended/unattended stream)  $\times$  REPETITION (1st/2nd presentation), 2x2x2, repeated-measures ANOVA.

### 2.2.1. N1 Component

No three-way or two-way interaction was significant. However, there was a significant main effect of attention ( $F(1,22) = 6.90$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.24$ ), where attention enhanced the N1 amplitude. No other main effect reached significance.

### 2.2.2. P2 component

No three-way or two-way interaction was significant. However, there was a significant main effect of repetition ( $F(1,22) = 14.07$ ,  $p \leq 0.001$ ,  $\eta_p^2 = 0.39$ ), where repetition enhanced the P2 amplitude. No other main effect reached significance.

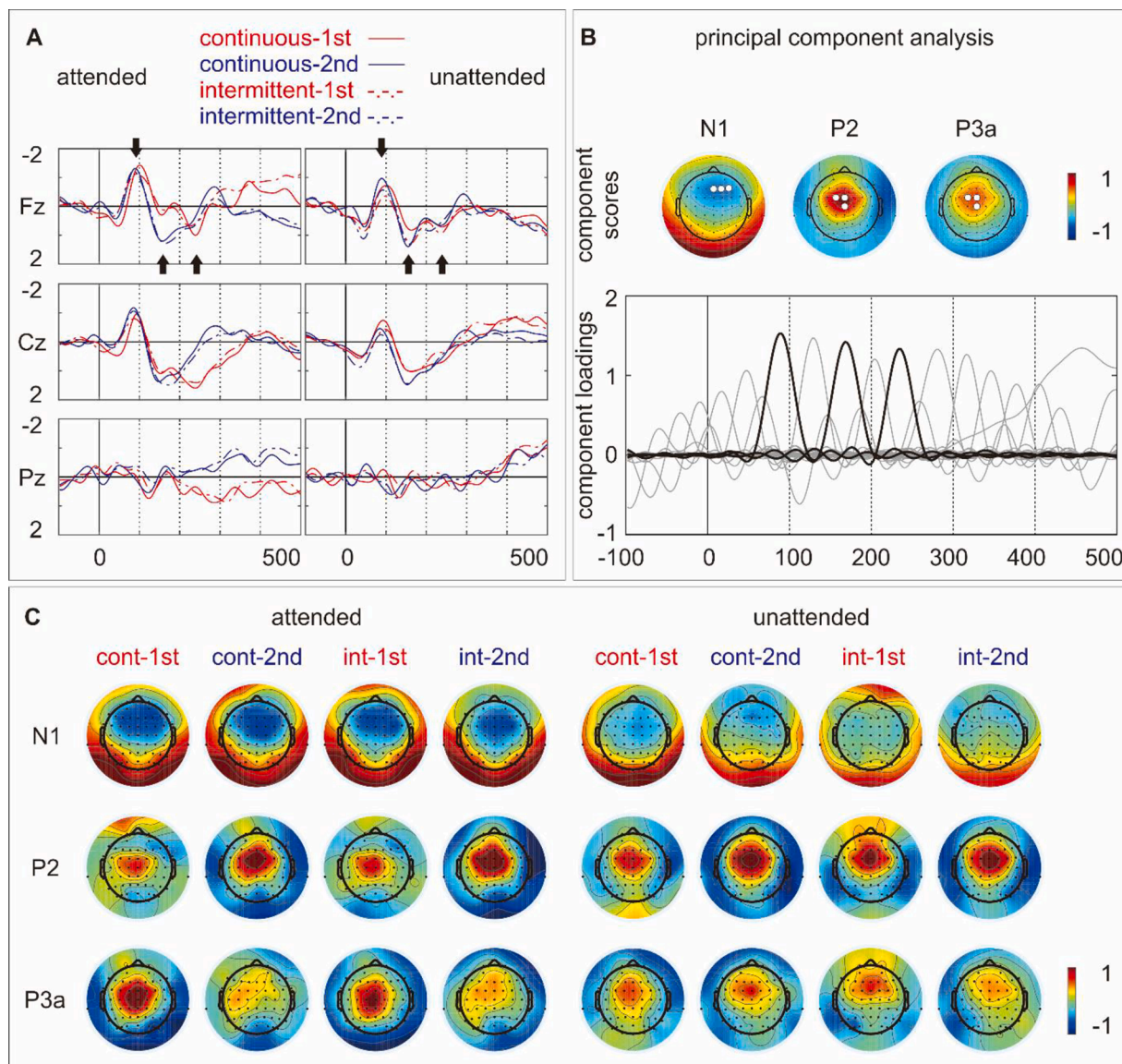
### 2.2.3. P3a component

There was no three-way interaction. However, there was a significant repetition  $\times$  attention interaction ( $F(1,22) = 13.95$ ,  $p \leq 0.001$ ,  $\eta_p^2 = 0.39$ ). Post hoc comparisons showed that repetition suppressed the P3a amplitude in attended ( $t(22) = 3.83$ ,  $p \leq 0.001$ ) but not unattended ( $t(22) = 0.38$ ,  $p = 0.71$ ) condition. No other interaction or main effect reached significance.

## 3. Discussion

Stimulus repetition is thought to result in the attenuation of PE

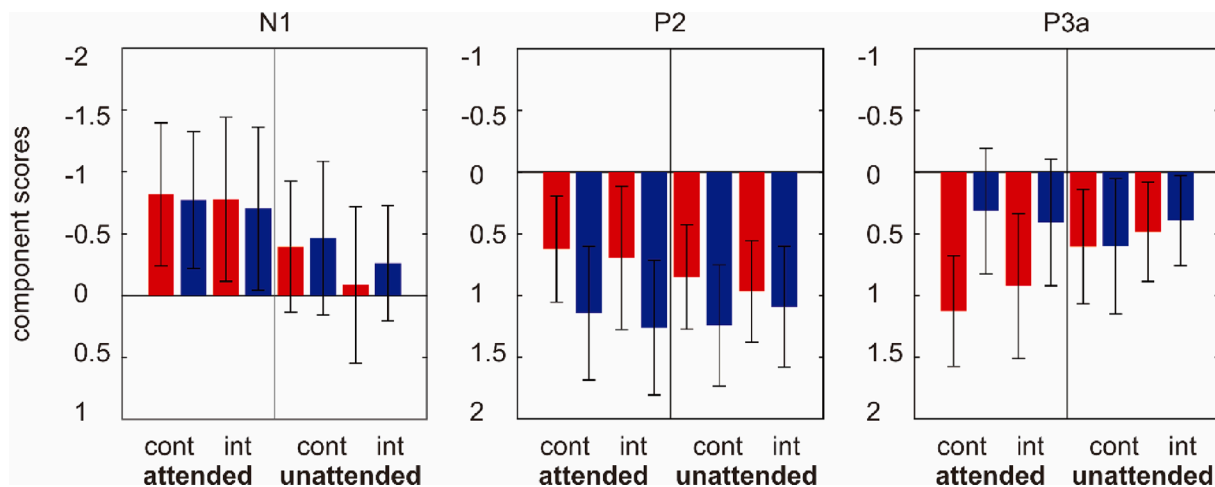




**Fig. 2.** (A) Grand average ERPs on three representative electrodes at midline (i.e., Fz, Cz, Pz). The N1, P2, and P3a are marked with arrows for ease of reference. (B) Component loadings of 24 components in the temporal PCA. The components corresponding to the N1, P2, and P3a (i.e., principal component 3, 4, and 6 respectively) are marked with thick lines with the component score topographic maps plotted on the top. Three electrodes showing the most negative/positive responses are marked as white dots. (C) The N1, P2, and P3a component score topographic maps in each condition.

(Summerfield et al., 2008, 2011; Costa-Faidella et al., 2011; Todorovic et al., 2011; Wacongne et al., 2012; Andics et al., 2013; Emberson et al., 2019). Previous research further showed that repetition effects comprised both attention-independent and attention-dependent components (Hsu et al., 2014). Here we investigated whether the attention-independent and attention-dependent repetition effects remain in a context of low periodicity where temporary disruption might be absent/present, which better represents the nature of our auditory environment. We found sequentially ordered attention-independent and attention-dependent repetition effects, reflected on the amplitude of P2 and P3a, respectively. This pattern is in line with previous research showing that the repetition effects comprised both attention-independent and attention-dependent components. Importantly, the attention dependency of repetition effects maintained its sequential order as in previous research, where the attention-independent repetition effect appeared first and the attention-dependent repetition effect appeared second, confirming that the attenuation of PE is automatically registered in the auditory system before the amount of attenuation is further modulated by attention.

Notably, the current research did not fully replicate our previous findings that repetition effects manifested as attention-independent and attention-dependent components respectively on N1 and P2 (Hsu et al., 2014). Here, the attention-independent repetition effect manifested as RE on P2 and the attention-dependent repetition effect manifested as RS on P3a. No repetition effects were observed on N1. This divergence from previous reports suggests that repetition effects may appear on different ERP components depending on contextual factors. Specifically, while our previous study (Hsu et al., 2014) utilised a roving stream consisting of pairs of identical tones so that the occurrence of the 1st (non-repeated) stimuli was highly predictable, the present research employed repetition trains of various lengths which made the occurrence of the 1st (non-repeated) stimuli rather unpredictable. Therefore, although the current results confirm that stimulus repetition seems to entail sequentially ordered attention-independent and attention-dependent effects regardless of the context, they also suggest that the way in which these effects specifically manifest and translate into the modulations of the ERP waveforms seems to be sensitive to differences in the statistical structure of the context, which may affect, for instance, the ease with



**Fig. 3.** The N1, P2, and P3a component scores averaged across three electrodes showing the most negative/positive responses (i.e., N1 negative cluster: Fz, F2, F4; P2 positive cluster: FCz, Cz, FC1; P3a positive cluster: FCz, Cz, FC1) in each condition. Colour red and blue respectively represent the 1st and 2nd presentation.

which the pattern of stimulus repetition is extracted from the environment and delay the processing of the PE, as we argue below.

### 3.1. The lack of repetition effect on the N1

First of all, N1 amplitude was modulated by attention, with larger amplitudes for attended than unattended stimuli regardless of stimulus repetition, confirming that the intended manipulation of attention worked as planned. Nevertheless, no repetition effect was observed, suggesting that PE was not yet processed at this stage. While the lack of repetition effect on N1 is inconsistent with our previous results (Hsu et al., 2014), a likely explanation would be that a context of low periodicity increased the informational entropy (i.e., the average surprise of outcomes sampled from a probability distribution), which in turn delayed the processing of PE. Though speculative, this hypothesis accords with reports that a decrease in temporal predictability could increase the latency at which the ERP waveforms exhibit repetition effects. Costa-Faidella et al. (2011), for instance, found that unpredictable stimulus timing abolishes the earlier part of the repetition effect, while leaving the later part unaffected. The hypothesis is also coherent with claims that the detection of regularity violations occurs at different levels of a hierarchically organized deviance detection system in the auditory pathway. In particular, it agrees with studies reporting that while the detection of violations of simple auditory regularities can manifest at very early latencies in the auditory evoked potentials, violations of more complex regularities fail to elicit early correlates but manifest later in the ERP waveforms (Althen et al., 2013; Cornella et al., 2012; Escera et al., 2014). In this regard, Recasens et al. (2014) employed magnetoencephalography (MEG) to study the violation of local and global regularities in a repetition context. They reported that while the violation of local regularities modulated the middle latency response (MLR) and an early MMNm response between 120 and 160 ms post-stimulus, the violation of global regularities was only reflected on the MMNm at a longer latency (140–220 ms). These results suggest that the complexity of the regularities violated, defined by either the features of the stimuli or the structure of the context, may determine the processing level at which PE would manifest. However, it is important to point out that we did not specifically test how the ERP components under study were modulated by changes in statistical structure. Therefore, it is not possible to draw strong conclusions from the divergence of results between studies. Future research should specifically address this in order to delineate the role of statistical factors in the processing of PE.

### 3.2. The sequentially order attention-independent/-dependent repetition effects

Despite the lack of repetition effect on the N1, PE evaluation manifested at later latencies, as sequentially ordered attention-independent/-dependent repetition effects on the P2 and P3a components, respectively. Specifically, while the attention-independent effect on the P2 manifested as RE, the attention-dependent effect on the P3a manifested as RS. The distinction provides further support to the concept of different, sequentially ordered, processing stages involved in the attenuation of PE in the auditory pathway, as described below.

The earliest manifestation of PE processing, the RE on P2 regardless of attention, could be part of the phenomenon of repetition positivity, a positive deflection spanning between 50 and 250 ms at frontocentral electrodes in the ERPs to standard sounds that increases its amplitude with increasing number of repetitions in the roving paradigm (Baldeweg et al., 1999, 2004), no matter whether participants are actively or passively listening to the auditory stimuli (Haenschel et al., 2005). It originates from a combined modulation of the ERPs involved at different time intervals (encompassing an increase of the P50, a decrease of the N1, and an increase of the P2), rather than from a unitary slow ERP component (Haenschel et al., 2005; Costa-Faidella et al., 2011; Recasens et al., 2015). Supportive of the predictive coding models of perception, repetition positivity could be considered as an index of PE attenuation during the formation of memory traces (Baldeweg, 2006, 2007). It is likely that the attention-independent RE on the P2 observed here reflects the same mechanism, where the attenuation of PE was automatically registered.

The attention-dependent effect on P3a, on the other hand, manifested as RS. No effects on this component were found in our previous study (Hsu et al., 2014). A possible explanation for this discrepancy could be that in our previous study each tone in the roving stream was repeated once before the next random selection was made, so that participants could be (explicitly or implicitly) certain of when the alternation occurs. Such foreknowledge may have prevented exogenous orienting of attention to stimulus changes (Sussman et al., 2003; Max et al., 2015), leading to smaller P3a responses. The P3a is often taken to reflect the mechanism of involuntary capture of attention towards significant stimuli in distraction-related processing (Schröger & Wolff, 1998; Schröger et al., 2000; Polich, 2007). According to this view, the larger P3a component to deviant stimuli would be the consequence of the PE manifested at earlier processing stages reaching a certain threshold and thus activating an additional processing stage, which involves an involuntary capture of attention (Waszak & Herwig, 2007; Horváth et al., 2008). Moreover, the P3a exhibits rapid habituation (for

a review see Friedman et al., 2001), so that its amplitude is expected to reduce in response to repeated (and therefore expected) stimuli. The RS found on the P3a in the present study fits well into this interpretation. However, our finding is inconsistent with previous reports that P3a RS is independent of the top-down modulation of attention. For example, Friedman et al. (1998) found that the P3a shows a reduction as a function of block number in both attended and unattended conditions. We speculate that the discrepancy might result from how the unattended condition was defined. While the current research adopted a filtering approach, Friedman et al. (1998) adopted a passive listening situation where participants were asked to read self-selected texts in the unattended condition. The unattended sounds might be suppressed to a larger extent in the current research, abolishing further processing of the stimuli. Also, the complexity of the low periodicity context, together with the absence/presence of temporary disruptions, might have made P3a less conspicuous in the absence of top-down attention. The ERPs depicted in Fig. 2 seem to support this hypothesis. While in the attended condition a strong P3a can be seen in response to the 1st stimuli, in the unattended condition this P3a response was less pronounced, which could be interpreted as the earlier PE processing stage reflected on P2 not reaching the necessary threshold to trigger the next processing stage of attentional capture indexed by P3a. Interestingly, Friedman et al. (1998) nevertheless documented a subtle difference between attended and unattended conditions in the topographical distribution of the P3a, which showed a greater frontal orientation but less bilateral temporal activation in the attended relative to the unattended conditions. Given that several brain structures are involved in generating the P3a (including the prefrontal, temporal, and parietal cortices, as well as the hippocampus, the parahippocampal, and the cingulate gyri) (for a review see Escera et al., 2000), it is possible that different brain regions are recruited for attended versus unattended conditions or that there are amplitude changes in a subset of those generators between attended and unattended conditions.

Lastly, temporary disruption of the periodicity did not modulate the attention-independent/-dependent components of repetition effect. It is possible that temporary disruption on a larger time-scale (over minutes) was irrelevant to the PE processing on a smaller time-scale (i.e., over a second). Alternatively, it might be that the amount of temporary disruption in the current research (i.e., 50 repetition trains + 15 random trains per block) was not conspicuous enough to affect PE processing. Future research is needed to examine whether and how temporary changes of stimulus regularity in the context might modulate repetition effects.

## 4. Methods and materials

### 4.1. Participants

A total of 28 healthy volunteers (average age 20; 6 males; 27 right-handed) participated in the experiment with no history of neurological, neuropsychiatric, or visual/hearing impairments as indicated by self-report. 5 participants were excluded from data analysis for poor behavioural performance in the target detection task (hit rate < 0.5 and/or false alarm rate greater than 0.5), leaving 23 participants in the sample (average age 20; 5 males; 22 right-handed). All participants gave written informed consent and were paid for participation. The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee at National Taiwan Normal University.

### 4.2. Stimuli

Sinusoidal tones were generated in Matlab and modified in Audacity. The duration of each tone was 50 ms (including 5 ms rise/fall times). The frequency of each tone was within the range of 261.626–493.883 Hz and 2093.000–3951.070 Hz, matching the absolute frequency of two

sets of seven natural keys on a modern piano (low-pitched set: C4 D4 E4 F4 G4 A4 B4; high-pitched set: C7 D7 E7 F7 G7 A7 B7). For each participant, roving streams were created with tones from one frequency set, and filler streams with tones from the other set. The assignment of the frequency sets to the roving and filler streams was counterbalanced between participants.

The roving streams consisted of trains of 2 to 6 tone repetitions presented in continuous succession. Within each repetition train, we included into analysis the 1st tone (a tone different from the preceding train, thus eliciting larger PE) and the 2nd tone (a repetition of the 1st tone, thus eliciting smaller PE). Two types of roving streams were created, i.e., continuous-roving and intermittent-roving. Continuous-roving streams contained 65 repetition trains (13 trains of each possible length, randomly intermingled). Intermittent-roving streams contained 50 repetition trains (10 trains of each possible length, randomly intermingled) and 15 random trains (3 trains of 2 to 6 non-repeated tones each), randomly interspersed (Fig. 1). The filler streams consisted of successions of tones selected from one of the frequency sets in a pseudo-random fashion, avoiding immediate tone repetitions.

For each experimental block, a sequence of tones was created by interleaving a roving stream with and a filler stream. As stated above, the two stimulus streams were selected from different frequency sets (low-pitched set versus high-pitched set) to allow for the efficient manipulation of attention (Fig. 1). Specifically, half of the participants were presented with low-pitched roving streams interleaved with high-pitched filler streams and half of the participants were presented with high-pitched roving streams interleaved with low-pitched filler streams. Each tone was presented with a 500 ms stimulus onset asynchrony (SOA) and an intensity of maximum 72 dB (51–70 dBA; 61–72 dBC).

### 4.3. Procedures

A total of 8 blocks of 65 trials were presented in randomised order, including 4 blocks of continuous-roving/filler stream and 4 blocks of intermittent-roving/filler stream. Participants were instructed to pay attention to the low-pitched streams in 4 blocks (including 2 blocks of continuous-roving/filler stream and 2 blocks of intermittent-roving/filler stream), and to the high-pitched stream in 4 blocks (including 2 blocks of continuous-roving/filler stream and 2 blocks of intermittent-roving/filler stream), so that their attention was directed to the roving streams in 50% of the blocks and filler streams in 50% of the blocks. In each block, 26 stimuli (i.e., 10% of the tones) in the attended stream were of attenuated loudness by 20 dB to serve as targets, and 26 stimuli (i.e., 10% of the tones) in the unattended stream were of attenuated loudness by 20 dB to serve as distractors.

A grey fixation cross against black background was presented on the screen for the duration of each block (viewed from a distance of 120 cm). Participants were required to press a key when they detect a softer tone in the attended stream, ignoring the stimulation in the unattended stream. When participants focused on the roving stream and ignored the filler stream, repetition effects in the conditions of **continuous-attended** and **intermittent-attended** were measured. When participants ignored the roving stream and focused on the filler stream, repetition effects in the conditions of **continuous-unattended** and **intermittent-unattended** were measured. The whole experiment took around 35 min. E-prime version 2.0 (Psychology Software Tools) was used for stimulus presentation. Stimulation was randomised individually for each participant and delivered binaurally via headphones (Sennheiser PX200-II).

### 4.4. Data recording and analysis

#### 4.4.1. EEG recording and pre-processing

EEG was recorded from 62 sintered Ag/AgCl electrodes on a Neuroscan quik-cap according to the extended 10–20 system. The ground electrode was placed at AFz and the reference electrode was placed



between Cz and CPz. Eye movements were monitored by additional four electrodes placed above and below the left eye and at the outer canthi of both eyes, which were bipolarized online to yield vertical and horizontal electrooculogram (EOG), respectively. All signals were amplified and online filtered at 0.1–100 Hz with the Neuroscan Synamps 2 amplifier (Compumedics Neuroscan, USA) and sampled at 500 Hz.

Epochs extended from –100 ms to 500 ms relative to stimulus onset, using a –100 ms to 0 ms pre-stimulus baseline. Ocular artefact correction was conducted with independent component analysis (ICA) in EEGlab 14.1.2b (Delorme & Makeig, 2004). Bad electrodes were identified (if there were more than 25% of the epochs containing voltage deviations exceeding  $\pm 100$   $\mu$ V relative to baseline) and interpolated using spherical interpolation. The data was recomputed to average reference. Epochs containing voltage deviations exceeding  $\pm 100$   $\mu$ V relative to baseline at any of the electrodes were rejected. Lastly, the data was lowpass-filtered at 20 Hz. The trial numbers after artefact rejection in each condition are listed in Table 1.

#### 4.4.2. ERP analysis

ERP analysis was based on a temporal principal component analysis (PCA) in SPSS 23. Since it was first introduced (Ruchkin et al., 1964; Donchin, 1966), PCA has been considered an effective linear reduction method for multivariate ERP data (Möcks, 1988a; 1988b; Duffy et al., 1992; Chapman & McCrary, 1995; Dien, 1998; Picton et al., 2000; Dien and Frishkoff, 2005; for reviews see Kayser & Tenke, 2003; Dien, 2012). PCA statistically decomposes the ERP waveforms into constituent building blocks, which affords data-driven ERP component measures compared with other conventional methods (Kayser et al., 1998; Beau-ducel et al., 2000; Kayser & Tenke, 2006). Moreover, it is not as susceptible to the influences of high-frequency noises and low-frequency drifts in the data as other conventional methods (Luck, 2005). Covariance matrix and Promax rotation were used here. All components accounting for a total of 99% of the variance (maximum iterations for convergence = 500) were included in the rotation (Promax kappa = 4). The decomposition provided a set of time-variant component loadings reflecting the contribution of each temporal component to the voltage at each time point and a set of time-invariant component scores (calculated using Bartlett method) representing the contribution of each temporal component to the ERP waveforms which can be subject to inferential statistics (Van Boxtel, 1998).

We identified one component at around 100 ms corresponding to the **N1** (i.e., principal component 3 accounting for 8.84% of the variance) and two components at around 200 ms corresponding to the **P2** (i.e., principal component 4 accounting for 5.67% of the variance) and the **P3a** (i.e., principal component 6 accounting for 3.20% of the variance) on the basis of the component loading latencies and the component score topographies. The component scores were averaged across three electrodes showing the most negative/positive responses across all conditions independent of experimental manipulation (i.e., **N1 negative cluster**: Fz, F2, F4; **P2 positive cluster**: FCz, Cz, FC1; **P3a positive cluster**: FCz, Cz, FC1).

Therefore, the averages of these electrodes can be considered as objective representatives of the components to serve as inputs for further statistical analyses. The advantage of averaging three maximum electrodes was twofold. First, it increased the signal-to-noise ratio of the components. Second, it avoided the problems inherited in the analysis of predefined areas that took an average of multiple electrodes over predefined regions, which might not correspond to the true topography in the experiment.

To test for the interaction of repetition and attention when temporary disruption was absent/present, a **DISRUPTION** (continuous/intermittent roving)  $\times$  **ATTENTION** (attended/unattended stream)  $\times$  **REPETITION** (1st/2nd presentation), 2x2x2, repeated-measures ANOVA was performed.

**Table 1**

Range, mean, and SD of trial numbers after artefact rejection in each condition.

		Attended		Unattended	
		1st	2nd	1st	2nd
Continuous	Range	46–92	47–92	41–92	45–95
	Mean	82.04	83.65	82.35	82.74
	SD	10.48	9.28	13.86	13.77
Intermittent	Range	57–91	55–91	63–91	62–92
	Mean	81.65	81.00	82.65	82.74
	SD	9.18	10.56	7.04	7.94

#### CRedit authorship contribution statement

**Yi-Fang Hsu**: Conceptualization, Investigation, Formal analysis, Writing - original draft, Funding acquisition. **Álvaro Darriba**: Visualization, Writing - review & editing. **Florian Waszak**: Conceptualization, Writing - review & editing.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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