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7 Abstract

8 How does the brain process and represent successive sound in close temporal proximity? By
9 investigating mismatch negativity (MMN) components, prior research (Sussman & Gumenyuk,
10 2005; Sussman, Ritter & Vaughan, 1998) has suggested that temporal proximity plays an
11 important role in how sounds are represented in auditory memory. Here, we investigate how
12 predictability affects the election of mismatch negativity components in auditory sequences
13 consisting of two tones (frequent tone A = 440 Hz, rare tone B = 494 Hz, fixed SOA 100 ms).
14 In the predictable condition, tones are presented in a fixed order whereas in the unpredictable
15 condition, standards and deviants are presented in a pseudo-random order. We expect to find
16 that B tones in the unpredictable condition will elicit a significant MMN while B tones in the
17 predictable conditions will not. A repeating five-tone pattern was presented at several
18 stimulus rates (200, 400, 600, and 00 ms onset-to-onset) to determine at what temporal
19 proximity the five-tone repeating unit would be represented in memory. The mismatch
20 negativity component of event-related brain potentials was used to index how the sounds were
21 organized in memory when participants had no task with the sounds. Only at the 200-ms
22 onset-to-onset pace was the five-tone sequence unitized in memory. At presentation rates of
23 400 ms and above, the regularity (a different frequency tone occurred every fifth tone) was not
24 detected and mismatch negativity was elicited by these tones in the sequence. The results
25 show that temporal proximity plays a role in unitizing successive sounds in auditory memory.
26 These results also suggest that global relationships between successive sounds are represented
27 at the level of auditory cortices.

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Introduction

– Introducing oddball paradigm – The auditory oddball paradigm is well-established type of experimental designs extensively used in event related potential (ERP) studies. In the most basic form of this paradigm, subjects are presented with a series of similar tones or sounds (so-called *standards*), interrupted by rare tones or sounds that differ in at least one feature (*deviants*) from the more frequent ones. Since it is assumed that the brain constantly makes predictions about future sensory impressions and deviating auditory events must violate these predictions, these rare sounds play an important role in understanding prediction and expectation in the human brain. Different measures have been used to quantify differences in processing between *standard* and *deviant* events,

– introducing MMN – One of the best-studied approaches to measure these differences in processing is known as the mismatch negativity (MMN) component, obtained by subtracting the response to deviant events from the response to standard events. Negativity is strongest in the fronto-temporal area of the scalp with a peak latency ranging from 100 to 250 ms after stimulus onset. The elicited MMN is not restricted to the repetition of physically identical stimuli but can also be observed when deviant events are of complex nature, e.g. when abstract auditory regularities are violated (Paavilainen, 2013). The regularities can come in the form of relationships between two tones (Saarinen et al. (1992) or multiple tones (Alain et al., 1994; Nordby et al., 1988; Schröger et al., 1996) a

– introducing Sussman's study – Sussman et al. (1998) presented participants with a sequence of frequent pure tones and rare pitch deviants. Tones were arranged in a predictable five-tone pattern consisting of four standard tones and one deviant (i.e. A-A-A-A-B-A-A-A-A-B, '-' indicating silence between the tones). ERPs to A and B tones were compared for rapid (SOA of 100 ms) and slow (SOA of 1200 ms) stimulation rates. For the 100 ms SOA, they also included a control condition in which tone order was pseudo-random (e.g. A-A-A-B-A-B-A-A-A) without altering deviant probability ($p_B = 20\%$). MMNs were only elicited if tone presentation was slow and predictable or fast and random. In a subsequent study, Sussman & Gumenyuk (2005) used the same pattern at different SOAs (200 ms, 400 ms, and 800 ms). Similarly to their previous study, grouped presentation at 400 ms and 800 ms SOA elicited a MMN, while at a stimulation rate of 200 ms such evidence was

absent. Sussman et al. attributed this observation to sensory memory limitations. Only when auditory memory accommodates enough repetitions of the five-tone pattern, tones could be integrated into a coherent representation allowing for accurate predictions of deviant tones (explaining the absence of MMNs. They further argued that while this must be the case for fast presentation rates with SOAs up to 200 ms, for longer SOAs pattern durations would be too long and thus exceed sensory memory capacity. The main weakness in their study is that they

– scharf muller – In a recent in-class replication study, (???). found that

Methods and Materials

Data Acquisition

Participants

100 ms Presentation Rate Twenty-three psychology undergraduate students (2 males, average age 22.6 yrs., $SD = 5.57$, range 18 - 42 yrs.) were recruited at the Institute of Psychology at the University of Leipzig. All participants reported good general health, normal hearing and had normal or corrected-to-normal vision. Written informed consent was obtained before the experiment. One-third (34.8%) of participants spent time engaging in musical activities at time of survey, while 8.7% had no prior experience in music training. Handedness was assessed using a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971, see appendix). A majority (00%) of participants favored the right hand. Participants were blinded in respect to the purpose of the experiment and received course credit in compensation.

150 ms Presentation Rate Twenty healthy participants (0 males, average age 00.0 yrs., $SD = 0.00$, range 00 - 00 yrs.) were recruited. Participants gave informed consent and reported normal hearing and corrected or corrected-to-normal vision. All participants were naive regarding the purpose of the experiment and were compensated in course credit or money. 00 participants (00%) had received musical training in the last 5 years before the experiment while 00 (00%) reported no musical experience. In addition, participants reported if streaming occurred during the presentation of the tones.

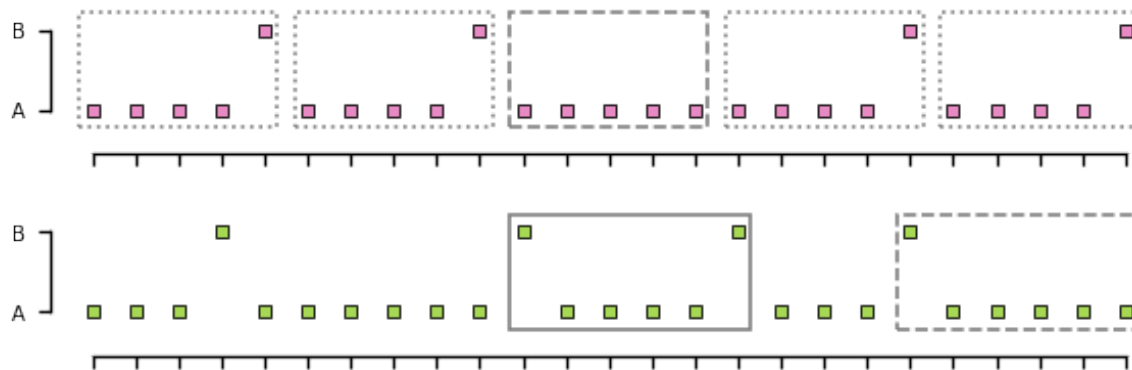
102 **Stimuli and Stimulus Delivery**

Figure 1. Tones of two different frequencies ($A=440$ Hz, $B=449$ Hz) were presented in two blocked conditions: In the “predictable” condition (top half), tones followed a simple pattern in which a single B-tone followed four A-tones. Some designated B-tones were replaced by A-tones (“pattern deviants”). In the “random” condition (lower half), tones were presented in a pseudo-random fashion ()

103 Participants were seated in a comfortable chair in a sound-insulated cabin. The
 104 experimental setup was practically the same as the one used by Sussman, but instead of
 105 reading a book, subjects were asked to focus their attention on a previously selected movie.
 106 Movies were presented with subtitles but without sound. Commercially available software
 107 (MATLAB R2014a; The MathWorks Inc, Natick, MA) in conjunction with the Psychophysics
 108 Toolbox extension (version 3.0.12, Brainard, 1997; Kleiner et al., 2007) was used to control
 109 stimulus presentation. Stimuli consisted of pure sinusoidal tones with a duration of 50 ms
 110 (including a 10 ms cosine on/off ramp), presented isochronously at a stimulation onsets
 111 asynchrony (SOA) of 100 ms for study 1 and 150 ms for study 2. Overall, a total of 40 blocks
 112 containing a mixture of frequent 440 Hz tones (“A” tones) and infrequent 449 Hz tones (“B”
 113 tones) were delivered binaurally using Sennheiser XY headphones. In one half of the blocks,
 114 tones were presented in pseudo-random order (e.g. A-A-A-B-A-B-A}, “random” condition),
 115 while in the remaining block tone presentation followed a simple pattern in which a
 116 five-tone-sequence of four frequent tones and one infrequent tone (i.e. A-A-A-A-B) was
 117 repeated cyclically (“predictable” condition). The ratio of frequent and infrequent tones was
 118 10% for both conditions. Within the predictable condition, 10% of designated (infrequent) B
 119 tones were replaced by A tones, resulting in sporadic five-tone sequences consisting solely of A

tones (i.e. A-A-A-A-A), thus violating the predictability rule. To assure comparability of local histories between tones in both conditions, randomly arranged tones were interspersed with sequences mimicking aforementioned patterns from the predictable condition (B-A-A-A-A-B and B-A-A-A-A-A) in the random condition. A grand total of 2000 tones in study 1 and 4000 tones in study 2 were delivered to each participant.

Data Acquisition

Electrophysiological data was recorded from active silver-silver-chloride (*Ag-AgCl*) electrodes using an ActiveTwo amplifier system (BioSemi B.V., Amsterdam, The Netherlands). Acquisition was monitored online to ensure optimal data quality. A total of 39 channels were obtained using a 32-electrode-cap and 7 external electrodes. Scalp electrode locations conformed to the international 10–20 system. Horizontal and vertical eye movement was obtained using two bipolar configurations with electrodes placed around the lateral canthi of the eyes and above and below the right eye. Additionally, electrodes were placed on the tip of the nose and at the left and right mastoid sites. Data was sampled at 512 Hz and on-line filtered at 1000 Hz.

Analysis Pipeline

Data preprocessing was implemented using a custom pipeline based on the *MNE Python* software package (Gramfort, 2013) using *Python 3.7*. All computations were carried out on a cluster operated by the University Computation Center of the University of Leipzig. Code used in thesis is publicly available at <https://github.com/marcpabst/xmas-oddballmatch>.

First, EEG data was subjected to the ZapLine procedure (de Cheveigné, 2020) to remove line noise contamination. A fivefold detection procedure as described by Bigdely-Shamlo et al. (2015) was then used to detect and subsequently interpolate bad channels. This specifically included the detection of channels that contain prolonged segments with very small values (i.e. flat channels), the exclusion of channels based on robust standard deviation (deviation criterion), unusually pronounced high-frequency noise (noisiness criterion), and the removal of channels that were poorly predicted by nearby channels (correlation criterion and predictability criterion). Channels considered bad by one or more of these methods were removed and interpolated using spherical splines (Perrin et al., 1989).

Electrode locations for interpolations were informed by the BESA Spherical Head Model.

For Independent Component Analysis (ICA), data 1-Hz-high-pass filtered (134th order hamming-windowed FIR) was applied prior to ICA (Winkler et al., 2015). To further reduce artifacts, Artifact Subspace Reconstruction (ASR, Mullen et al., 2015) was used to identify parts of the data with unusual characteristics (bursts) which were subsequently removed. ICA was then carried out using the *Picard* algorithm (Ablin et al., 2018, 2017) on PCA-whitened data. To avoid rank-deficiency when extracting components from data with one or more interpolated channels, PCA was also used for dimensionality reduction. The EEGLAB (version 2020.0, Delorme & Makeig, 2004) software package and the IClab plugin (version 1.2.6, Pion-Tonachini et al., 2019) were used to automatically classify estimated components. Only components clearly classified (i.e. confidence above 50%) as resulting from either eye movement, muscular, or heartbeat activity were zeroed-out before applying the mixing matrix to unfiltered data.

In line with recommendations from Widmann et al. (2015) and de Cheveigné & Nelken (2019), a ORDER finite impulse response (FIR) bandpass filter from 0.1 Hz to 40 Hz (Hamming window, 0.1 Hz lower bandwidth, 4 Hz upper bandwidth, 0.0194 passband ripple, and 53 dB stopband attenuation). Continuous data was epoched into 400 ms long segments around stimulus onsets. Epochs included a 100 ms pre-stimulus interval. No baseline correction was applied. Segments exceeding a peak-to-peak voltage difference of 100 μ V were removed. No data set meet the pre-registered exclusion criterion stated of less than 100 trials per condition, thus data from all participants (20 for 100 ms presentation rate and 23 for 150 ms presentation rate) was analysed.

Statistical Analysis

MMN

The dependent variable for analysing mismatch response was calculated by averaging amplitudes in a time window extending ± 25 ms around the maximum negativity obtained by subtracting the mean ERP timecourse following the (expected) deviant event from the ERP following the (expected) standard event. To obtain mean amplitudes, ERPs to 4th position A tones (A-A-A-**A**-X, **boldface** indicates the tone of interest) and B tones (A-A-A-A-B) were

178 averaged separately for both the *random* and the *predictable condition*. For the *random*
179 *condition*, only tones that were part of a sequence matching the patterns in the *predictable*
180 *condition* were included.

181 In accordance with the original analysis by Sussman & Gumenyuk (2005), mean
182 amplitudes for frontocentral electrodes (FZ, F3, F4, FC1, and FC2) and the two mastoid
183 positions (M1 and M2) were averaged separately. Then, for both SOAs, independent
184 three-way repeated measures analyses of variance with factors *condition* (factors *predictable*
185 and *random*), *stimulus type* (factors *A tone* and *B tone*), *electrode locations* (levels
186 *fronto-central* and *mastoids*), and all possible interactions were calculated.

Results

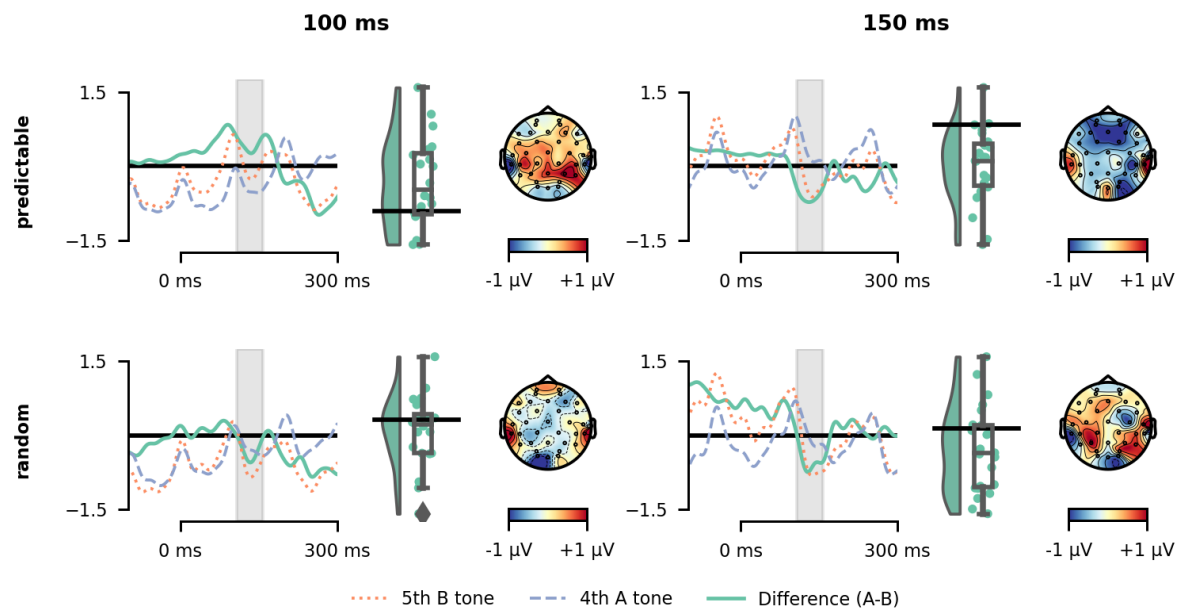


Figure 2. ERP grand averages (pooled FZ, F3, F4, FC1, and FC2 electrode locations) for an SOA of 100 ms (left) and 150 ms (right), for A tones (A-A-A-A-X, blue dashed lines) and B tones (A-A-A-A-B, orange dashed line) and their difference (B - A, green solid line). Upper panels show ERPs for tones presented in a predictable pattern (predictable condition) while lower panels show ERPs for tones presented in pseudo-random order (random condition). Shaded area marks MMN latency window (110 ms to 160 ms) used to calculate the distribution of amplitude differences across participants (middle of each panel) and the difference of topographic maps averaged over the same interval (right of each panel).

Grand averages of event-related potentials (ERP) at pooled FZ, F3, F4, FC1, and FC2 electrode locations to A tones (A-A-A-A-X), B tones (A-A-A-A-B), and their difference (B tone minus A tone) are displayed in Figure X for both 100 ms (left panel) and 150 ms (right panel) stimulus onset asynchronies. Top half of each panel shows ERPs in the *predictable condition* while lower half depicts ERPs in the *random condition*. For both presentation rates, clear rhythms matching the presentation frequency of 10 Hz (100 ms) and respectively 6.667 Hz (150 ms) are seen as a result from substantial overlap of neighboring tones. Panels also show the distribution of mean amplitude differences in the MMN latency window (as defined above, 110 ms to 160 ms after stimulus onset) across participants and the difference of topographies averaged over the same interval. Similarly, waveforms and mean amplitude

198 difference distributions at pooled mastoid sites are shown in Figure X.

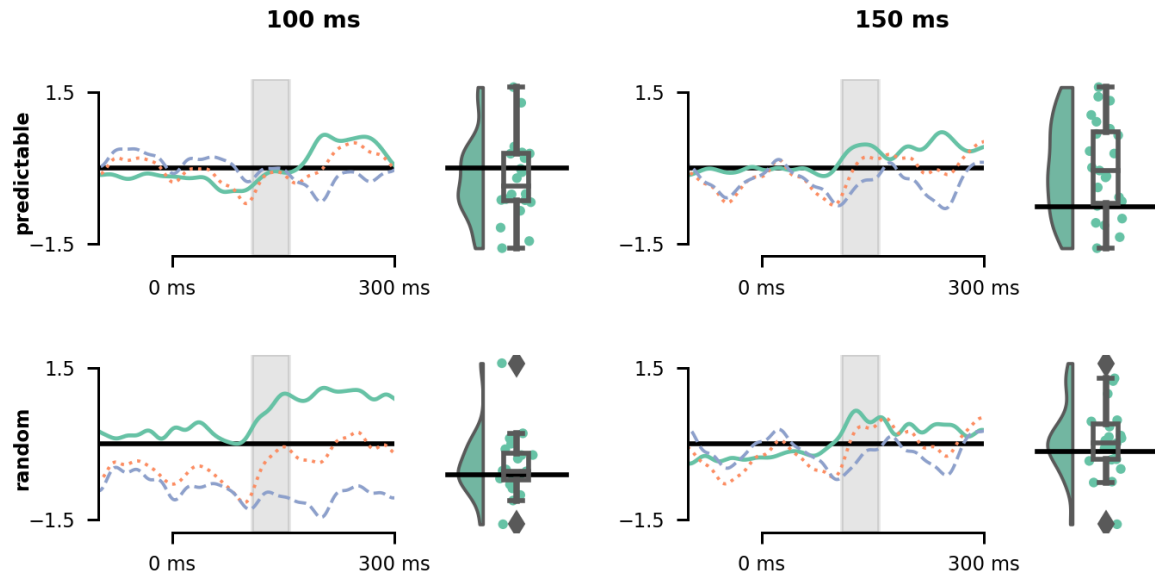


Figure 3. ERP grand averages (pooled M1, M2 electrode locations) for an SOA of 100 ms (left) and 150 ms (right), for A tones (A-A-A-A-X, blue dashed lines) and B tones (A-A-A-A-B, orange dashed line) and their difference (B - A, green solid line). Upper panels show ERPs for tones presented in a predictable pattern (predictable condition) while lower panels show ERPs for tones presented in pseudo-random order (random condition). Shaded area marks MMN latency window (110 ms to 160 ms) used to calculate the distribution of amplitude differences across participants.

199 Evoked responses to A and B tones were compared by calculating mean amplitudes in
 200 the MMN latency window. Mean amplitudes in the MMN latency window and their standard
 201 deviantions (SD) for all conditions are shown in Table X. Descriptively, mean amplitudes at
 202 pooled fronto-central electrode locations were more negative for randomly presented B tones
 203 than for randomly presented A tones, regardless of tone presentation rate (100 ms:
 204 $\Delta M = -0.358 \mu V$; 150 ms: $\Delta M = -0.555 \mu V$) This also held true for tones presented in a
 205 predictable fashion, but for the slower of the two presentation rates only ($\Delta M = -0.582 \mu V$).
 206 In contrast, when predictable tone patterns occurred at a faster 100 ms rate, B tones elicited
 207 descriptively more positive responses than A tones ($\Delta M = 0.383 \mu V$). Descriptive comparison
 208 of evoked responses from pooled left and right mastoids revealed that pseudo-randomly
 209 presented B tones were more positive in the MMN latency window than A tones (100-ms-SOA:
 210 $\Delta M = 0.746 \mu V$, 150-ms-SOA: $\Delta M = 0.510 \mu V$). A similar observation could be made for

precitable B tones compared to the preceeding A tones at a SOA of 150 ms ($\Delta M = 0.399 \mu V$)
but not for the faster presentation rate ($\Delta M = -0.132 \mu V$).

SOA	Condition	StimulusType	Mean	SD	Mean	SD
100	predictable	A	-0.431	1.23	-0.052	1.51
		B	-0.0477	1.22	-0.184	1.56
	random	A	-0.225	1.82	-1.04	2.64
		B	-0.583	2.16	-0.296	3.23
150	predictable	A	0.25	0.967	-0.349	1.19
		B	-0.331	1.09	0.0492	1.33
	random	A	0.0233	1.75	-0.292	1.64
		B	-0.531	1.82	0.218	2.38

Statistical analyses provided support for these findings. For the 100 ms stimulation rate, the three-way ANOVA yielded a significant three-way interaction effect (*condition* x *stimulus type* x *electrode locations*; $F(1, 19) = 7.53$, $p = 0.0130$) but failed to reveal main effects for factors *stimulus type* ($F(1, 19) = 1.05$, $p = 0.3180$), *condition* ($F(1, 19) = 0.83$, $p = 0.3730$), and *electrode locations* ($F(1, 19) = 0.04$, $p = 0.8520$). In contrast, for tones presented at a SOA of 150 ms only the two-way interaction term *stimulus type* x *electrode locations* had a significant effect ($F(1, 22) = 20.76$, $p = 0.0002$). Mean amplitudes in the MMN latency window however did not differ for factors *stimulus type* ($F(1, 22) = 0.32$, $p = 0.5790$), *electrode locations* ().

Two-way ANOVAs (*condition* x *stimulus type*) were carried out seperatly for pooled fronto-central and mastoid electrode locations. For 100 ms tone presenation rate, the *condition* x *stimulus type* interaction only revealed a significant effect for the fronto-central electrode cluster ($F(1, 19) = 16.75$, $p = 0.0006$) but not for pooled mastoid sites ($F(1, 19) = 2.37$, $p = 0.1410$) indicating that the three-way interaction effect *condition* x *stimulus type* x *electrode* is indeed driven by the amplitude differnces in te fronto-central electrode locations . Contrary to this, for the 150 ms presentation rate, main effects for *stimulus type* were significant for both fronto-central and mastoid sites, suggesting that there was both a MMN at fronto-central locations as well as a polarity-reversal at the mastoid electrodes.

Table 1

Results of the 3-way ANOVA (condition x stimulus x electrode) for repeated measures conducted on the mean ERP-amplitudes (time window 111 - 161 ms) at electrode Fz (upper section). The significant interaction between the three factors included was further analyzed by 2-way ANOVAS (stimulus x electrode) conducted separately for the random condition (middle section) and the predictable condition (lower section).

	Effect	DFn	DFd	F	p	p<.05	ges
100 ms	Condition	1	19	0.831	0.373		0.008
	StimulusType	1	19	1.05	0.318		0.002
	Electrode	1	19	0.036	0.852		0.000331
	Condition x StimulusType	1	19	0.051	0.823		7.55e-05
	Condition x Electrode	1	19	0.763	0.393		0.002
	StimulusType x Electrode	1	19	0.797	0.383		0.001
	Condition x StimulusType x Electrode	1	19	7.53	0.013	*	0.01
150 ms	Condition	1	22	0.08	0.78		0.000263
	StimulusType	1	22	0.317	0.579		0.000339
	Electrode	1	22	0.035	0.854		0.000301
	Condition x StimulusType	1	22	0.16	0.693		0.000124
	Condition x Electrode	1	22	1.13	0.299		0.003
	StimulusType x Electrode	1	22	20.8	0.000155	*	0.026
	Condition x StimulusType x Electrode	1	22	0.053	0.819		4.63e-05

231 Figure X shows EEG waveform averages for five-tone sequences (A-A-A-A-B)
 232 presented in a *predictable* (top panel) and *random* contexts (lower panel).

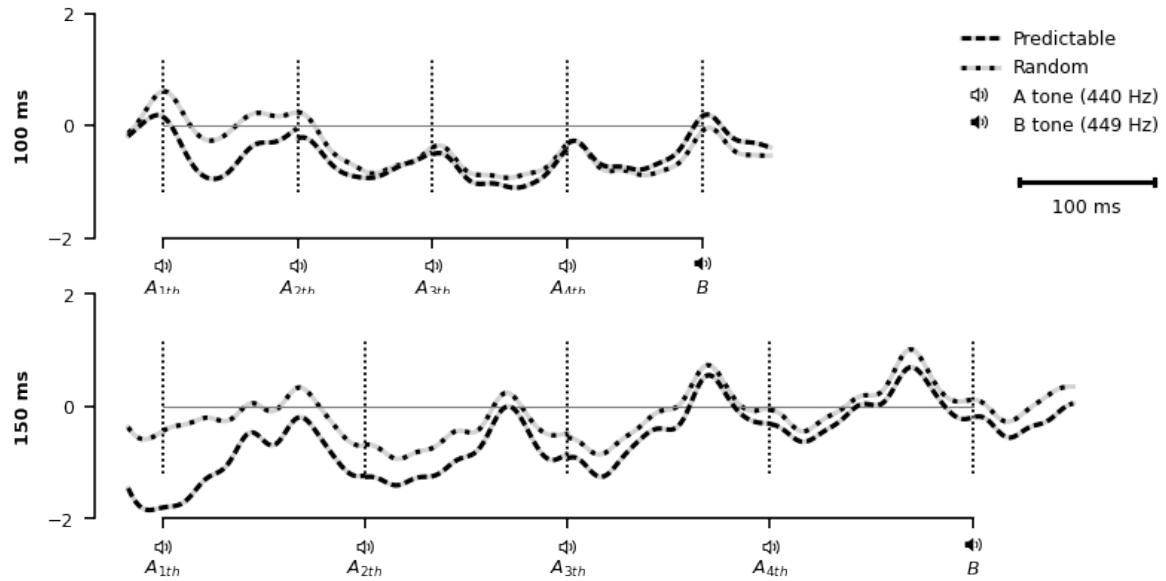


Figure 4. EEG waveforms for five-tone sequences presented in an predictable context (dotted line) and pseudo-random condition (dashed line) for 100 ms presentation rate (top panel) and 150 ms presentation rate (lower panel). Vertical lines indicate tone onset.

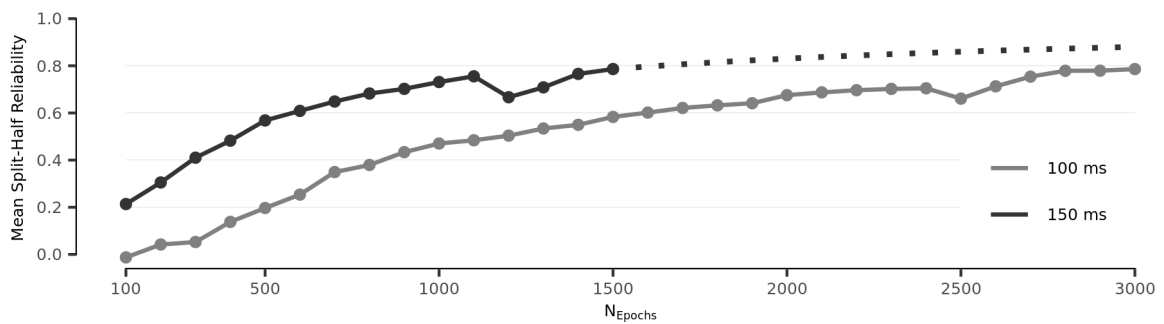


Figure 5. EEG waveforms for five-tone sequences presented in an predictable context (dotted line) and pseudo-random condition (dashed line) for 100 ms presentation rate (top panel) and 150 ms presentation rate (lower panel). Vertical lines indicate tone onset.

Table 2

Results of the 3-way ANOVA (condition x stimulus x electrode) for repeated measures conducted on the mean ERP-amplitudes (time window 111 - 161 ms) at electrode Fz (upper section). The significant interaction between the three factors included was further analyzed by 2-way ANOVAS (stimulus x electrode) conducted separately for the random condition (middle section) and the predictable condition (lower section).

		Effect	DFn	DFd	F	p	p<.05	ges
100 ms	Frontal	Condition	1	19	0.16	.694		0.003
		StimulusType	1	19	0.006	.938		1.5e-05
		Condition x StimulusType	1	19	16.7	<.001	*	0.013
	Mastoids	Condition	1	19	1.28	.272		0.014
		StimulusType	1	19	1.21	.285		0.004
		Condition x StimulusType	1	19	2.37	.141		0.009
150 ms	Frontal	Condition	1	22	0.947	.341		0.006
		StimulusType	1	22	22.7	<.001	*	0.038
		Condition x StimulusType	1	22	0.028	.868		2.2e-05
	Mastoids	Condition	1	22	0.206	.655		0.001
		StimulusType	1	22	6.56	.018	*	0.018
		Condition x StimulusType	1	22	0.122	.730		0.00028

References

- Ablin, P., Cardoso, J.-F., & Gramfort, A. (2018). Faster independent component analysis by preconditioning with Hessian approximations. *IEEE Transactions on Signal Processing*, 66(15), 4040–4049. <https://doi.org/10.1109/TSP.2018.2844203>
- Ablin, P., Cardoso, J.-F., & Gramfort, A. (2017). Faster ICA under orthogonal constraint. *arXiv:1711.10873 [Stat]*. <http://arxiv.org/abs/1711.10873>
- Alain, C., Woods, D. L., & Ogawa, K. H. (1994). Brain indices of automatic pattern processing: *NeuroReport*, 6(1), 140–144.

<https://doi.org/10.1097/00001756-199412300-00036>

Bigdely-Shamlo, N., Mullen, T., Kothe, C., Su, K.-M., & Robbins, K. A. (2015). The PREP pipeline: standardized preprocessing for large-scale EEG analysis. *Frontiers in Neuroinformatics*, 9. <https://doi.org/10.3389/fninf.2015.00016>

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436. <https://doi.org/10.1163/156856897X00357>

de Cheveigné, A. (2020). ZapLine: A simple and effective method to remove power line artifacts. *NeuroImage*, 207, 116356. <https://doi.org/10.1016/j.neuroimage.2019.116356>

de Cheveigné, A., & Nelken, I. (2019). Filters: When, Why, and How (Not) to Use Them. *Neuron*, 102(2), 280–293. <https://doi.org/10.1016/j.neuron.2019.02.039>

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>

Gramfort, A. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience*, 7. <https://doi.org/10.3389/fnins.2013.00267>

Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psychtoolbox-3. *Perception*, 36(14), 1–16. <https://nyuscholars.nyu.edu/en/publications/whats-new-in-psychtoolbox-3>

Mullen, T. R., Kothe, C. A. E., Chi, Y. M., Ojeda, A., Kerth, T., Makeig, S., Jung, T.-P., & Cauwenberghs, G. (2015). Real-time neuroimaging and cognitive monitoring using wearable dry EEG. *IEEE Transactions on Biomedical Engineering*, 62(11), 2553–2567. <https://doi.org/10.1109/TBME.2015.2481482>

Nordby, H., Roth, W. T., & Pfefferbaum, A. (1988). Event-Related Potentials to Breaks in Sequences of Alternating Pitches or Interstimulus Intervals. *Psychophysiology*, 25(3), 262–268. <https://doi.org/10.1111/j.1469-8986.1988.tb01239.x>

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory.

Neuropsychologia, 9(1), 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)

Paavilainen, P. (2013). The mismatch-negativity (MMN) component of the auditory event-related potential to violations of abstract regularities: A review. *International Journal of Psychophysiology*, 88(2), 109–123. <https://doi.org/10.1016/j.ijpsycho.2013.03.015>

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, 72(2), 184–187. [https://doi.org/10.1016/0013-4694\(89\)90180-6](https://doi.org/10.1016/0013-4694(89)90180-6)

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*, 198, 181–197. <https://doi.org/10.1016/j.neuroimage.2019.05.026>

Saarinen, J., Paavilainen, P., Schöger, E., Tervaniemi, M., & Näätänen, R. (1992). Representation of abstract attributes of auditory stimuli in the human brain: *NeuroReport*, 3(12), 1149–1151. <https://doi.org/10.1097/00001756-199212000-00030>

Schröger, E., Tervaniemi, M., Wolff, C., & Näätänen, R. N. (1996). Preattentive periodicity detection in auditory patterns as governed by time and intensity information. *Cognitive Brain Research*, 4(2), 145–148. [https://doi.org/10.1016/0926-6410\(96\)00023-7](https://doi.org/10.1016/0926-6410(96)00023-7)

Sussman, E., Ritter, W., & Vaughan, H. G. (1998). Predictability of stimulus deviance and the mismatch negativity: *NeuroReport*, 9(18), 4167–4170. <https://doi.org/10.1097/00001756-199812210-00031>

Sussman, E. S., & Gumenyuk, V. (2005). Organization of sequential sounds in auditory memory: *NeuroReport*, 16(13), 1519–1523. <https://doi.org/10.1097/01.wnr.0000177002.35193.4c>

Widmann, A., Schröger, E., & Maess, B. (2015). Digital filter design for electrophysiological data – a practical approach. *Journal of Neuroscience Methods*, 250, 34–46. <https://doi.org/10.1016/j.jneumeth.2014.08.002>

Winkler, I., Debener, S., Müller, K.-R., & Tangemann, M. (2015). On the influence of

294 high-pass filtering on ICA-based artifact reduction in EEG-ERP. *2015 37th Annual*
295 *International Conference of the IEEE Engineering in Medicine and Biology Society*
296 *(EMBC)*, 4101–4105. <https://doi.org/10.1109/EMBC.2015.7319296>