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No evidence for auditory N1 dishabituation in healthy adults after presentation of rare novel distractors

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ABSTRACT

Previous studies were not able to show that presentation of change stimuli leads to dishabituation of the auditory evoked potential (AEP) component N1 for repeated stimuli. However, these change stimuli were usually themselves repeatedly presented. Here, we tested whether the presentation of non-repeating distractor stimuli ('novels') would lead to N1 dishabituation. The study sample consisted of 18 healthy participants who had to identify auditory target stimuli (targets) among repeated standard stimuli and rare novels. AEPs to standards were separately averaged, depending on the preceding stimulus (standards after standards, standards after targets, and standards after novels) and were compared by F statistics and Bayesian *t*-test. Moreover, N1 repetition effects within recording blocks were analyzed in single trial analyses. The analyses showed that targets elicited significantly larger N1 amplitudes than standards and standards elicited larger N1 amplitudes than novels. In contrast, the N1 amplitude to standards did not vary with the preceding stimulus. The single trial analyses revealed significant, but similar N1 amplitude decreases within the recording blocks for all standards. The current study revealed no evidence for N1 dishabituation, as the N1 amplitude for standards after novels was not increased as compared to the N1 for standards after standards. Thus, stimulus variation had no impact on the N1 of repeated standards, as also suggested by the single trial analyses. The lack of N1 dishabituation is at odds with the assumption that the N1 amplitude decrease after repeated stimulation results from habituation.

1. Introduction

Repetition is a ubiquitous phenomenon in nature. When an auditory stimulus is repeated within a short time range (0.4 s to 10 s), the auditory evoked potential (AEP) component N1 decreases from the initial to the repeated stimulus (for review Näätänen and Picton, 1987; Rosburg and Mager, 2021). Such immediate repetition effects are also described for other AEP components (such as the P1) and other evoked potential components elicited in other modalities (such as somatosensory evoked potentials). For the repetition-related N1 decrease, there are two opposing explanatory models, namely habituation and N1 refractoriness. There is yet no consensus which of the two models is appropriate for conceptualizing this kind of N1 decrease (Rosburg and Mager, 2021; Ruusuvirta, 2021). This is an important question as alterations of the N1 decrease after repeated stimulation in clinical populations (such as schizophrenia) remain a poorly understood phenomenon as long as one does not know what such N1 decreases signify in terms of either physiological processes, psychological functions, or both (Rosburg, 2018).

Habituation as one explanatory model is considered as a simple, non-associative form of learning. It may be described "as the ability to ignore the familiar, predictable, and inconsequential" (McDiarmid et al., 2017, p. 286). As a simple form of learning, it is found and can be studied even in simple organisms, like the *Caenorhabditis elegans*, a 1 mm roundworm (for review Giles and Rankin, 2009), or the *Aplysia* (Glanzman, 2009; Pinsker et al., 1970). As decreased responses after repeated stimulation could in principle also be related to adaptation of the receptors and fatigue of the effectors, a larger set of criteria was developed in order to differentiate response decreases related to habituation from response decreases related to other causes (Thompson and Spencer, 1966; Rankin et al., 2009). One criterion for habituation is that stimulus change leads to response recovery. Even though habituation refers to a simple form of learning, its physiological basis is complex and is presumed to involve

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multiple mechanisms, with glutamate neurotransmission at the core (Giles and Rankin, 2009; Glanzman, 2009).

N1 refractoriness as the other major explanatory model refers to the idea that the neural N1 generators require a certain time before they are fully recovered and fully responsive again. The concept of N1 refractoriness is closely related to concepts of (stimulus-specific) adaptation (Helson, 1948; Näätänen et al., 1988; O'Shea, 2015; Ulanovsky et al., 2003), but N1 refractoriness exclusively refers to the immediate past (Rosburg and Mager, 2021; Ross and Hamm, 2020). N1 refractoriness has in particular been studied by varying the interval between stimuli (Berti et al., 2017; Chapman et al., 1981; Davis et al., 1966; Hari et al., 1982; Herrmann et al., 2016; Javitt et al., 2000; Pereira et al., 2014; Rosburg et al., 2010; Teichert et al., 2016). Such studies showed that for interstimulus intervals (ISIs) > 0.4 s the N1 amplitude increased with increasing ISIs, until the N1 amplitude saturates at ISIs of about 10 s. Since the N1 generators are partly stimulus specific (Butler, 1968; Herrmann et al., 2014; Näätänen et al., 1988; Picton et al., 1978; Yagcioglu and Ungan, 2008), N1 refractoriness hypothesis predicts, similar to the N1 habituation account, that larger stimulus change results in an N1 response recovery. Thus, the two accounts do not necessarily make different predictions, and some repetition effects, such as the N1 facilitation at very short ISIs (Budd and Michie, 1994) cannot be explained either by habituation or N1 refractoriness, as previously discussed elsewhere in more detail (Rosburg and Mager, 2021).

However, the two accounts cannot be considered as denoting the same process from different perspectives (a behavioral learning perspective vs. a physiological perspective), as suggested by some researchers (Ethridge et al., 2016), because they differ with regard to other predictions. One prime differentiation between the two accounts is the following: Based on the habituation account, the presentation of a change stimulus affects the processing of the subsequent repeated stimulus and leads to dishabituation (an increased response to the previously habituated stimulus). Dishabituation has been considered as the most important method of distinguishing habituation from fatigue (Thompson, 2009). In contrast, the N1 refractoriness account would predict that any response recovery to the repeated stimulus after presenting a change stimulus crucially depends on the change stimulus and, even for large change stimuli, would result in only a small response recovery (Rosburg and Sörös, 2016; Rosburg and Mager, 2021).

Previous findings might be better explained by the N1 refractoriness account because all previous studies revealed no evidence for N1 dishabituation, i.e. the N1 to the repeated standard was never found to be increased in amplitude after presenting a change stimulus (Barry et al., 1992; Budd et al., 1998; Muenssinger et al., 2013; Rosburg et al., 2006; Rosburg and Mager, 2021; Rosburg and Sörös, 2016; Yadon, 2010). The observation of N1 dishabituation would be a game changer when weighting the pros and cons for the habituation and N1 refractoriness accounts. However, given the absence of evidence for N1 dishabituation, the N1 decrease after repeated stimulation should not light-handedly be labeled as habituation. Naturally, individual null-findings should not be over-interpreted because such findings might sometimes just reflect a lack of statistical power or poor data quality. However, if studies repeatedly provide null-findings, the underlying effect is either absent or very small, or some systematic characteristic of the previous studies might have hindered the observation of N1 dishabituation.

The first possibility (small effects) would render the characteristic of N1 dishabituation as non-meaningful. The second possibility (of systematic characteristics hindering the observation of N1 dishabituation) cannot be ruled out because all previous studies investigating N1 dishabituation were similar in one regard and this similarity could indeed have biased null-findings. All studies that sought to provide evidence for N1 dishabituation used just one or two kinds of change stimuli (Barry et al., 1992; Budd et al., 1998; Rosburg et al., 2006; Rosburg and Mager, 2021; Rosburg and Sörös, 2016; Yadon, 2010). This means the change stimuli themselves were repeatedly presented throughout the experiment. As the effect of dishabituation was proposed to habituate ('habituation of dishabituation', Rankin et al., 2009), the N1 dishabituation effect might have so rapidly diminished that it became unobservable across the experimental blocks.

To the best of our knowledge, no study has previously addressed the possibility that habituation of dishabituation could have had an impact on the study findings. The current study tested whether N1 dishabituation would occur after presenting non-repeating distractor stimuli (novels). Three-stimulus oddball experiments, consisting of repeated standard tones, rare targets, and rare novel distractors offer the possibility to investigate whether habituation of dishabituation could have hindered the observation of N1 dishabituation. We hypothesized that the N1 amplitude for standards preceded by novels would be larger than for standards preceded by standards (reflecting N1 dishabituation) and larger than for standards preceded by targets (resulting from habituation of N1 dishabituation). Furthermore, we hypothesized that, due to habituation of N1 dishabituation, the N1 amplitude for standards preceded by targets would show a larger decrease throughout recording blocks than the N1 amplitude for standards preceded by novels.

To this end, we re-analyzed data from a previous ERP study using a 3-stimulus active oddball paradigm (Weigl et al., 2016). This previous study investigated the effects of frontal transcranial direct current stimulation (tDCS) on stimulus discrimination in a pretest-posttest design, using both a passive and active oddball paradigm. Effects of anodal and cathodal tDCS were restricted to the passive oddball; in the active condition, there were no tDCS effects on ERPs (including the N1, P2, and novelty- and target-P3). Given this, the active oddball data set was well suited for the current research purpose. Due to the within-subject crossover design, the data set contained six separate recording blocks per participant. This considerably increased the statistical power for detecting N1 dishabituation. None of the current results was reported in the original study.

2. Methods

2.1. Participants

Study participants were 18 healthy adults (6 female), all students of the Saarland University ranging in age from 20 to 29 years (median age 26 years). The study was conducted according to the declaration of Helsinki. Study participation was voluntary and participants could quit at any point of the study without the need of providing any explanation. No participant made use of this right. All participants gave written informed consent for study participation and were reimbursed with 10 €/h.

2.2. Stimulation

There were three recording days with two recording blocks each. The stimulation in each block consisted of 500 auditory stimuli. There were three different kinds of stimuli: repeatedly presented standard tones (80% likelihood), as well as rarely interspersed target stimuli and novels (10% likelihood each). All stimuli had a duration of 200 ms. The standard was a 600-Hz sinus tone, the target stimulus a 1000-Hz sinus tone, both presented at 70 dB sound pressure level, as measured by a digital sound level meter (Professional GM1351, Tiang Tech, Guangdong, China). Standards and targets did not vary within recording blocks. The novels were environmental, spectrally rich, dynamic sounds (taken from Mecklinger et al., 1997) that were only repeated from one recording day to another, but not within recording blocks/days. The standards and targets had 10-ms onset and offset ramps, whereas the onsets and offsets of the novels were highly variable. The sound intensity of novels was similar to the sound intensity of standards and targets, based on the subjective impression of two experimenters (MW and TR), but no attempt was made to equalize the total sound energy of novels on the one hand and standards/targets on the other. The stimulus-onset-asynchrony was 1500 ms. Targets and novels were always followed by

at least one standard. Participants had to press the "M"-key on a computer keyboard in response to targets, whereas novels and standards did not require a behavioral response. The study of Weigl et al. (2016) was designed as single-blinded, cross-over study. This means the participants were not aware of the test conditions and were tested in all three conditions, defined by the tDCS stimulation protocol (frontal anodal tDCS, frontal cathodcal tDCS, and frontal sham tDCS). Each tDCS protocol took place on separate recording days. There were two recording blocks on each experimental day (one before the tDCS application, one after it). Thus, there were six recording blocks per participant in total.

2.3. EEG recording

EEG was recorded from 21 silver/silverchloride electrodes (Fz, F4, F8, FCz, FC4, FC6, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, O2) embedded in an elastic cap (Easycap, Herrsching, Germany), as well as from the left and right mastoid (M1, M2), with a sampling rate of 500 Hz. For recordings, data were referenced to M1. Due to the frontal tDCS application, several other frontal electrodes of the 10–20 system could not be attached (for visualization, see Weigl et al., 2016, Fig. 2). Ocular activity was recorded by two pairs of electrodes placed at the outer canthi, as well as above and below the left eye.

2.4. Data processing

EEG data were processed by using the software package BrainVision Analyzer 2.2.0 (Brain Products, Gilching, Germany). EEG data were initially highpass filtered at 0.1 Hz (48 dB) and down-sampled to 250 Hz. Subsequently, the data were segmented in overlapping epochs for standards, novels, and targets with 4500 ms length (3000 ms prestimulus activity) and subjected to an independent component analysis (ICA) in order to remove all activity related to ocular and electrocardiographic artefacts after manual selection. ICA was based on a restricted Infomax algorithm. After removal of such ICA components (on average 3.3 components, range 2 to 6), data were re-referenced to linked mastoids and low-pass filtered at 30 Hz (48 dB). As segments of standards following novels showed some slow potential shift in the prestimulus period, segments were highpass filtered at 1 Hz (24 dB) for the analysis of ERPs to standards, preceded by different kinds of stimuli. This slow potential shift in the pre-stimulus period was related to a long-lasting negativity that followed the P3a to novels, starting at ~500 ms, and that was still present at the onset of the subsequent standard. The 1 Hz highpass removed this slow wave activity. Epochs with 2000 ms duration were created for standards following standards (std_std), standards following novels (std_nov), and standards following targets (std_tar), including 500 ms prestimulus activity. These epochs were baseline corrected (−200 to 0 ms). Epochs with absolute amplitudes larger than 100 μV at any scalp electrode were rejected as artefacts. Subsequently, the epochs were averaged for the three kinds of standard stimuli.

For contrasting the ERPs of standards with ERPs to targets and novels, the 1-Hz filter was not used, as it would have diminished the P3-related activity. Otherwise, data processing for the ERPs to targets (tar) and novels (nov) was identical to the processing of the standard stimuli, as described before. For contrasting the N1 for targets, novels, and standards preceded by standards, the ERPs to the latter were re-calculated without the 1-Hz filter. Of note, the N1 amplitude to standards following standards was hardly influenced by the 1-Hz filter. Within the figures, all displayed data had identical filter parameters. ERPs were calculated on the basis of all artefact-free trials, without considering the response accuracy. Only novels elicited a noteworthy number of commission errors. False alarms to novels and standards following false alarms to novels were included in calculating the ERPs because dishabituation should be driven by the sensation of stimuli that differ from the repeated standards, and not by their correct classification as nontarget.[1]

2.5. Statistics

Since our previous study (Weigl et al., 2016) did not reveal any effects of the tDCS stimulation protocol on the N1 and P2, the stimulation protocol was not considered for the current analysis. The statistical analysis considered, however, the pretest-posttest design (factor '*Recording Block*'). Of note, the factor Recording Block does not reflect specific tDCS effects but unspecific effects (related primarily to the longer duration of the recording session, but maybe also to the expectation of tDCS effects). We previously showed that the P3a and P3b amplitudes decreased from the first to second recording block across all stimulation protocols (Weigl et al., 2016, Fig. 3 and Table 2). Only significant interactions between Recording Block and tDCS protocol would have indicated specific tDCS effects (Weigl et al., 2016).[2] The current ERP analysis was restricted to the midfrontal electrode FCz, showing the largest N1 deflection.

In an initial analysis, we tested whether the presentation of targets led to an N1 response recovery. To this end, the mean N1 amplitudes of standards preceded by standards, of targets, and of novels were exported for a 40-ms time window around the grand average N1 peak maximum (76 to 116 ms). These mean amplitudes were subjected to a repeated measure analysis of variance (ANOVA) with Recording Day (1 vs. 2 vs. 3), Recording Block (pre vs. post), and Stimulus (std vs. nov vs. tar) as within-subject factors, using SPSS 25.0 (IBM, Armonk, NY, USA).

In a second analysis, we tested whether the presentation of targets, novels, or both resulted in an N1 dishabituation. To this end, mean N1 amplitudes (76 to 116 ms) were exported for the three kinds of standards, which were defined by the preceding stimulus (context). These mean amplitudes were subjected to a repeated measure ANOVA with Recording Day (1 vs. 2 vs. 3), Recording Blocks (pre vs. post), and Context (std_std vs. std_nov vs. std_tar) as within-subject factors. In addition, the mean N1 amplitudes across blocks and recording days were entered into a Bayesian paired sample *t*-test with the default Cauchy width of 0.707. These tests were conducted, using the free opensource software package JASP Version 0.14.1, sponsored by the University of Amsterdam (JASP Team, 2020). By the Bayesian testing, the evidence for H0 and H1 was weighted. In an exploratory analysis, mean amplitudes were also extracted for the P2 (160 to 200 ms) and N2 (276 to 316 ms) and subjected to a repeated measure ANOVA with Recording Day, Recording Block, and Context as within-subject factors. The latter results can be found in Supplementary materials.

Finally, in order to explore the variation of the N1 within recording blocks, the N1 amplitudes were extracted for each trial and subsequently z-transformed across the trials of each recording block at electrode FCz. Subsequently, a linear regression analysis was calculated with Trial Number (1 to 50) as predictor for the N1 amplitude. Data of all six recording blocks of each individual were entered into this analysis. Adding interaction terms (Trial Number x Recording Day, Trial Number x Recording Block, Trial Number x Recording Day x Recording Block) to the regression model did not significantly improve the prediction accuracy. For the sake of simplicity and brevity, we therefore report only the simple linear regression models. We hypothesized that the N1 for standards preceded by targets might show a decline across trials, as consequence of habituation of dishabituation. We also hypothesized that

[1] The comparison of grand average data (all epochs vs. false alarm data excluded) suggested that this technical detail had no relevant impact on the results (data not shown).

[2] The factor 'Recording Block' was labeled 'TIME' in Weigl et al. (2016).

this decline would be weaker (and maybe even absent) for standards preceded by novels. Possible differences between the N1 decreases of std_tar and std_nov within blocks were tested in a combined regression analysis, by using Trial Number as sole predictor and subsequently adding a Trial Number x Context interaction term to the regression model. Since there were six times more trials for std_std than for std_nov and std_tar, trials of std_std were redefined in order to allow direct comparison of the regression coefficients between std_nov, std_tar, and std_std. Six succeeding trials were merged in so newly defined trial (e.g. trials 1 to 6: trial6 = 1). In order to assess the variation of attentional processes across trials, we also ran linear regression analyses for the P3a of novels (268 to 308 ms) and P3b of targets (296 to 336 ms), again extracted at FCz. The main purpose of the linear regression analyses was the quantification of the N1, P3a, and P3b amplitude decreases. Other kinds of curve fits might be considered as theoretically more appropriate, but only for the P3a there was some empirical evidence that the linear model was inferior to other kinds of curve fits (Supplementary materials **Table S1**).

3. Results

3.1. Behavioral performance

As previously reported (Weigl et al., 2016), the performance in the oddball task was characterized by a high accuracy in detecting the targets. The rate of misses was <0.1%. Likewise, the false alarm rate to standards was with <0.1% extremely low. There were no false alarms at all to standards after novels and standards after targets. In response to novels, participants created false alarms in 3.0% (SD 5.0%) of the trials.

3.2. N1 response recovery

Both the N1 refractoriness hypothesis as well as the habituation account predict a N1 response recovery for target stimuli (increased N1 to targets as compared to standards). Such an increase was verified in the initial three-way ANOVA, showing a main effect of Stimulus ($F_{2, 34} = 34.750$, $p < .001$, partial $\eta^2 = 0.671$). The N1 amplitude was largest for targets ($N1_{tar}$: M = −7.21 μV, SE = 0.59 μV), intermediate for standards ($N1_{std\_std}$: M = −5.60 μV, SE = 0.54 μV), and smallest for novels ($N1_{nov}$: M = −3.12 μV, SE = 0.71 μV), with data filtered at 0.1 Hz (Fig. 1). Moreover, there was a significant Stimulus x Block interaction ($F_{2, 34} = 6.092$, $p = .005$, partial $\eta^2 = 0.264$). This was due to differential N1 amplitude changes from the first to the second block for each kind of stimulus. Across the two blocks of a recording day, the N1 was quite stable for standards (1st block: M = −5.60 μV, SE = 0.53 μV; 2nd block: M = −5.60 μV, SE = 0.56 μV; $F_{1, 17} = 0.006$, n.s., partial $\eta^2 \leq 0.001$), as well as for targets (1st block: M = −7.34 μV, SE = 0.61 μV; 2nd block: M = −7.07 μV, SE = 0.61 μV; $F_{1, 17} = 0.779$, n.s., partial $\eta^2 = 0.044$). In contrast, the N1 amplitude of novels showed a significant amplitude increase from the 1st to the 2nd block (1st block: M = −2.83 μV, SE = 0.67 μV; 2nd block: M = −3.42 μV, SE = 0.77 μV; $F_{1, 17} = 7.090$, $p = .016$, partial $\eta^2 = 0.294$).[3] All other effects did not reach significance.

3.3. N1 dishabituation

The N1 amplitude of standards did not vary with Context, neither as main factor ($F_{2, 34} = 2.297$, n.s., partial $\eta^2 = 0.119$) nor in interaction with other factors (all $F < 1.0$, n.s., all partial $\eta^2 < 0.03$). Numerically, the N1 amplitude was largest for standards preceded by targets, the N1 was smallest for standards preceded by novels ($N1_{std\_tar}$: M = −5.88 μV, SE = 0.59 μV; $N1_{std\_std}$: M = −5.56 μV, SE = 0.48 μV; $N1_{std\_nov}$: M = −5.31 μV, SE = 0.68 μV, Fig. 2), whereas we had hypothesized that the N1 for standards preceded by novels would be largest. As to-be-expected from the absent interaction effects, inclusion of only the first recording blocks revealed quite similar results.

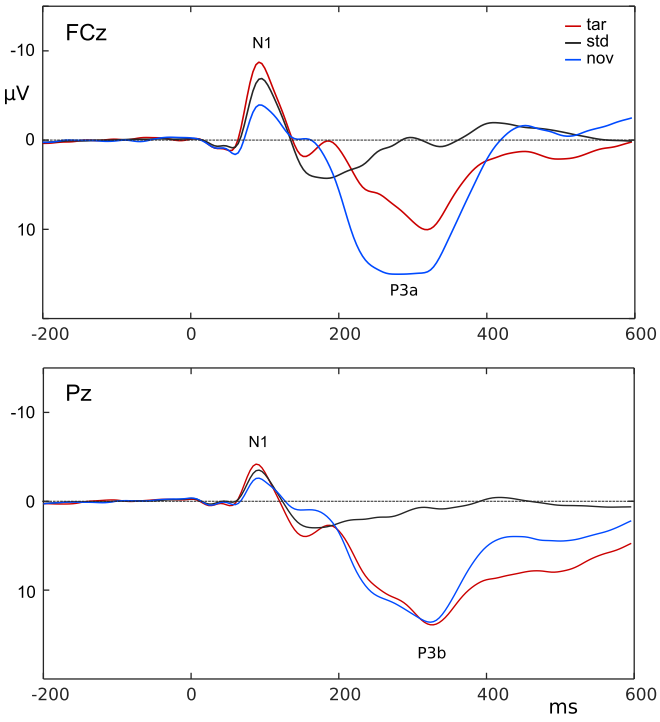

Fig. 1. The ERPs to targets (tar), standards after standards (std), and novels (nov) at the midfrontal electrode FCz (top) and centro-parietal electrode Pz (bottom). The N1 amplitude was largest for targets, intermediate for standards, and smallest for novels. ERPs to novels were characterized by a pronounced P3a, which was larger in amplitude at FCz than at Pz, as to be expected. All data were highpass-filtered at 0.1 Hz.

The Bayesian factor BF_{+0} for the directional hypothesis $N1_{std\_tar} > N1_{std\_std}$ was 1.047, which means that the findings speak neither in favor of the null hypothesis nor the alternative hypothesis. The corresponding Bayesian factor BF_{+0} for the directional hypothesis $N1_{std\_nov} > N1_{std\_std}$ was 0.144, indicating that the data provided more evidence for the null hypothesis than for the alternative hypothesis. Thus, it is likely that the presentation of novel stimuli was not associated with N1 dishabituation for the repeated standard. The results of the two Bayesian paired sample *t*-tests are provided in some greater detail in **Fig. S1** in Supplementary materials, displaying the inferential plots and the Bayes factor robustness checks.

Standards following deviants might elicit a mismatch negativity (MMN, Sams et al., 1984). An MMN with an early onset could theoretically mimic an N1 dishabituation. However, in our previous study, an MMN-like deflection did not start before 200 ms (Rosburg and Mager, 2021). Similar to this previous finding, the ERPs to standards preceded by targets or by novels were more negative at latencies >200 ms (Fig. 2, "N2"). Importantly, the P2 amplitudes of standards preceded by targets or by novels were larger (more positive) than the P2 of standards preceded by standards (Fig. 2, "P2", see also Supplementary materials).

3.4. N1, P3a, and P3b amplitude decreases across trials

The N1 amplitudes to standards preceded by targets, novels, and

[3] This effect presumably reflects a heightened sensitivity for distractor stimuli, associated to the participant's *expectation* of a tDCS effect. Of note, only pre-post differences varying between the tDCS protocols (anodal vs. cathodal vs. sham tDCS) were considered as genuine tDCS effect in the original study (Weigl et al., 2016). Since the observed Recording Block effect on the N1 to novels is of little relevance for the current study context, we do not address the finding in the discussion.

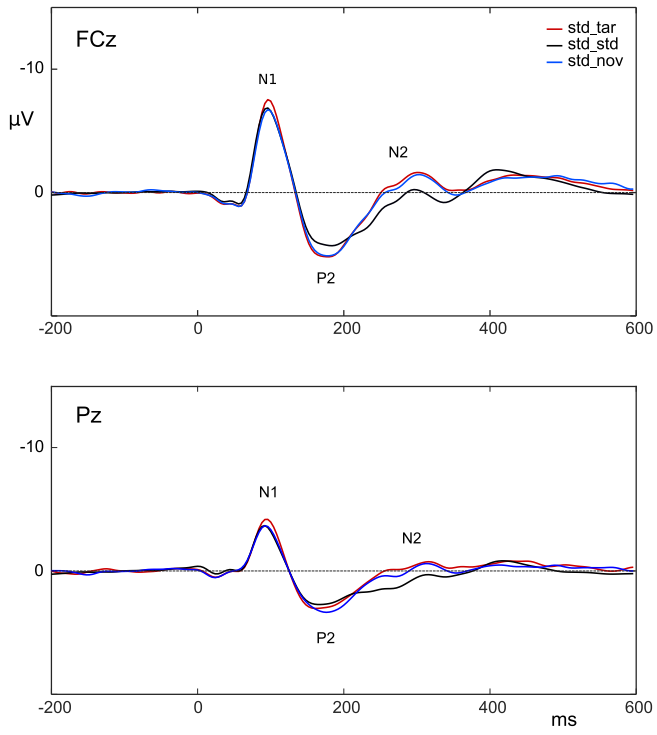

Fig. 2. The ERPs to standards preceded by targets (std_tar), by standards (std_std), and by novels (std_nov) at the midfrontal electrode FCz (top) and centro-parietal electrode Pz (bottom). The N1 amplitude did not systematically vary between the three kinds of standards, but was numerically smallest for standards preceded by novels. Thus, the findings provided no evidence for N1 dishabituation. All data were highpass-filtered at 1.0 Hz.

standards all showed a significant decrease across trials during the recording blocks (Table 1, **Fig. S2**). This N1 decrease was numerically more pronounced for standards preceded by novels than for standards preceded by targets. This finding was opposite to the assumption that the varying stimulation would attenuate such decrease. When analysing the N1 to std_nov and std_tar together, adding a Trial number x Context interaction term to the regression model did not significantly improve the prediction accuracy. This suggests that the N1 amplitude decrease of standards did not systematically vary between standards preceded by targets and standards preceded by novels. For targets and novels, there was no N1 amplitude decrease (Table 1). Both the novelty-related P3a and the target-related P3b exhibited relatively pronounced decreases in amplitude across trials (P3a: $F_{1,\ 5398} = 38.311$, $p < .001$, $zP3a_{predicted} = -0.0057 * trial + 0.1464$, $R^2 = 0.0070$; P3b: $F_{1,\ 5398} = 49.345$, $p < .001$, $zP3b_{predicted} = -0.0065 * trial + 0.1660$, $R^2 = 0.0095$, **Fig. S3**).

4. Discussion

The study sought to provide evidence for N1 dishabituation for repeated standards after the inserted presentation of rare target stimuli and novel distractors. However, the study could not reveal such evidence: The N1 to standards varied only marginally with the preceding stimulus.

Table 1
Linear regression models of the N1 amplitude.

zN1	b1	b0	R^2	F statistics
std_tar	0.0024	−0.0616	0.0012	$F_{1,\ 5398} = 6.723$, $p = .010$
std_nov	0.0034	−0.0876	0.0025	$F_{1,\ 5398} = 13.606$, $p < .001$
std_std	0.0034	−0.0850	0.0023	$F_{1,\ 32,130} = 74.669$, $p < .001$
tar	<0.0001	0.0002	<0.001	$F_{1,\ 5398} < 0.001$, $p = .995$
nov	<0.0001	0.0070	<0.001	$F_{1,\ 5398} = 0.088$, $p = .767$

$zN1_{predicted} = b1 * trial + b0$.

4.1. No N1 dishabituation after target presentation

For standards preceded by targets, increased negativities were only observed at latencies >200 ms, possibly reflecting MMN-like deflections, similar to those previously described for standards preceded by deviants (Rosburg and Mager, 2021; Sams et al., 1984). In contrast, the N1 to standards preceded by targets was only minimally larger than the N1 to standards preceded by standards. This lack of N1 dishabituation after targets was not unexpected, as all previous studies failed to show N1 dishabituation after presenting deviants as uniform change stimuli in passive oddball experiments (one kind of deviant: Barry et al., 1992; Budd et al., 1998; Muenssinger et al., 2013; Rosburg et al., 2006; Rosburg and Sörös, 2016; Yadon, 2010; two kinds of deviants: Rosburg and Mager, 2021). In principle, these repeated null-findings would suggest that N1 dishabituation is either absent or very small. However, this conclusion might be misleading under the premise that the cited studies shared characteristics that might systematically have hampered the observation of N1 dishabituation. We have previously suggested that the repeated presentation of uniform change stimuli (as one common characteristic in all these studies) could possibly have contributed to the null-findings (Rosburg and Mager, 2021) because the dishabituation effect itself is presumed to habituate ('habituation of dishabituation', Rankin et al., 2009). Thus, the working hypothesis was that N1 dishabituation was previously not observed due to the uniform presentation of change stimuli. If true, the N1 dishabituation should be present when change stimuli vary. No previous study addressed this assumption.

4.2. No N1 dishabituation after novel distractors

In our study, the distractor stimuli were constantly varied in order to maintain a strong P3a and high level of distraction. Indeed, the distractor stimuli elicited a pronounced P3a, as expected (Fig. 1, blue curve). However, contrary to our hypothesis, the N1 amplitude to standards was not modulated by the presentation of novels in the preceding trial. Thus, similar to targets as constant change stimuli, presentation of novels did not lead to N1 dishabituation of the repeated standard and increased negativities were only observed at latencies >200 ms. This lack of an N1 modulation suggests that previous null-findings with regard to N1 dishabituation were unlikely due to the lack of variation in the change stimulus.

4.3. No evidence for habituation of dishabituation

Habituation of dishabituation should also have led to a stronger N1 decrease for standards after targets than for standards after novels within recordings blocks. However, the single trial analysis revealed no such evidence: There was a similar N1 decrease within recording blocks for all standards, irrespective of the context (Table 1).

Long-term decrements of the N1 amplitude over the range of minutes and hours have previously been reported (Roeser and Price, 1969; Rosburg et al., 2000, 2002; Salamy and McKean, 1977; Woods and Courchesne, 1986). It is important to stress that such N1 long-term decrements are functionally dissociated from its short-term decrements (or immediate N1 repetition effects, as we labeled them here). Long-term decrements of the N1 amplitude are unlikely explained by changes in arousal level as they were accompanied by faster reaction times and were reported not to influence any short-term decrements (Woods and Courchesne, 1986). We previously revealed that long-term decrements of the neuromagnetic N1 (or N1m) amplitude were accompanied by increases of the N1m latency (Rosburg et al., 2002), whereas immediate repetitions (change from the 1st to the 2nd stimulus of a stimulus train) were associated with decreases in N1m latency (Rosburg, 2004). Most strikingly, the vast majority of studies

investigating short-term decrements of the N1 by presenting trains of stimuli showed that the N1 amplitude decrease was widely completed with the presentation of the 2nd stimulus (for review Rosburg and Sörös, 2016), whereas studies on the long-term decrement of the N1 usually revealed a continuous, more asymptotic N1 decrease (Roeser and Price, 1969; Rosburg et al., 2000, 2002; Salamy and McKean, 1977; Woods and Courchesne, 1986).

Long-term decrements occurred not only for the N1 but also for the P3b, which is in line with previous studies (Lew and Polich, 1993; Polich, 1989; Romero and Polich, 1996). Similarly, the P3a amplitude to novels showed some decrease within recordings blocks. Thus, the variation of the distractors did not completely prevent a P3a decrease over time, which is very rapid for repeated standard stimuli (Barry et al., 2016). The P3a decrease over time had no impact on the N1 to subsequent standards, as the N1 to standards preceded by novels showed a similar decrease in amplitude within recordings blocks as the N1 to standards preceded by standards (i.e. N1 to standards, which were not preceded by a P3a).

4.4. N1 to targets and novels

Targets elicited larger N1 amplitudes than standards, as expected based on both the habituation account and N1 refractoriness hypothesis, whereas the N1 amplitudes to novels were smaller than the N1 to standards. At first glance, the smaller N1 to novels might be considered as surprising, considering other studies showing an opposite finding (e.g. Berti et al., 2017). However, the novels in our study had generally less steep and more variable stimulus onsets than standards and targets. We presume that these two features of novels likely resulted in the observed smaller N1 amplitudes of such stimuli, as the N1 amplitude increases with the steepness of the stimulus onset (Spreng, 1980). However, also other characteristics of the novels might have contributed to the smaller N1 amplitudes, such as variable amplitude envelopes. Given the considerable differences in the physical characteristics of novels and standards, the N1 difference between standards and novels cannot and should not be functionally interpreted as effect of novelty.

We consider it as unlikely that the lack of N1 dishabituation for the repeated standard after novels was due to the small N1 responses to novels, because any stimulus perceived as different could trigger dishabituation (Rankin et al., 2009). Furthermore, with regard to dishabituation, even weak change stimuli can be very effective (Marcus et al., 1988). However, as the novels continuously elicited large amplitude P3a responses within the experimental blocks, participants permanently perceived the distractors as strongly different from standards, as intended by the experimental set-up.

4.5. Role of attention

The current ERP data were obtained in an active oddball paradigm that required the participant to pay attention to the auditory stimulation and to react on stimuli defined as targets by button press. In general, attention is assumed to increase the N1 amplitude (Hackley et al., 1990; Hillyard et al., 1973; Näätänen et al., 1981; Woldorff and Hillyard, 1991). One could speculate that the increased N1 for targets (as compared to standards) stems from attention effects. Such increased N1 amplitudes for targets were reported in previous studies as well (Barry et al., 2016; McDonald et al., 2010). However, in equiprobable NoGo tasks, similar frontal N1 amplitudes were found for Go stimuli (targets) and NoGo stimuli (nontargets, Borchard et al., 2015), or Go stimuli were even associated with slightly smaller frontal N1 amplitudes than NoGo stimuli (Fogarty et al., 2020). These latter findings suggest that the designation of change stimuli as targets does not per se explain the N1 response recovery to these stimuli. In line with such notion, the N1 response recovery was found to be quite similar in amplitude for ignore and attend conditions (Barry et al., 1992). Therefore, the N1 response recovery for target stimuli, as observed, was unlikely due to attention but to the frequency difference between standards and targets.

4.6. No significant N1 response recovery for standards preceded by targets

Based on the N1 refractoriness account, a minor N1 response recovery was expected for standards preceded by targets (Rosburg and Mager, 2021; Rosburg and Sörös, 2016) because the cell assemblies generating the N1 to the repeated 600 Hz-standard just partly overlap with cell assemblies generating the N1 to the 1000-Hz target stimulus (Butler, 1968; Herrmann et al., 2014; Näätänen et al., 1988; Picton et al., 1978; Yagcioglu and Ungan, 2008). All specific N1 generators would thus have a longer recovery time when standards are preceded by targets as when standards are preceded by other standards. However, in our study, the N1 to standards preceded by targets just showed a small, insignificant N1 increase. The reason for this null-finding remains open at this point. One could speculate that the fixed order of stimuli contributed to it. The occurrence of targets was not predictable except that two targets never occurred in succession. It was thus in principle possible that participants lowered their attention towards standards after targets because participants implicitly learned that stimuli after targets never required a response. However, the single trial data does not support the assumption of such attention effects because the N1 amplitude decline within recordings was similar for standards preceded by standards and standards preceded by targets.

In our study, we primarily sought to obtain possible evidence for dishabituation. The lack of a significant N1 response recovery for standards preceded by targets means that the current study itself did not provide evidence for the N1 refractoriness account. Yet, the current experimental and analytical design was not particularly suited to reveal such evidence, either. Classical study designs, which systematically vary the difference in frequency of two succeeding stimuli (or other stimulus characteristics), are clearly preferable to test the relatively few predictions of the refractoriness account (Butler, 1968; Näätänen et al., 1988; Picton et al., 1978; Rosburg and Mager, 2021). To our best knowledge, the two main predictions (the N1 amplitude increases with increasing ISI, until this increase saturates at ISIs of 10 to 20 s; with increasing similarity of two succeeding stimuli in frequency, the N1 amplitude to the 2nd stimulus is more decreased) are in principle not disputed (Rosburg and Mager, 2021). However, not only the underlying neurophysiological mechanisms of N1 refractoriness, but also its modulation by stimulus parameters, as well as by psychological and pathological processes have remained poorly understood, last but not least due to the relatively small number of studies conducted in this field of research. Among others, it is not known if N1 refractoriness varies with stimulus intensity (loudness), is modulated by task-related factors (like the requirement to actively discriminate the stimuli), or whether N1 refractoriness varies with arousal and effort. To make things more complicated, other effects than refractoriness might come into play when spectrally rich auditory stimuli are presented in sequences, such as lateral inhibition (Okamoto et al., 2005, 2004; Pantev et al., 2004). In contrast to the gaps in basic research, there is some considerable evidence from clinical research that N1 deficits in schizophrenia are more pronounced at long than at short ISIs (Rosburg, 2018; Rosburg et al., 2008), suggesting that the N1 recovery function is affected in schizophrenia.

5. Conclusion

N1 dishabituation was not observed, neither after the presentation of targets as constant change stimuli nor after the presentation of distractor stimuli that constantly varied across recordings. The findings confirm and extend previous studies that used exclusively constant change stimuli and did not observe N1 dishabituation either (Barry et al., 1992; Budd et al., 1998; Muenssinger et al., 2013; Rosburg et al., 2006; Rosburg and Mager, 2021; Rosburg and Sörös, 2016; Yadon, 2010). The

current study suggests that usage of a constant change stimulus did likely not contribute to the repeated null-findings. The single trial analysis revealed no evidence either that habituation of the dishabituation might have played a role for the absence of N1 dishabituation, as we had hypothesized. Based on the current evidence, we assume that immediate N1 repetition effects are primarily related to N1 refractoriness and not to habituation (Barry et al., 1992; Budd et al., 1998; Rosburg and Mager, 2021).

Declaration of competing interest

All authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2022.01.013.

References

Barry, R.J., Cocker, K.I., Anderson, J.W., Gordon, E., Rennie, C., 1992. Does the N100 evoked potential really habituate? Evidence from a paradigm appropriate to a clinical setting. Int. J. Psychophysiol. 13, 9–16.

Barry, R.J., Steiner, G.Z., De Blasio, F.M., 2016. Reinstating the novelty P3. Sci. Rep. 6 https://doi.org/10.1038/srep31200.

Berti, S., Vossel, G., Gamer, M., 2017. The orienting response in healthy aging: novelty P3 indicates no general decline but reduced efficacy for fast stimulation rates. Front. Psychol. 8 https://doi.org/10.3389/fpsyg.2017.01780.

Borchard, J.P., Barry, R.J., De Blasio, F.M., 2015. Sequential processing in an auditory equiprobable Go/NoGo task with variable interstimulus interval. Int. J. Psychophysiol. 97, 145–152. https://doi.org/10.1016/j.ijpsycho.2015.05.010.

Budd, T.W., Michie, P.T., 1994. Facilitation of the N1 peak of the auditory ERP at short stimulus intervals. Neuroreport 5, 2513–2516.

Budd, T.W., Barry, R.J., Gordon, E., Rennie, C., Michie, P.T., 1998. Decrement of the N1 auditory event-related potential with stimulus repetition: habituation vs. refractoriness. Int. J. Psychophysiol. 31, 51–68.

Butler, R.A., 1968. Effect of changes in stimulus frequency and intensity on habituation of the human vertex potential. J. Acoust. Soc. Am. 44, 945–950.

Chapman, C.R., Colpitts, Y.H., Mayeno, J.K., Gagliardi, G.J., 1981. Rate of stimulus repetition changes evoked potential amplitude: dental and auditory modalities compared. Exp. Brain Res. 43, 246–252.

Davis, H., Mast, T., Yoshie, N., Zerlin, S., 1966. The slow response of the human cortex to auditory stimuli: recovery process. Electroencephalogr. Clin. Neurophysiol. 21, 105–113.

Ethridge, L.E., White, S.P., Mosconi, M.W., Wang, J., Byerly, M.J., Sweeney, J.A., 2016. Reduced habituation of auditory evoked potentials indicate cortical hyper-excitability in fragile X syndrome. Transl. Psychiatry 6. https://doi.org/10.1038/tp.2016.48.

Fogarty, J.S., Barry, R.J., Steiner, G.Z., 2020. The first 250 ms of auditory processing: no evidence of early processing negativity in the Go/NoGo task. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-61060-9.

Giles, A.C., Rankin, C.H., 2009. Behavioral and genetic characterization of habituation using Caenorhabditis elegans. Neurobiol. Learn. Mem. 92, 139–146. https://doi.org/10.1016/j.nlm.2008.08.004.

Glanzman, D.L., 2009. Habituation in aplysia: the Cheshire cat of neurobiology. Neurobiol. Learn. Mem. 92, 147–154. https://doi.org/10.1016/j.nlm.2009.03.005.

Hackley, S.A., Woldorff, M., Hillyard, S.A., 1990. Cross-modal selective attention effects on retinal, myogenic, brainstem, and cerebral evoked potentials. Psychophysiology 27, 195–208.

Hari, R., Kaila, K., Katila, T., Tuomisto, T., Varpula, T., 1982. Interstimulus interval dependence of the auditory vertex response and its magnetic counterpart: implications for their neural generation. Electroencephalogr. Clin. Neurophysiol. 54, 561–569.

Helson, H., 1948. Adaptation-level as a basis for a quantitative theory of frames of reference. Psychol. Rev. 55, 297–313.

Herrmann, B., Schlichting, N., Obleser, J., 2014. Dynamic range adaptation to spectral stimulus statistics in human auditory cortex. J. Neurosci. 34, 327–331. https://doi.org/10.1523/JNEUROSCI.3974-13.2014.

Herrmann, B., Henry, M.J., Johnsrude, I.S., Obleser, J., 2016. Altered temporal dynamics of neural adaptation in the aging human auditory cortex. Neurobiol. Aging 45, 10–22. https://doi.org/10.1016/j.neurobiolaging.2016.05.006.

Hillyard, S.A., Hink, R.F., Schwent, V.L., Picton, T.W., 1973. Electrical signs of selective attention in the human brain. Science (80-.) 182, 177–180.

Javitt, D.C., Jayachandra, M., Lindsley, R.W., Specht, C.M., Schroeder, C.E., 2000. Schizophrenia-like deficits in auditory P1 and N1 refractoriness induced by the psychomimetic agent phencyclidine (PCP). Clin. Neurophysiol. 111, 833–836. https://doi.org/10.1016/S1388-2457(99)00313-2.

Lew, G.S., Polich, J., 1993. P300, habituation, and response mode. Physiol. Behav. 53, 111–117. https://doi.org/10.1016/0031-9384(93)90018-B.

Marcus, E.A., Nolen, T.G., Rankin, C.H., Carew, T.J., 1988. Behavioral dissociation of dishabituation, sensitization, and inhibition in Aplysia. Science (80-.) 241, 210–213. https://doi.org/10.1126/science.3388032.

McDiarmid, T.A., Bernardos, A.C., Rankin, C.H., 2017. Habituation is altered in neuropsychiatric disorders—a comprehensive review with recommendations for experimental design and analysis. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2017.05.028.

McDonald, C.G., Gabbay, F.H., Rietschel, J.C., Duncan, C.C., 2010. Evidence for a new late positive ERP component in an attended novelty oddball task. Psychophysiology 47, 809–813. https://doi.org/10.1111/j.1469-8986.2010.00986.x.

Mecklinger, A., Opitz, B., Friederici, A.D., 1997. Semantic aspects of novelty detection in humans. Neurosci. Lett. 235, 65–68. https://doi.org/10.1016/S0304-3940(97)00712-X.

Muenssinger, J., Stingl, K.T., Matuz, T., Binder, G., Ehehalt, S., Preissl, H., 2013. Auditory habituation to simple tones: reduced evidence for habituation in children compared to adults. Front. Hum. Neurosci. 7, 377. https://doi.org/10.3389/fnhum.2013.00377.

Näätänen, R., Picton, T., 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. Psychophysiology 24, 375–425.

Näätänen, R., Gaillard, A.W., Varey, C.A., 1981. Attention effects on auditory EPs as a function of inter-stimulus interval. Biol. Psychol. 13, 173–187.

Näätänen, R., Sams, M., Alho, K., Paavilainen, P., Reinikainen, K., Sokolov, E.N., 1988. Frequency and location specificify of the human vertex N1 wave. Electroencephalogr. Clin. Neurophysiol. 69, 523–531. https://doi.org/10.1016/0013-4694(88)90164-2.

O'Shea, R.P., 2015. Refractoriness about adaptation. Front. Hum. Neurosci. 9 https://doi.org/10.3389/fnhum.2015.00038.

Okamoto, H., Ross, B., Kakigi, R., Kubo, T., Pantev, C., 2004. N1m recovery from decline after exposure to noise with strong spectral contrasts. Hear. Res. 196, 77–86. https://doi.org/10.1016/j.heares.2004.04.017.

Okamoto, H., Kakigi, R., Gunji, A., Kubo, T., Pantev, C., 2005. The dependence of the auditory evoked N1m decrement on the bandwidth of preceding notch-filtered noise. Eur. J. Neurosci. 21, 1957–1961. https://doi.org/10.1111/j.1460-9568.2005.04022.x.

Pantev, C., Okamoto, H., Ross, B., Stoll, W., Ciurlia-Guy, E., Kakigi, R., Kubo, T., 2004. Lateral inhibition and habituation of the human auditory cortex. Eur. J. Neurosci. 19, 2337–2344. https://doi.org/10.1111/J.0953-816X.2004.03296.X.

Pereira, D.R., Cardoso, S., Ferreira-Santos, F., Fernandes, C., Cunha-Reis, C., Paiva, T.O., Almeida, P.R., Silveira, C., Barbosa, F., Marques-Teixeira, J., 2014. Effects of inter-stimulus interval (ISI) duration on the N1 and P2 components of the auditory event-related potential. Int. J. Psychophysiol. 94, 311–318. https://doi.org/10.1016/j.ijpsycho.2014.09.012.

Picton, T.W., Campbell, K.R., Baribeau-Braun, J., Proulx, G.B., 1978. The neurophysiology of human attention: a tutorial review. In: Requin, J. (Ed.), Attention and Performance. Erlbaum, Hillsdale, NJ, pp. 429–467.

Pinsker, H., Kupfermann, I., Castellucci, V., Kandel, E., 1970. Habituation and dishabituation of the gill-withdrawal reflex in Aplysia. Science (80-.) 167, 1740–1742. https://doi.org/10.1126/science.167.3926.1740.

Polich, J., 1989. Habituation of P300 from auditory stimuli. Psychobiology 17 (1), 19–28.

Rankin, C.H., Abrams, T., Barry, R.J., Bhatnagar, S., Clayton, D.F., Colombo, J., Coppola, G., Geyer, M.A., Glanzman, D.L., Marsland, S., McSweeney, F.K., Wilson, D. A., Wu, C.-F., Thompson, R.F., 2009. Habituation revisited: an updated and revised description of the behavioral characteristics of habituation. Neurobiol. Learn. Mem. 92, 135–138. https://doi.org/10.1016/j.nlm.2008.09.012.

Roeser, R.J., Price, L.L., 1969. Effects of habituation on the auditory evoked response. J. Aud. Res. 9, 306–313.

Romero, R., Polich, J., 1996. P3(00) habituation from auditory and visual stimuli. Physiol. Behav. 59, 517–522. https://doi.org/10.1016/0031-9384(95)02099-3.

Rosburg, T., 2004. Effects of tone repetition on auditory evoked neuromagnetic fields. Clin. Neurophysiol. 115, 898–905. https://doi.org/10.1016/j.clinph.2003.11.011.

Rosburg, T., 2018. Auditory N100 gating in patients with schizophrenia: a systematic meta-analysis. Clin. Neurophysiol. 129, 2099–2111. https://doi.org/10.1016/j.clinph.2018.07.012.

Rosburg, T., Mager, R., 2021. The reduced auditory evoked potential component N1 after repeated stimulation: refractoriness hypothesis vs. Habituation account. Hear. Res. 400, 108140 https://doi.org/10.1016/j.heares.2020.108140.

Rosburg, T., Sörös, P., 2016. The response decrease of auditory evoked potentials by repeated stimulation - is there evidence for an interplay between habituation and sensitization? Clin. Neurophysiol. 127, 397–408. https://doi.org/10.1016/j.clinph.2015.04.071.

Rosburg, T., Kreitschmann-Andermahr, I., Nowak, H., Sauer, H., 2000. Habituation of the auditory evoked field component N100m in male patients with schizophrenia. J. Psychiatr. Res. 34, 245–254.

Rosburg, T., Haueisen, J., Sauer, H., 2002. Habituation of the auditory evoked field component N100m and its dependence on stimulus duration. Clin. Neurophysiol. 113, 421–428.

Rosburg, T., Trautner, P., Boutros, N.N., Korzyukov, O.A., Schaller, C., Elger, C.E., Kurthen, M., 2006. Habituation of auditory evoked potentials in intracranial and extracranial recordings. Psychophysiology 43, 137–144. https://doi.org/10.1111/j.1469-8986.2006.00391.x.

Rosburg, T., Boutros, N.N., Ford, J.M., 2008. Reduced auditory evoked potential component N100 in schizophrenia–a critical review. Psychiatry Res. 161, 259–274. https://doi.org/10.1016/j.psychres.2008.03.017.

Rosburg, T., Zimmerer, K., Huonker, R., 2010. Short-term habituation of auditory evoked potential and neuromagnetic field components in dependence of the interstimulus interval. Exp. Brain Res. 205, 559–570. https://doi.org/10.1007/s00221-010-2391-3.

Ross, J.M., Hamm, J.P., 2020. Cortical microcircuit mechanisms of mismatch negativity and its underlying subcomponents. Front. Neural Circuits 14, 13. https://doi.org/10.3389/fncir.2020.00013.

Ruusuvirta, T., 2021. The release from refractoriness hypothesis of N1 of event-related potentials needs reassessment. Hear. Res. 399, 107923. https://doi.org/10.1016/j.heares.2020.107923.

Salamy, A., McKean, C.M., 1977. Habituation and dishabituation of cortical and brainstem evoked potentials. Int. J. Neurosci. 7, 175–182. https://doi.org/10.3109/00207457709147665.

Sams, M., Alho, K., Näätänen, R., 1984. Short-term habituation and dishabituation of the mismatch negativity of the ERP. Psychophysiology 21, 434–441.

Spreng, M., 1980. Influence of impulsive and fluctuating noise upon physiological excitations and short-time readaptation. Scand. Audiol. Suppl. 299–306.

Team, J., 2020. JASP Version 0.14.1.

Teichert, T., Gurnsey, K., Salisbury, D., Sweet, R.A., 2016. Contextual processing in unpredictable auditory environments: the limited resource model of auditory refractoriness in the rhesus. J. Neurophysiol. 116, 2125–2139. https://doi.org/10.1152/jn.00419.2016.

Thompson, R.F., 2009. Habituation: a history. Neurobiol. Learn. Mem. 92, 127–134. https://doi.org/10.1016/j.nlm.2008.07.011.

Thompson, R.F., Spencer, W.A., 1966. Habituation: a model phenomenon for the study of neuronal substrates of behavior. Psychol. Rev. 73, 16–43.

Ulanovsky, N., Las, L., Nelken, I., 2003. Processing of low-probability sounds by cortical neurons. Nat. Neurosci. 6, 391–398. https://doi.org/10.1038/nn1032.

Weigl, M., Mecklinger, A., Rosburg, T., 2016. Transcranial direct current stimulation over the left dorsolateral prefrontal cortex modulates auditory mismatch negativity. Clin. Neurophysiol. https://doi.org/10.1016/j.clinph.2016.01.024.

Woldorff, M.G., Hillyard, S.A., 1991. Modulation of early auditory processing during selective listening to rapidly presented tones. Electroencephalogr. Clin. Neurophysiol. 79, 170–191.

Woods, D.L., Courchesne, E., 1986. The recovery functions of auditory event-related potentials during split-second discriminations. Electroencephalogr. Clin. Neurophysiol. 65, 304–315.

Yadon, C.A., 2010. Three Types of Sensory Gating: Exploring Interrelationships, Individual Differences, and Implications. Colorado State University, Fort Collins, Colorado.

Yagcioglu, S., Ungan, P., 2008. Refractoriness, habituation, and mismatch effects in the auditory event-related potential to alternating stimuli. Neuroreport 19, 49–53.