EEG-based and Self-perceived Assessment of Auditory Discrimination and Attentional Responses to Intensity, Pitch and Localization Changes

Sergio M-Cam[a], Priscila Montoya-Beltrán[a], Ricardo Ortega-Ramírez[a], Luz M. Alonso-Valerdi[a], David I. Ibarra-Zarate[a]
[a]*Tecnologico de Monterrey. School of Engineering and Sciences* Monterrey, México
corresponding author email address: david.ibarra@tec.mx

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***Abstract*—Auditory displays use sounds to communicate or monitor states and processes without the need for visual indicators. These auditory cues need people's attentional shift towards them. Auditory attentional processes can be measured through perceptual tests, and electrophysiological tests, such as auditory evoked potentials, that function as an indicator when different stimuli are presented. Assessment through auditory evoked potentials often use the oddball paradigm composed by frequent and deviant stimuli, where deviant stimuli can vary different auditory features (pitch, intensity, time, localization, speech). This study tests the attentional acoustic feature differences perceived through auditory evoked potentials. The discrimination paradigm was applied to 12 normal hearing students 18-25 years old, to measure their electrophysiological response changes using electroencephalogram readings in pitch, intensity, and localization of deviant sounds. Participants were also asked to fill in a questionnaire about their perception of attention during the test and the ease of discrimination. N2-P3a complex analysis indicated better attentional discrimination for pitch changes, followed by intensity and localization, supported by participant's questionnaire answers and number of deviants count-ed. These findings suggest that from these features, pitch changes can be widely considered when designing auditory displays that aim to easily shift people's attention towards the sound.**

Keywords—Auditory Evoked Potentials, Auditory Discrimination, Electroencephalography,

I. Introduction

Auditory displays are sounds designed to monitor information states and processes without the need for visual indicators using the human auditory system as an interface [1]. Alarms and alerts transmit messages that require people's immediate attention to take an action or decide [2]. The human ability to discriminate sounds and assign them attentional relevance is a fundamental and complex process in situations where quick responses may be needed [3]. Acoustic stimuli, such as alarms, are used in various contexts, from aviation to medicine, with the purpose of communicating essential information immediately [4]. Auditory attention allows focus on specific auditory stimuli while ignoring those irrelevant, ensuring accurate responses. Exogenous attention causes an automatic attraction towards salient or novel stimuli in the environment [5], generated by the stimuli physical properties [6]. In auditory perception, certain acoustic changes, such as pitch and intensity differences, serve as exogenous cues that can automatically capture attention regardless of the listener's anticipations. For instance, sounds higher in pitch or louder are more likely to attract attention, even without conscious effort [7]. This automatic attentional process is crucial where immediate responses to unexpected sounds are necessary.

The selection of sounds attributes plays a key role in the effectiveness of these signals, as different attributes are processed differently by the auditory system [8]. Traditionally, studies on auditory attention have focused on pitch discrimination, where changes in frequency serve as the primary method of altering auditory stimuli. Previous studies have shown that an increase in pitch and intensity typically generates faster and more robust responses, both behaviorally and neurophysiologically [9]. Exogenous attention is particularly relevant where these cues capture attention automatically. In an oddball paradigm, deviant changes in frequency or intensity typically elicit stronger cortical responses, as they are perceived as novel or deviant [10].

A widely used way of assessing auditory attention is through Auditory Evoked Potentials (AEPs), electrophysiological responses showing brain responses to deviant or novel stimuli [11]. AEPs, particularly the long-latency components, have been widely studied as markers of attentional processing. The N2 and P3 components are widely related as an indicator of selective auditory attention [12]. These components are particularly relevant for reflecting the brain's allocation of resources during auditory processing. Importantly, the P3 response is often elicited by deviant stimuli, making it an ideal measure for assessing auditory attention and cognitive processing [13].

This study aims to compare how frequency, intensity, and spatial localization interact to influence auditory attentional processes. Spatial localization, while more recently researched, plays a crucial role in auditory attention by providing spatial cues, as interaural differences which help determine the origin of sound sources [14], being a more complex characteristic than the previous two. These spatial characteristics can significantly enhance attentional capture, making them particularly relevant in situations requiring rapid responses to auditory stimuli [15]. By incorporating spatial localization, this study aims to offer new insights into how

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diverse sound characteristics influence exogenous attention and attentional shifts, towards effective auditory display designs, as the need has been suggested [16].

II. Methods

A. Participants

12 participants (6 males, 6 females; age 18-26, M = 22.5, SD = 2.25) were recruited. All were required to sign an informed consent sheet. An initial audiometry ensured auditory thresholds below 20 dB HL in both ears.

B. Materials

Pure-tone audiometry was done with an Interacoustics AD26 audiometer by air-conduction with supra headphones DD-45. EEG was recorded using a Hybrid Unicorn Black system with 8 channels (Fz, Cz, C3, C4, Pz, Oz, PO7, PO8), sampled at 250 Hz, with ground electrodes at both mastoids. A 1-minute baseline with closed eyes was registered before discrimination assessment.

Oddball paradigm was applied under controlled conditions: 3 minutes per acoustic feature (pitch, intensity and localization), each with 180 sounds in an 80-20 frequent-deviant pseudorandom sequence. Stimuli lasted 100 ms with a 900 ms ISI as shown on Fig. 1.

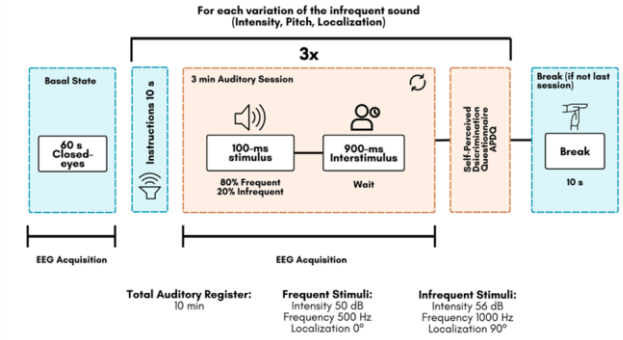

Fig. 1. Auditory discrimination assessment diagram. Both basal state and acoustic variations with closed eyes.

For all acoustic features, pure-tone stimuli were used. Pitch frequent stimuli were 0.5 kHz and deviant of 1 kHz. The intensity frequent stimuli were ~60 dB SPL and deviant of ~67 dB SPL. Horizontal localization frequent stimuli were 0° and deviant of 90° to the left.

EEG was recorded using OpenVibe; stimuli were delivered via Super Collider using the Open Sound Control (OSC) protocol on a Windows 10 computer with 'Shure SRH 440'

C. Experimental Setting

Participants were instructed to count the perceived deviant stimuli, and to press "A" on the keyboard upon detecting each one. After each stage, participants completed a questionnaire, which consists of 6 questions, between each acoustic feature. This questionnaire considers auditory processing relevant questions to determine the ease on deviant sounds detection and assess their level of attention during the experiment. Hypothesis suggests that attentional shifting due to auditory stimuli will generate a more significant auditory response, expecting an amplitude increase and shorter latency in AEPs.

For each subject four EEG recordings were acquired, each corresponding to one of the three variations done and the basal state. Data preprocessing was done using the EEGLAB toolbox (2023.0 version) in MATLAB. Raw data was analyzed for segment rejection and baseline removal. Signal was filtered with a FIR band pass filter of 1-30 Hz. Individual Component Analysis (ICA) was performed obtaining a brain activity of 94.54%. Time window analysis was done of 600 ms with an epoch baseline of -200 ms before stimuli onset. Fz and Cz electrode positions were mainly analyzed due to the nature of cortical auditory evoked potentials although event related potential was most visible in Fz.

III. Results

The dataset containing all raw and preprocessed EEG recordings is available in Euro-pean Data Format (EDF), General Data Format (GDF), and Comma-separated values (CSV) formats via the following link: https://data.mendeley.com/datasets/3tp7dfrtcm/1. This includes participant data and event latencies.

Figure 2 presents the AEPs for subject 5 of the participants in response to both frequent and deviant stimuli across three auditory parameters: pitch (frequency), intensity (amplitude) and localization (space). These AEPs were extracted from the Fz channel, which focuses on frontal cortical activity, a region closely linked to attentional processes and auditory discrimination.

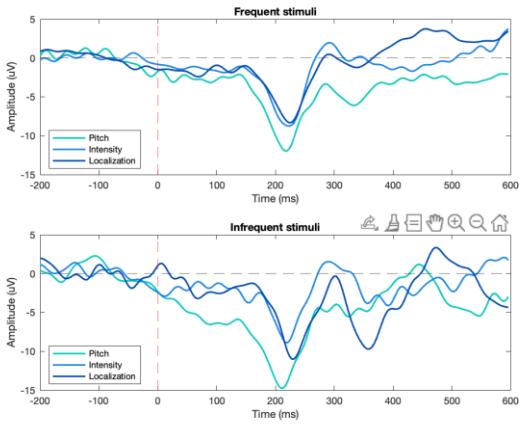

Fig. 2. Infrequent and frequent auditory evoked response to acoustic features for Fz channel.

A. Auditory Evoked Potentials

The frequent stimuli plotted in Fig. 2 illustrates the AEPs elicited by frequent stimuli. The Fz channel displays typical responses with latencies of approximately 150 ms and 300 ms, corresponding to the N2 and P3a complex, respectively (characterized by attentional tasks).

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The amplitude of these responses is relatively similar across the three types of stimuli (intensity, pitch, and localization). Notably changes can be observed in frequency result in a larger negative potential around 250 ms, reaching approximately -10 µV. In contrast, the localization and amplitude changes showed a slightly lower AEP morphology, suggesting reduced variability in the evoked potentials for those stimuli.

The deviant stimuli shown in Fig. 2 displays the AEPs for deviant stimuli, where notable differences emerge compared to frequent stimuli. Changes in pitch elicited a higher amplitude response at approximately 200 ms, suggesting a stronger response of an exogenous attention to novel stimuli. N2 shows a clearer morphology suggesting a robust relationship with the auditory discrimination task. Deviant stimuli produced its most positive peak at around 300 ms, indicating a slight overview of the P3a component.

Average results for all participants shown in Table 1 confirm better discrimination for deviant stimuli based on higher amplitude and lower latency for all acoustic features.

TABLE I. AVERAGE RESULTS OF FREQUENT (F) AND DEVIANT (D) ACOUSTIC STIMULI FOR N2 COMPONENT AMPLITUDE AND LATENCIES.

Questionnaire	**Tested Sound Features**		
Questions	***Pitch (std)***	***Intensity (std)***	***Localization (std)***
Did you listen attentively?	4 (0)	3.92 (0.27)	3.92 (0.27)
Did you understand the instructions?	3.85 (0.55)	3.92 (0.27)	4 (0)
Did you distinguish the totality of the deviant stimuli?	3.46 (0.12)	3.23 (0.92)	2.85 (1.14)
Was it difficult to distinguish them?	1 (0)	2.46 (1.19)	2.31 (1.18)
Did you have any distraction when distinguishing them?	1.31 (0.48)	1.54 (0.77)	1.31 (0.48)
Was the stimulus volume correct?	4 (0)	3.92 (0.27)	4 (0)

Pitch deviants showed an increased mean amplitude of 1.06 µv and latency decreased by 4 ms. Intensity deviants increased mean amplitude by 0.76 µv and decreased latency by 12 ms. Localization deviants increased negative mean peak by 1.21 µv and decreased latency by 8 ms.

Comparing frequent and deviant stimuli, pitch deviants evoked higher amplitudes in the N2-P3 complex in Fz than intensity and localization. These findings suggest that pitch changes are more noticeable in sensorial and exogenous attentional processes generating stronger discrimination.

B. Inter-trial Coherence and Event Related Spectral Perturbation

To support the results, the Inter-trial Coherence (ITC) and Event Related Spectral Perturbation (ERSP) were computed through the EEGLAB toolbox, within the limits of epochs -200 596, taking baseline as -200 to onset, frequency range of 8-20 Hz. Channel Fz was chosen for the calculation, due to auditory evoked potential main location in frontal lobe presenting an AEP higher amplitude as shown in Fig. 3. A 4x Padding was set for a better resolution and significance level was set to 0.05. Three cycle wavelets with a Hanning-tapered window are used for the ITC (event-related phase-locking) analysis and ERSP (event-related shifts in the power spectrum).

As can be seen on Fig. 4a ITC and ERSP reach significance

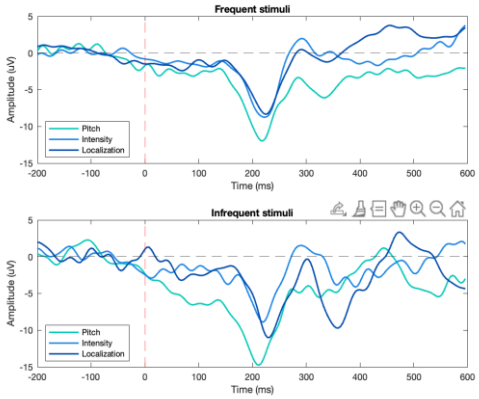
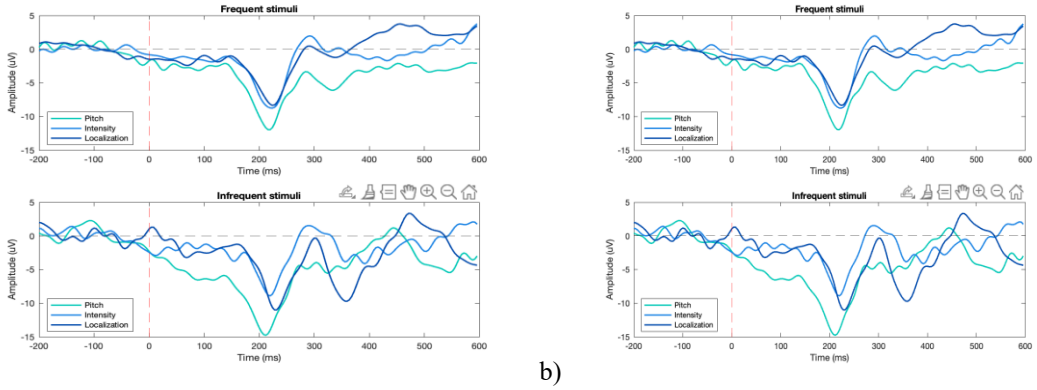


Fig. 3. AEP distribution in EEG channels for deviant stimuli average.



a) b)

Fig. 4. Example of a subject ITC and ERSP. a) Top: evoked potentials across trials, (Fz channel) and average waveform. Middle and bottom: ERSP values above 0.05 significance. b) Green areas indicate non-significant ERSP and ITC. Both plots use 108 deviant events (36 each for intensity, pitch, and localization).

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threshold (blue shadowing). Fig. 4b shows specific time where significance is reached by ITC meaning that single trials are phased-locked (not phase-random) with respect to the auditory events.

C. Self-Perceived Discrimination Questionnaire

In addition to the AEP analysis, participants completed a 6-item behavioral discrimination questionnaire. This questionnaire aimed to assess attention and discrimination performance during the tests.

Participants rated each item on a Likert scale from 1 to 4, where "1" was "not at all" and "4" was "completely". The results (shown in Table 2) show participants mean answers demonstrating that participants were generally attentive during the tests, with only minor distractions reported, ensuring that results correctly reflect auditory discrimination and attentional shift. However, the ability to distinguish deviant stimuli was slightly lower for localization compared to pitch and intensity, which support the electrophysiological findings of reduced ease for localization changes.

TABLE II. QUESTIONNAIRE AVERAGE RESULTS FROM 12 PARTICIPANTS.

Average Results	**EEG Signal Features**	
Stimuli	***N2 Amplitude (μv)***	***N2 Latency (ms)***
F-intensity	-2.94 (sd = 4.19)	228
F-pitch	-4.84 (sd = 3.89)	216
F-localization	-3.50 (sd = 3.03)	236
D-intensity	-3.70 (sd = 5.04)	216
D-pitch	-5.90 (sd = 5.52)	212
D-localization	-4.71 (sd = 3.52)	228

These results complement the AEPs findings by providing insight into the subjective experience of participants during the task, particularly in terms of their exogenous attention and ease of discriminating between different auditory stimuli.

IV. DISCUSSION

Each of the acoustic features were counted by participants during discrimination tests. A total of 36 deviant stimuli were sent for each feature. Participants counted a mean of 33 (sd = 4.84) for pitch, 29.38 (sd = 10.69) for intensity, and 25.5 (sd = 12.41) for localization.

As can be seen, pitch was the most recognizable feature variant during the paradigm in both AEPs and perceived discrimination task, followed by intensity and last for localization.

Although expected cortical AEPs components were obtained, P3a, early subcomponent of P3, had a slight morphology suggesting a more exogenous attention or sensorial mechanism and less voluntary discrimination process or attention shifting. Thus, N2 can be observed as a stronger auditory component to basic sound changes. As revised in literature, the N2-P3a complex can reflect stimulus evaluation processes and perceptual allocation, as P3a reflects unexpected events attention orienting and N2 is also sensitive to novelty stimuli caused by oddball paradigm, although P3a component is considered as a more complex top-down mechanism [3].

Since differences in stimuli were over acoustic minimum perceived intervals, auditory evoked potentials were clearly obtained, indicating discrimination processes. If these evoked potentials were not clear enough, it could suggest that acoustic intervals were not over the just noticeable difference values, so the subject wouldn't be able to get an attentional response to the stimuli.

Localization feature difficult to detect can be explained since it belongs to a more complex acoustic feature that may combine time, intensity and pitch differences [16] and involves a mixed integration in the auditory pathway not easily processed and basic features alone.

V. CONCLUSION

The auditory discrimination process has been characterized by AEPs amplitude and latency, relating better discrimination to higher amplitude and lower latency. A relationship between behavioral discrimination tests and electrophysiological assessment was established, characterizing acoustic stimuli attentional response for the mean of the twelve subjects. The important highlight is that for both stimulus, frequent and deviant, auditory discrimination measured through evoked potential and behavioral tests had a better response in pitch feature. This strongly suggests that modulation or changes in pitch may cause an easier exogenous attention and may be an indicator of early attentional shifting in automatic processes.

These findings contribute to a better understanding and implementation of auditory displays design aiming to explain exogenous attention towards acoustic changes to have stronger effects of attentional shifting and improving data monitoring of the auditory interfaces.

Limitations for the work presented include a better system calibration to obtain a non-bias response due to devices transfer function and frequency filtering, as well as a normalization and validation of the auditory performance questionnaire. A bigger sample would also need to perform a more robust statistical analysis and have more significant results.

As healthy subjects were used for this discrimination assessment, statistical analysis should be later performed for this to be considered as a normalization for specific sample characteristics.

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