Collecting, Processing, and Analyzing EEG Data Using the Passive Auditory Oddball Task as an Example

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S1: Electroencephalography (EEG)
MBB–MA–AM–4: Imaging and Recording Brain Activity

August 31, 2023

Introduction

The passive auditory oddball task is a commonly used experimental paradigm that provides valuable insight into cognitive processes. It allows us to measure the brain's response through electroencephalography (EEG) to deviant stimuli presented within a sequence of standard stimuli. This report aims to provide a fundamental overview of the process of collecting, processing, and analyzing EEG data, using the passive auditory oddball task as an example. I will start by providing a simple breakdown of the experimental setup, followed by an examination of the waveforms of event-related potentials (ERPs) commonly observed during this task. I will then elaborate on the collection of EEG data, touching on topics such as electrode placements, stimulus presentation, and signal acquisition. Moving on, I will discuss the initial preprocessing of the data, which involves noise reduction and artifact removal. To wrap up, I will introduce some basic statistical analyses that can be applied to EEG data, and I will present and discuss the results that these analyses reveal within the context of the oddball paradigm.

Passive Auditory Oddball Task

The oddball task is a widely used experimental paradigm in cognitive neuroscience that is designed to investigate how the brain processes rare or infrequent stimuli (deviants) presented within a sequence of more frequent stimuli (standards). The

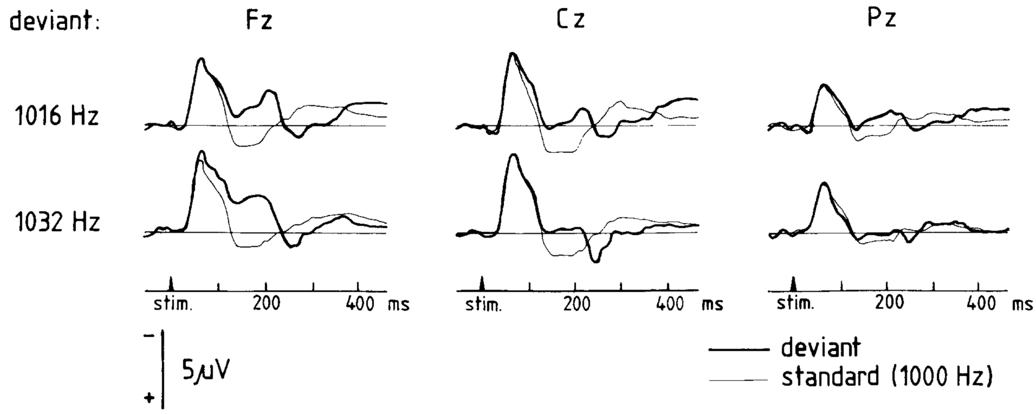

Figure 1. Parent waveforms (1002, 1004, and 1008 Hz deviants not shown) recorded by Sams et al. (1985). Negative polarity plotted upwards. While no statistically significant difference was observed for the mean N100 peak amplitudes, such a difference was found for the mean N200 peak amplitudes.

Note. Adapted from "Auditory frequency discrimination and event-related potentials," by M. Sams, P. Paavilainen, K. Alho and R. Näätänen, 1985, *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62*(6), p. 440 (https://doi.org/https://doi.org/10.1016/0168-5597(85)90054-1). Copyright 1985 by Elsevier Ireland Ltd.

component of the ERP often associated with this type of task is the *mismatch negativity* (MMN), which is a negative deflection in the EEG waveform that occurs when the brain detects a change in a stimulus. Here, I provide a brief description of the experimental setup of the passive auditory oddball task and the main characteristics of the MMN.

Experimental Paradigm. The central concept of the oddball paradigm involves the infrequent presentation of novel stimuli amidst a sequence of repetitive (and identical) stimuli. In the auditory oddball task, the deviant stimuli may, for example, differ in pitch as in the study by Sams et al. (1985). By observing how the brain responds to these "oddball" stimuli, researchers gain insight into cognitive mechanisms related to novelty detection, attention, and stimulus discrimination. While the oddball paradigm is not necessarily limited to the auditory domain, I will focus solely on the auditory oddball task, as this is the experiment we conducted in class.

There are two primary variants of the oddball paradigm: passive and active oddball tasks. The distinction between these two is the participants' level of engagement in the task. In the *passive* oddball task, participants are usually instructed to ignore the auditory stimuli and are asked to engage in another activity such as reading comics (Sams et al., 1985). On the contrary, in the *active* oddball paradigm, participants are required to pay close attention to the auditory stimuli and to indicate the presentation of a deviant stimulus (e.g., by pressing a button) (Sams et al., 1985).

Mismatch Negativity. The active and passive oddball paradigms may elicit different ERP waveform patterns (e.g., Sams et al., 1985). The ERP component that is commonly observed in the passive auditory oddball task is labelled the mismatch negativity. It is characterized by a negative deflection that typically peaks around 150–250 ms after stimulus onset (Sams et al., 1984, 1985; Näätänen et al., 1997, 2001, 2010). Additionally, it is automatic in nature, occurring even when participants are not explicitly focused on the stimuli (e.g., Sams et al., 1985). Thus, the MMN component can be considered a reflection of automatic sensory processing.

The results of Sams et al. (1985) demonstrating the MMN are shown in Figure 1. The experiment conducted by Sams et al. (1985) consisted of two blocks per deviant, each consisting of 500 stimuli presented to the participant's right ear at an intensity of approximately 80 dB. Standards were characterized by a frequency of 1000 Hz, while deviants varied in frequency[1] from 1002 to 1032 Hz. Standards were presented in 80% of the trials, and deviants were presented in the remaining trials. The order of blocks and the order of stimuli within a block were randomized. Six university students served as participants.

For the 1016 and 1032 Hz deviants, the authors observed the typical MMN component characterized by "a prominent negative N200 deflection approximately at 170 ms" (Sams et al., 1985). The waveforms depicting the differences in ERPs shown in Figure 1 are presented in Figure 2.

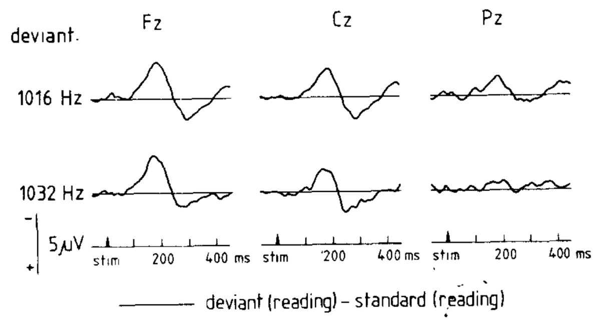

Figure 2. Difference waveforms obtained by subtracting grand average ERPs to the standard tones from those to the deviant tones. Negative polarity plotted upwards.

Note. Adapted from "Auditory frequency discrimination and event-related potentials," by M. Sams, P. Paavilainen, K. Alho and R. Näätänen, 1985, *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62*(6), p. 441 (https://doi.org/https://doi.org/10.1016/0168-5597(85)90054-1). Copyright 1985 by Elsevier Ireland Ltd.

[1]Only one type of deviant was presented within a single block of trials. Results for the 1002, 1004, and 1008 Hz deviants are not shown here because no significant difference was found between ERPs to standards and deviants in these conditions.

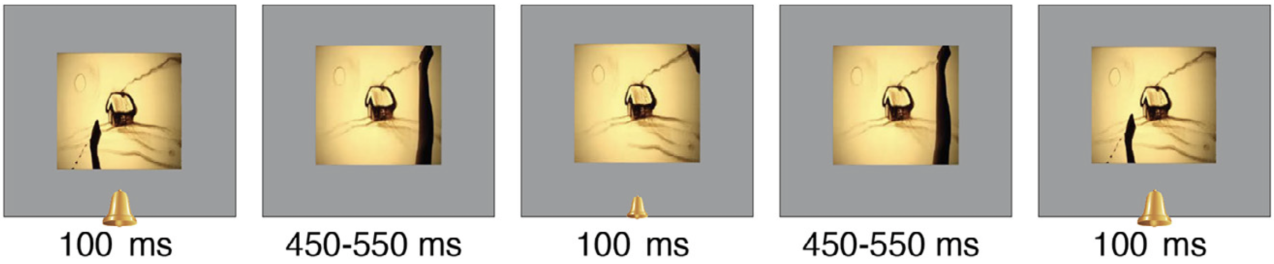

Figure 3. Experimental setup of the oddball task used by Kappenman et al. (2021). The large bells represent the presentation of standard tones (80 dB), the small bell represents the presentation of a deviant tone (70 dB). Auditory stimuli with an interstimulus interval (ISI) of 450–550 ms were presented for 100 ms.

Note. Adapted from "ERP CORE: An open resource for human event-related potential research," by E. S. Kappenman, J. L. Farrens, W. Zhang, A. X. Stewart and S. J. Luck, 2021, *NeuroImage, 225* (https://doi.org/https://doi.org/10.1016/j.neuroimage.2020.117465). CC-BY 2.0.

Data Collection

The data used to practice the preprocessing of EEG data were collected in one of the lab sessions of the EEG seminar. Statistical analysis was performed on data from the ERP CORE resource (Kappenman et al., 2021), which is freely available online at https://doi.org/10.18115/D5JW4R. We tested our subject using the *Passive Auditory Oddball MMN* task also used by Kappenman et al. (2021), which is modeled on Näätänen et al. (2004).

Stimuli and Task. A schematic illustration of the experiment by Kappenman et al. (2021) is depicted in Figure 3. Auditory stimuli with a constant frequency of 1000 Hz and varying intensities were presented through loudspeakers. Standard and deviant tones differed solely in intensity, with deviants being 10 dB *less* intense[2] than standards. The first 15 tones presented in the experiment were all of a higher intensity (i.e., 80 dB) to establish this tone as the standard stimulus. The remaining 985 tones were presented in random order, with the constraint that two deviants were never presented in succession. Deviants were presented with a probability of 20%. During the task, participants watched a silent movie of sand drawings and were instructed to focus on the movie while ignoring the tones. The timing of the movie was independent of the presentation of the tones.

EEG Recording. Testing was performed in a room that was both electrically shielded and sound-attenuated. The participant was

[2]This was done intentionally "to ensure that an increased ERP response to the deviant stimulus could not be the result of a greater intensity" (Kappenman et al., 2021).

seated in a height-adjustable chair to ensure a comfortable viewing position. Two separate monitors were used for presenting the stimuli and monitoring the EEG data during testing. A 64-electrode setup was used for the collection of EEG data. The electrodes were mounted in an elastic cap that was carefully placed on the participant's head to ensure placement of the electrodes according to the international 10-20 system. We recorded data from 61 locations (see Fig. 4), using three electrodes to record the horizontal (HEOG) and vertical electrooculograms (VEOG). The former was recorded from two

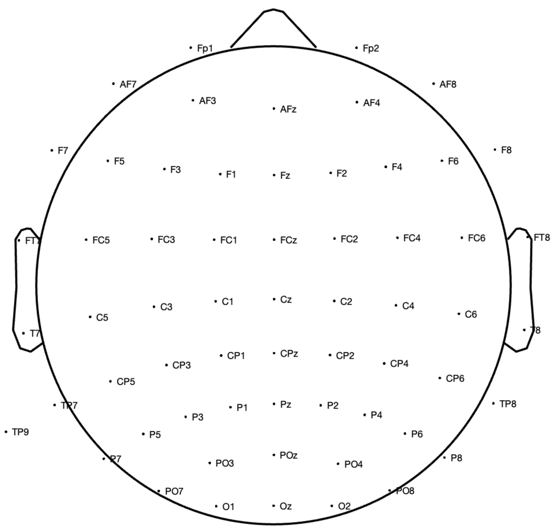

Figure 4. Schematic illustration of the 61 recording sites. Ground electrode was placed at site Fpz, reference at site TP10 (not shown).

electrodes placed lateral to the outer canthus of each eye, the latter was recorded from a single electrode placed just below the right eye. The ground electrode was placed at site Fpz, while site TP10 (right mastoid) was used as reference. During preprocessing, the collected data were re-referenced to the average of the left and right mastoids (i.e., TP9 and TP10). The experiment was started as soon as electrode impedance was less than 30 kΩ for all electrodes.

Preprocessing

The preprocessing steps detailed in this section were applied to the EEG dataset that was collected during one of the hands-on sessions of the EEG seminar. Preprocessing was performed in MATLAB (The MathWorks Inc., 2023) using the EEGLAB toolbox extension (Delorme & Makeig, 2004).

Downsampling. A sampling rate of 1000 Hz was used during the experiment. Upon loading the dataset into EEGLAB, the sampling rate was downsampled to 250 Hz.

Re-referencing. To avoid any lateralization bias, we re-referenced the data to the averaged mastoids[3] (i.e., TP9 and TP10).

Filtering. After re-referencing the data, we applied a high-pass filter with a cutoff frequency of 0.1 Hz. Subsequently, we eliminated any DC offsets. This step is critical

[3] In contrast, Kappenman et al. (2021) referenced the EEG signals "to the average of P9 and P10 (located adjacent to the mastoids)".

because computations of ERPs can be affected by baseline shifts triggered by DC offsets. Lastly, we removed the line noise at 50 Hz (see Fig. 5) using the Zapline-plus extension (Klug & Kloosterman, 2022).

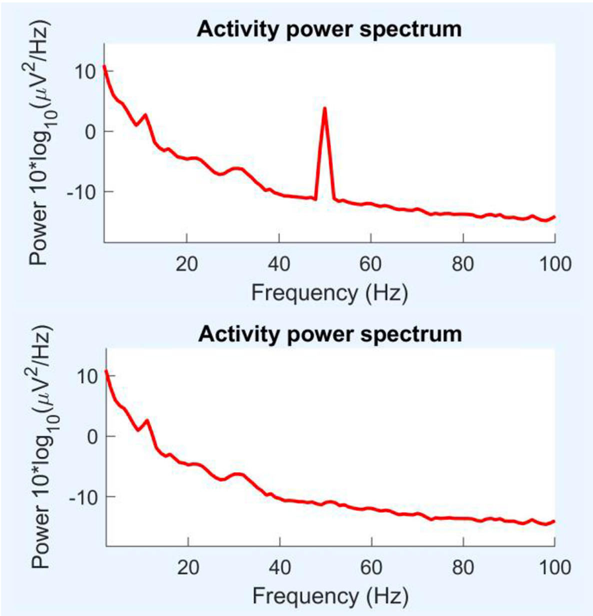

Figure 5. Effect of removing line noise with Zapline-plus. *Top*, a distinct peak in the power spectrum at 50 Hz. *Bottom*, the peak at 50 Hz is successfully removed.

Removal of artifacts. Next, the objective was to eliminate artifacts from the data via independent component analysis (ICA). To accomplish this, we prepared a separate dataset to serve as input for the ICA. The weights obtained therefrom would then be assigned to the pre-ICA dataset to subsequently remove any artifacts. The separate dataset was prepared in the following manner: First, we applied a more stringent[4] high-pass filter with a cutoff frequency of 0.5 Hz. Second, we epoched our data using a time window ranging from -200 to 550 ms, which was time-locked to the three event types of the oddball experiment (i.e., deviant, standard preceded by a standard, and standard preceded by a deviant). This was done to apply the ICA only to meaningful data, and not to any data acquired before or after the experiment or during breaks. Subsequently, we manually selected and rejected any epochs that contained non-stereotypical noise before performing the ICA decomposition using the `runica` algorithm. The resulting ICA weights were then assigned to the pre-ICA dataset and the components were classified using the ICLabel plug-in (Pion-Tonachini et al., 2019) available through the EEGLAB extension manager. Finally, we removed any eye and heart artifacts (see Fig. 6) labeled as such with a probability greater than 90% by the ICLabel algorithm.

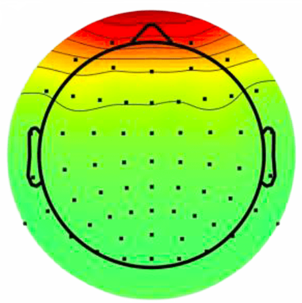

Figure 6. Scalp topography of a typical eye blink artifact.

[4]The high-pass filter applied to the pre-ICA dataset used a cutoff frequency of 0.1 Hz.

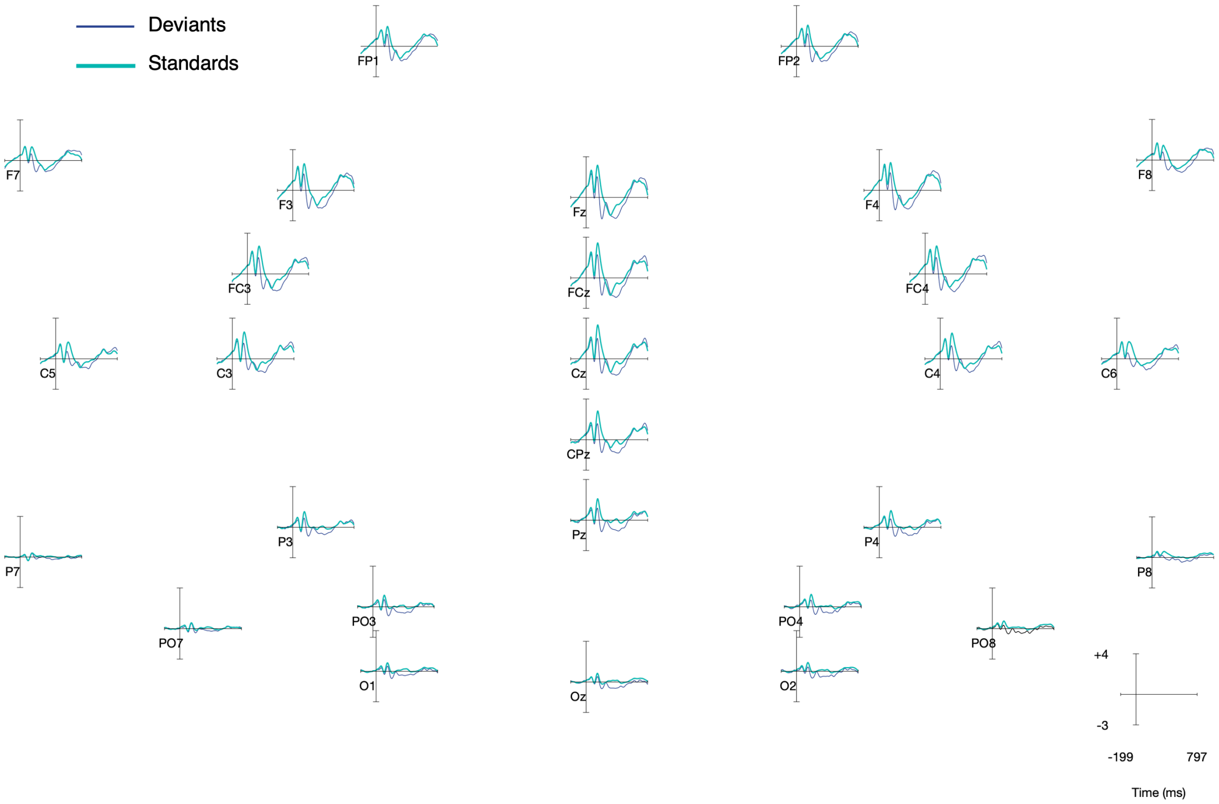

Figure 7. Grand average ($N = 39$) parent ERP waveforms of the two main experimental conditions in the oddball paradigm (i.e., deviants and standards preceded by a standard) plotted in a topographical layout.

Segmentation & baseline correction. Finally, we segmented the data and performed baseline correction using an epoch window from -200 to 800 ms and a baseline period from -200 to 0 ms. The presentation of the tones served as the time-locking event(s). These settings are the ones recommended by Kappenman et al. (2021).

Results

While the preprocessing described in the preceding section was performed on data collected during the EEG seminar, the data referred to in this section are from the ERP CORE resource (Kappenman et al., 2021), which is freely available online at https://doi.org/10.18115/D5JW4R. It should be noted that these data have undergone a marginally different preprocessing, which is discussed in Section 2.4 of Kappenman et al. (2021). Most importantly, the data in this section represent the averages of a population of $N = 39$ young adults. Unless stated otherwise, the figures presented in this section were generated using the ERPLAB toolbox (Lopez-Calderon & Luck, 2014).

The MMN component was quantified by Kappenman et al. (2021) using electrode site

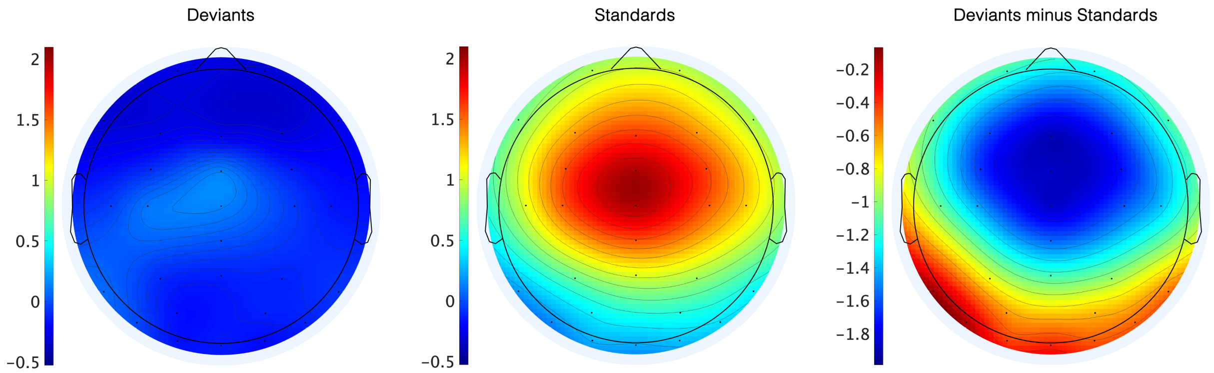

Figure 8. Grand average ($N = 39$) scalp topographies of the mean amplitude over the 125–225 ms measurement window relative to stimulus onset. Measurements are referenced to the average of P9 and P10, located adjacent to the mastoids. *Left* and *center*, parent waveforms of deviants and standards (preceded by a standard), respectively. *Right*, difference waveforms obtained by subtracting standards from deviants. Note the different color map scales for parent and difference waveforms.

FCz, as the MMN "was largest in the difference wave" at this site. In addition, all analyses were based on the data collected at this site. The grand average parent ERP waveforms of the two main conditions (i.e., deviants and standards preceded by a standard), as well as the resulting difference waveform at electrode site FCz, are shown in Figure 9. The grand average parent waveforms obtained for the remaining sites are shown in Figure 7, arranged in a topographical layout. As expected, "the auditory deviants (...) elicited a negativity peaking near 200 ms with a maximum over medial frontocentral cortex" (Kappenman et al., 2021). The distribution of the recorded mean amplitudes across the scalp for both deviants and standards is illustrated in Figure 8.

The average amplitude recorded at site FCz over the measurement window[5] from 125 to 225 ms relative to stimulus onset was 0.121 μV for deviants and 1.977 μV for stan-

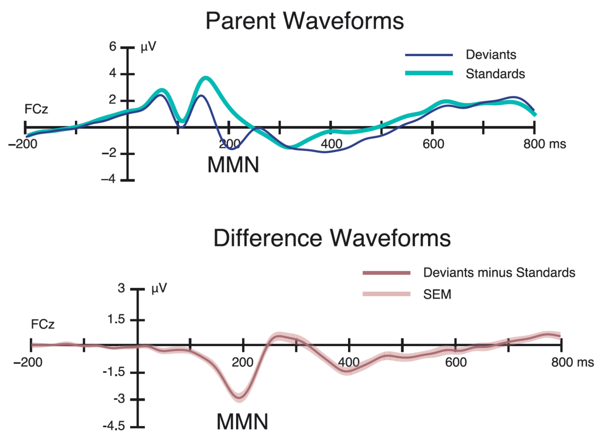

Figure 9. Grand average ($N = 39$) ERP waveforms. *Top*, parent waveforms for the two main experimental conditions (i.e., deviants and standards). *Bottom*, difference waveforms obtained by subtracting standards from deviants.

Note. Adapted from "ERP CORE: An open resource for human event-related potential research," by E. S. Kappenman, J. L. Farrens, W. Zhang, A. X. Stewart and S. J. Luck, 2021, *NeuroImage, 225* (https://doi.org/https://doi.org/10.1016/j.neuroimage.2020.117465). CC-BY 2.0.

[5]This time window was selected based on a mass univariate approach combined with an extensive literature review, for details see Section 2.6.2 of (Kappenman et al., 2021).

dards, resulting in a mean amplitude of the difference waveform of approximately -1.86 μV. A one-sided t-test revealed that this amplitude was significantly less than 0 μV ($p < 0.0001$). The effect size of the difference in amplitude from 0 μV was $d_z = 1.52$ (Kappenman et al., 2021).

Latency measures[6] were also computed by Kappenman et al. (2021). Peak latency was 187.60 ms, 50% area latency and onset latency were 185.20 and 146.94 ms, respectively.

Discussion of Results. The results of Kappenman et al. (2021) are exactly as expected: the deviant stimuli elicited a (grand average) ERP difference waveform characterized by a prominent negative deflection at a peak latency of approximately 190 ms after stimulus onset. This is well within the range of peak latencies commonly reported for the MMN (e.g., Sams et al., 1984, 1985; Näätänen et al., 1997, 2001, 2010). Theoretically, Kappenman et al. (2021) ran the risk of "inflating the Type I error rate" by "cherry picking" the electrode site with the largest effect to perform the analyses, as this would "bias the data in favor of the presence of an effect." However, since the presence of the MMN component in the oddball paradigm is well established, this is not a serious drawback of the results published by Kappenman et al. (2021).

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[6] Again, these measures refer to electrode site FCz.

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