

Effect of Attention on Prestimulus Neural Noise

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Abstract

Attending to a target sound increases the number of cortical resources allotted towards processing the target stimuli, leading to larger response amplitudes for the cortical auditory evoked potentials (CAEPs). However, the effect of attention on the neural noise, as well its definition, is still not clear. Having defined neural noise as the neural activity immediately preceding a stimulus, we aimed to explore the effects of attention on the prestimulus activity when measured using CAEPs. Using a 256-channel montage, we compared the global RMS amplitudes of the prestimulus (PreRMS), poststimulus (PostRMS), and the difference between PostRMS and PreRMS (DiffRMS) measured under active attention and passive attention conditions. Paired *t*-tests revealed a significant attention-related increase in the amplitudes of all three measures. We suppose that the attention-related excitation of target-relevant cortical pathways as well as the inhibition of target-irrelevant mechanisms, in combination, resulted in an increase in the overall neural activity in the three measures. Higher prestimulus activity can, therefore, be used as an objective index of attention and is likely to indicate anticipatory cortical preparation. Our results further validate the supposition that prestimulus activity is not merely neural noise, but indicates the neurophysiological activity associated with complex sensory and/or cognitive functions.

Keywords: cortical auditory evoked potentials; attention; neural noise; prestimulus; anticipatory; RMS

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Introduction

Paying attention to the target stimulus while recording cortical auditory evoked potentials (CAEPs) is known to alter the characteristics of CAEPs and can result in shorter latencies (Alho, 1992; Hillyard et al., 1973) and/or larger amplitudes (Getzmann et al., 2017; Zendel et al., 2016; Zhang et al., 2016). Additionally, studies that assessed the effects of attention on brain wave (alpha, beta, gamma, and/or delta) oscillations (Debener et al., 2003; Foxe & Snyder, 2011; Horton et al., 2013) and degree of cortical entrainment (Fuglsang et al., 2017; Olguin et al., 2018) also have found significant attention-related changes—mostly showing stronger or enhanced responses. In concordance with the “Gain Theory” of attention (Hillyard et al., 1973),

these effects are often attributed to the increased activity of cortical generators corresponding to the allocation of additional cortical resources towards processing the target stimuli (Bennet et al., 2012; Sussman et al., 2005; Zhang et al., 2016). It is proposed that attention (specifically, selective attention) acts as a gating mechanism which works by inhibiting the unattended stimuli and enhancing the responses to attended stimuli (Foxe & Snyder, 2011).

In addition to such enhancements, attention is also suggested to improve the perception of the attended stimuli by increasing the response strength for the attended stimuli and reducing the “neural noise” in the brain (Luck et al., 1997; Nandy et al., 2019). However, the method to calculate and define neural

noise is variable across studies. While some studies have measured neural noise as the variability in intertrial response consistency (Dwyer et al., 2022; Haigh, 2018), others have measured it as the brain activity unrelated to stimulus in the prestimulus time period (Krizman, Bonacina, et al., 2021; Krizman, Lindley, et al., 2020). For our current study, we prefer to define and calculate the neural noise based on the strength and amplitude of the prestimulus neural activity, as this is a more physiologically appropriate metric. Intertrial response consistency, at a physiological level, is a measure of the time (or frequency)-based consistency of occurrence of an expected neural activity, such as a negative or positive “peak” associated with the onset of stimuli. Additionally, this measure is likely to be affected or modulated by the concurrent brain activity in response to the stimuli presented. It is therefore more a measure of neural “jitter” rather than that of noise in the brain. Prestimulus activity, on the other hand, is largely devoid of concurrent stimulus-evoked activity and more likely a measure of spontaneous neural activity (similar to the spontaneous firing rate of a large number of individual neurons measured at the scalp). Attention-related modulation of neural spiking has already been implicated in the visual modality (Luck et al., 1997). Therefore, we chose to use the prestimulus activity to measure the effects of attention on neural noise.

When measured using an event-related potential (ERP) approach, prestimulus activity is the brain activity that occurs in the gap between two successive stimulus presentations (assuming the stimulus presentation paradigm has already accounted for the time taken for the brain activity to return to its baseline levels). This prestimulus (baseline) activity was previously considered to be a metric of the contamination of the response by nonneural sources such as muscular activity, electrical noise, etc. Therefore, prior studies have used it as an index of the quality of response recording (Musacchia et al., 2006; Russo et al., 2004).

However, other studies suggest that the prestimulus activity reflects cortical or neural dynamics associated with various brain functions (Alhanbali et al., 2022; Harris et al., 2018; Kayser et al., 2016; Rahn & Basar, 1993). For example, Bastiaansen and Brunia (2001) presented evidence of anticipatory attention-related changes in brainwave activity, particularly in the frequencies around 10 Hz. Studies have also suggested that the prestimulus cortical activity is likely to reflect complex neural

processing associated with task performance or attention (Alhanbali et al., 2022; Henry et al., 2017; Mathewson et al., 2009; McNair et al., 2019). In addition to such immediate online changes, evidence suggests that neural noise is also shaped by life experiences. For example, studies have shown that neural noise is significantly lesser in athletes, compared to nonathletes (Krizman et al., 2020), while an impoverished brain (due to underexposure to linguistically and cognitively stimulating conditions—a consequence of lower socioeconomic status) is shown to be significantly noisier than those with sufficient linguistic and cognitive stimulation (Skoe et al., 2013).

These studies show that the prestimulus neural activity provides an index of the global neurocortical functioning associated with a task at hand. Given this supposition, a need arises to study how neural noise is affected by cognitive tasks such as attention. Previous studies have shown that prestimulus brainwave activity, especially alpha activity, is modulated by attention (Alhanbali et al., 2022; Fellingner et al., 2011; Henry et al., 2017; McNair et al., 2019). However, such approaches using specific brain wave activities provide a very restricted view of the cortical activity, largely limited to a few cortical regions, despite using multichannel EEG recordings. When measured with a high-density EEG recording, prestimulus neural activity, on the other hand, provides a more broadband metric of how a larger number of brain regions work in unison. Therefore, in the current study, we aimed to explore the effects of active attention on prestimulus (and the consequent poststimulus) neural activity. Specifically, we measured and compared the root-mean-square (RMS) amplitudes of the prestimulus (PreRMS) activity of the Global Field Power (GFP) when CAEPs were recorded in either active or passive attention conditions using a high-density EEG system. The GFP characterizes the combined contemporaneous activity of all the electrodes across the epoch (Lehmann & Skrandies, 1980), and hence is well suited for the purposes of our study. When appropriate care is taken to record and analyze the EEG, the PreRMS in ERPs has been suggested to be primarily “neural,” and not related to the nonbrain activity such as muscular or electrode-related (impedance) artifacts (Krizman et al., 2021). Hence, PreRMS could be utilized to study brain-related activity prior to stimulus presentation, and we predict evident attention-related changes in the PreRMS measure.

We also explored the effects of attention on the RMS activity in the poststimulus (PostRMS) time

periods as well as the difference between the PreRMS and PostRMS activity (DiffRMS). The PostRMS measure will provide information regarding the overall increased neurocortical activity in the poststimulus time period, a fact that is commonly reported in previous literature (Alho, 1992; Getzmann et al., 2017; Hillyard et al., 1973). The DiffRMS measure, on the other hand, has commonly been considered a measure of the response signal-to-noise ratio (SNR). Given the previous literature's support that prestimulus activity can and does reflect complex neurocognitive mechanisms (at least the preparation stages of such mechanisms), it is our opinion that the DiffRMS is not a straightforward measure of SNR, at least at the cortical level. Therefore, we intend to explore the possible attention-related changes in this measure. We hypothesize that the systematic differences in the three metrics under the two attention conditions likely provide newer insights into the attention-related changes in the cortical processing of sounds.

Method

Participants

A total of 26 volunteers (10 females, 16 males) in the age range of 18 to 30 years (mean age = 23.15 years) participated in the study. All participants had normal hearing thresholds (better than 15 dB HL) in the octave frequencies between 0.25–8 kHz, normal middle ear (Type 'A' tympanogram with the presence of acoustic reflexes) and normal outer hair cell functioning between 1–6 kHz (TEOAE amplitude of more than 3 dB). Ensuring "normal" peripheral hearing was an essential control mechanism since literature has reported neural hyperactivity in the central auditory system in the face of damage to the peripheral hearing mechanism (Zhao et al., 2016). A detailed history, taken before the commencement of the testing, ensured no relevant history of any otological, neurological, psychological, and/or speech-language deficits. All participants passed the Screening Checklist for Auditory Processing in Adults (SCAP-A; Vaidyanath & Yathiraj, 2014) and were right-handed as evaluated using the Edinburgh Handedness Inventory (Oldfield, 1971). Further, all participants were native speakers of the Kannada language (a language spoken in the South Indian state of Karnataka) and had at least 12 years of formal education with English as the medium of instruction. They signed informed consents before the testing, for their participation in the study. The experimental procedures were reviewed and approved by the Ethics Committee of the All India Institute of Speech and Hearing, Mysuru (Ref No: Ph.D/AUD-2/2016-17).

Stimuli

Stimuli consisted of four meaningful bisyllabic words—*gadi*, *gade*, *gaja*, and *ganya*—in the Kannada language. The first syllable was the same in all the words, while only the second syllable differed. The participants could recognize the words only after listening to the second syllable, which ensured that the participants paid attention to the complete word. These words were spoken by a native female speaker in a neutral tone and were recorded using a unidirectional microphone kept at 5 cm from the mouth. The recorded samples were digitally stored having a sampling frequency of 44,100 Hz. Although four different stimuli were included in the experiment, only the word *gadi* was considered as the target word. The other three words were used only as distractor words.

Recording ERPs

The ERP recordings were carried out in a sound-treated and electrically shielded double-room setup with noise levels within the prescribed standards (American National Standards Institute, 1999). The participants were seated in a comfortable reclining chair. Raw EEGs were recorded from each participant using a 256-channel EGI Geodesic sensor net (EGI, Inc., Eugene, OR) connected to a GES-400 amplifier. The electrode impedance was ensured to be below 50 k Ω (Ferree et al., 2001). Further, the impedances across all electrodes were measured at the end of EEG recordings which confirmed that the impedances did not fall below the 50 k Ω limit. This ensured that there were no spurious electrode-related noises in the recorded raw EEG. The EEG was recorded at a sampling frequency of 1000 Hz with Cz as the reference.

Using the E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA) software, the stimuli were presented binaurally at 70 dB SPL using ER-3A (Etymotic Research Inc., Elk Grove Village, IL) insert receivers. The interstimulus interval (onset-to-onset) was 3 s (jitter of 0.3 s). A total of 100 stimuli were presented, such that the four words were presented randomly with a probability of 0.7, 0.1, 0.1, and 0.1. The target stimulus *gadi* was presented with a probability of 0.7 (70 presentations) while the three distractor stimuli (*gade*, *gaja*, and *ganya*) were presented with a probability of 0.1 each (10 presentations each).

The responses were recorded under two attention conditions—Passive and Active. In the passive attention condition, the responses were recorded while the participants ignored the stimuli and watched a muted close-captioned video. In the

active attention condition, the participants were instructed to press appropriate buttons on a numerical keypad (1 for *gadi*, 2 for *gade*, 3 for *gaja*, and 4 for *ganya*) as soon as they recognized the words. The responses were always recorded first in the passive attention condition and then in the active attention condition to ensure no subconscious bias towards the target stimuli in the passive attention condition.

Preprocessing and Analyses of the EEG

The raw EEG obtained from each participant was exported from Net Station 4 to EEGLAB Version 14.1.1 (Delorme & Makeig, 2004) using Matlab. Continuous raw EEG from each participant was downsampled to 256 Hz, filtered between 1 Hz and 30 Hz, visually inspected for bad data (and removed, if any), screened for line interferences using the Cleanline plugin, interpolated (removed bad channels) using a spherical spline interpolation method, and rereferenced to the “common average.” The rereferenced data was subjected to Independent Component Analyses (ICA; Infomax) with a Principal Component Analysis option of 64. ICA was used to reject “nonbrain” responses such as eye blinks, ocular movements, heartbeat, muscular artifacts, etc. Cleaned data was then epoched between -1000 ms (prestimulus) and 2000 ms (poststimulus). Any epochs exceeding ± 50 μV were rejected, and only the clean sweeps were averaged to obtain separate waveforms for the active and passive attention conditions.

Calculation of Prestimulus and Poststimulus RMS, and Difference Measures

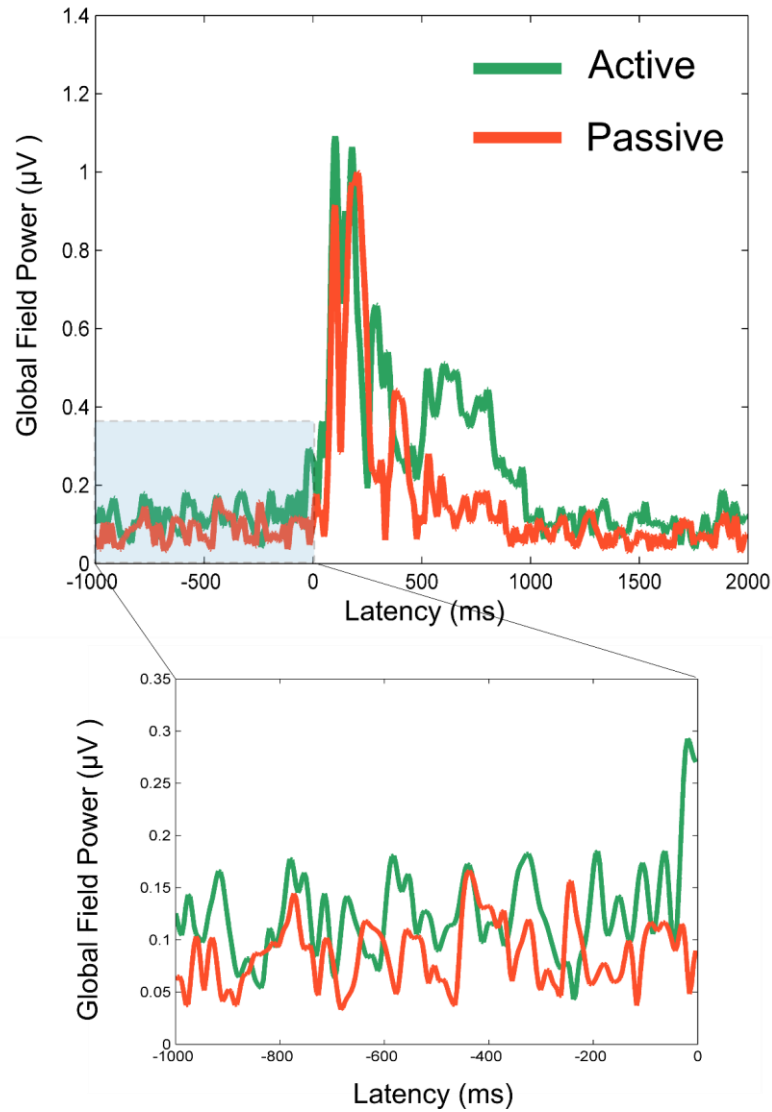
The RMS amplitudes of the PreRMS and PostRMS time regions were calculated on the GFP waveforms. The GFP characterizes the combined contemporaneous activity of all the electrodes

across the epoch (Lehmann & Skrandies, 1980). It is obtained by calculating the standard deviation across all electrodes and channels as a function of time. Because of this property, GFP is always positive and hence was specifically used to calculate the RMS amplitudes. Separate GFP waveforms were obtained for the two attention conditions for all participants. The PreRMS was obtained, for each participant, by using the RMS function in Matlab for the time period between -1000 – 0 ms (with reference to the trigger). Similarly, the PostRMS was calculated for the time period between 0 – 1000 ms (with reference to the trigger). Finally, the DiffRMS was calculated as the difference between PostRMS and PreRMS. Figure 1 shows the mean GFPs of the passive and active attention conditions, with a zoomed-in view of the prestimulus time period.

Results

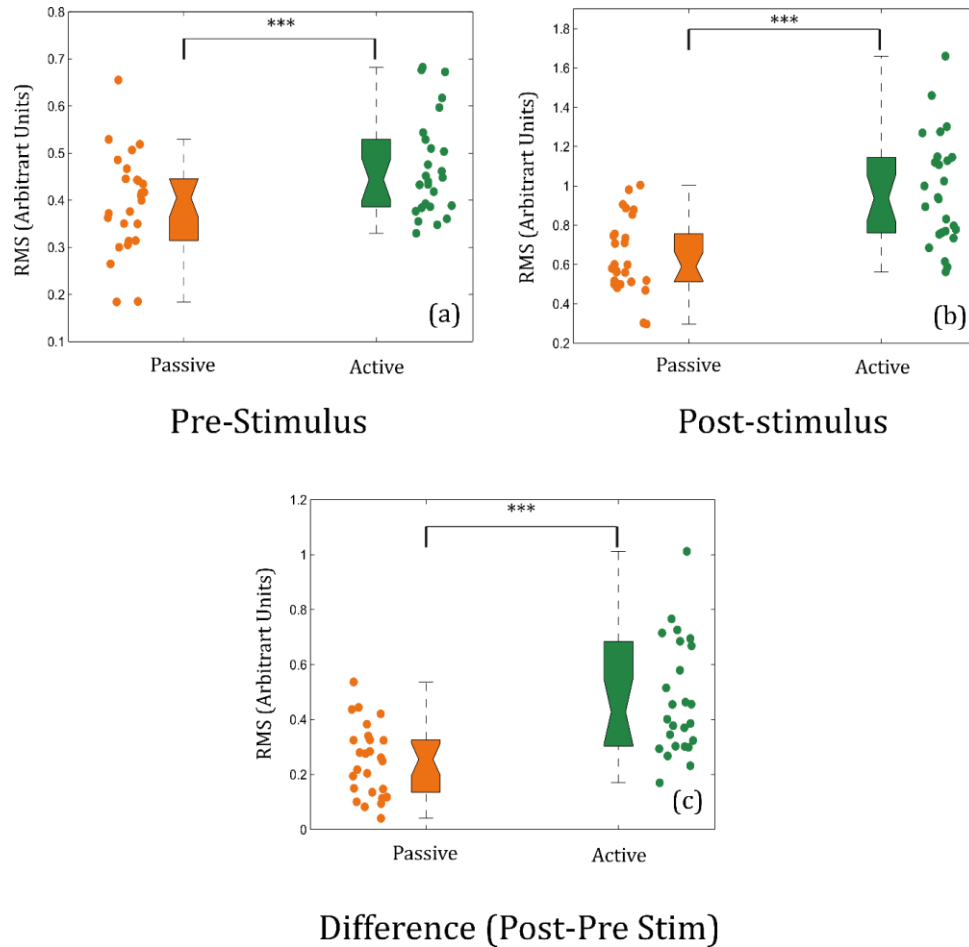
The JASP (version 0.8.5.1) statistical package (The JASP Team, 2017) was used to statistically analyze the data. Figure 2 (panels a, b, and c) shows the individual and the median RMS amplitudes in the two attention conditions for the three measures (PreRMS, PostRMS, and DiffRMS, respectively). The results showed that the active attention condition had higher (median) RMS amplitudes for the PreRMS (panel a), PostRMS (panel b) as well as the DiffRMS (panel c) metrics, compared to the passive attention condition. Paired-samples *t*-test showed significant differences between active and passive attention conditions for the PreRMS [$t(25) = 3.686$, $p = .001$, $d = 0.723$], PostRMS [$t(25) = 6.047$, $p < .001$, $d = 1.257$], as well as DiffRMS [$t(25) = 4.572$, $p < .001$, $d = 0.879$] metrics.

Figure 1. Mean Global Field Power (GFP) Waveforms of the Active (Green Trace) and Passive (Orange Trace) Attention Conditions.



Note. The prestimulus time period (shaded region) is zoomed-in (inset figure below) for better visualization of the differences between the two attention conditions.

Figure 2. Comparison of RMS Amplitudes Between Active (Green Color) and Passive (Orange Color) for the Prestimulus (PreRMS; Panel A), Poststimulus (PostRMS; Panel B), and Difference (DiffRMS; Panel C) Activities.



Note. The filled green dots in each of the panels represent the individual data points of the different participants for the Active attention condition. The filled orange dots represent the individual data for the Passive attention condition. The box plots to the right of the individual data plots (green boxes for Active, and orange boxes for Passive) show the median (thick black line) and the quartiles (thinner black lines) for the corresponding conditions. The distribution plots to the right show the data distribution for the active (pink color) and passive (blue color) attention conditions for each of the RMS metrics.

Discussion

In the current study, we explored the attention-related changes in the neural noise as measured using the prestimulus RMS amplitudes of CAEPs. Specifically, we calculated and compared three RMS measures—PreRMS, PostRMS, and DiffRMS—measured between two attention conditions—active and passive attention. Results showed a statistically significant increase in all three RMS amplitudes for the active attention condition compared to the passive attention condition.

Previous studies have already shown significant brain wave activity in the prestimulus time period when the target is attended to. These studies have shown changes in the prestimulus activity such as event-related desynchronization (ERD) in anticipation of stimuli (Bastiaansen & Brunia, 2001; Pfurtscheller & Da Silva, 2011) and stronger alpha activity (Alhanbali et al., 2022; Fellingner et al., 2011), etc. when attention (or similar cognitive functions) is involved in the task. Increased cortical brain wave activity, especially increased alpha power, has been positively associated with better cognitive (including attention) function (Klimesch et al., 2007). However,

using alpha power restricts the response activity to a narrow band of frequencies, typically between 8–12 Hz. In our study, we have used a much broader range of frequencies to extract the GFPs, a global measure of the activity from all electrodes employed for the study. Hence, we believe that this measure provides an orthogonal metric of understanding the neural activity, compared to the narrowband measures such as alpha power. However, the stronger prestimulus brain wave activity (such as increased alpha), even in a smaller range of frequencies, associated with attention is likely represented as increased PreRMS amplitudes observed in the active attention condition of the current study.

Pfurtscheller and Da Silva (2011) propose a “cortical idling” hypothesis (Pfurtscheller & Da Silva, 2011; Pfurtscheller et al., 1996). According to this hypothesis, activity in cortical areas (brain waves) changes such that the regions involved in (or related to) the task at hand undergoes a time-locked desynchronization (ERD). On the other hand, the cortical areas that are not directly related to the task at hand are put into an idling state—an increase in brain wave activity or synchrony (event-related synchrony). It appears that when the brain anticipates an incoming stimulus, especially one that it needs to specifically attend to, it puts a greater emphasis on idling the task-irrelevant brain activity (inhibitory or suppressive action) to improve the perception of the attended task-relevant stimulus. This activity, likely, is represented as an increase in the preRMS amplitude, as observed in the active attention conditions of our study. Irrespective of the increase or decrease in brain wave synchronization, however, there is greater overall brain activity associated with paying attention to the task-relevant stimulus, which can be observed as higher preRMS amplitude. In other words, preRMS can be considered a global index of attention.

Another aspect of the PreRMS measure is the possible association with the neurophysiological processes related to anticipatory attention. Anticipatory attention is proposed to manifest itself as increased cortical activity in the neurophysiological responses (Bastiaansen & Brunia, 2001). Bastiaansen and Brunia (2001) suggest that the increased cortical activation is probably due to an enhanced thalamocortical transfer in the relevant modality. This increased activity would then serve in “presetting” the neurophysiological processes necessary for the fast and efficient processing of the impending sensory input. Additionally, it is even shown that attention

increases the neural firing rate in the prestimulus time periods (Luck et al., 1997). Luck et al. (1997) reported an increase in neural firing rate by 42% (an increase from 10.1 spikes/s to 14.4 spikes/s) when attention was directed towards the target. Therefore, increased PreRMS could also be thought of as an indicator of anticipatory attention.

The results of the study also showed that active attention resulted in significantly higher PostRMS amplitudes compared to the passive attention condition. The presence of high RMS EEG activity in the poststimulus time periods is expected. Multiple studies have shown increased peak (N1 and/or P2) amplitudes when the target stimulus was paid attention (Folyi et al., 2012; Harris et al., 2012; Mast & Watson, 1968; Zhang et al., 2016). A straightforward translation of this observation would be higher RMS amplitudes in the entire poststimulus time period.

The higher DiffRMS amplitudes observed in our study for the active attention condition, compared to the passive attention condition, is an interesting one. This observation is in spite of a significant increase in the preRMS amplitudes in the active attention condition. To the best of our knowledge, no previous study has evaluated the effects of attention on the SNR (DiffRMS) amplitudes (difference in RMS activity between poststimulus and prestimulus time periods). However, Fellingner et al. (2011) have demonstrated evidence of the magnitude of prestimulus alpha wave activity influencing the amplitude of the poststimulus P1 peak. They suggest that the absolute amplitude of the P1 peak is based on a complex interaction of the prestimulus and poststimulus activity. On similar lines, the PreRMS in the active attention condition could cause increased PostRMS amplitudes, resulting in larger DiffRMS amplitudes. It appears that attending to the target stimulus can help offset the increased prestimulus activity (noise according to traditional views) by increasing the activity in the poststimulus activity (signal), thereby ensuring that the resultant SNR is still more than sufficient to reveal clean and robust CAEPs.

Conclusion

In the current study, we aimed to observe the effects of attention on the neural noise as measured using the prestimulus EEG (RMS) activity. By measuring CAEPs in response to speech tokens, under active and passive attention conditions, we show that the prestimulus activity (as well as the poststimulus activity and the difference between the poststimulus

and prestimulus activity) was significantly larger when the participants attended to the target stimulus. Higher prestimulus amplitude, subsequently, resulted in an attention-related enhancement in the poststimulus response amplitudes. The prestimulus neural noise can, therefore, be used as an objective index of attention, especially in anticipation of an upcoming target sound. The results provide further evidence to the assumption that prestimulus activity is not merely noise, but indicates the neurophysiological activity associated with complex sensory and/or cognitive functions.

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