

Research Article

Effect of noise on T-complex responses: an evoked-related potential study

Zohreh Ahmadi ^a, Shanna Kousaie ^b, Benjamin Rich Zendel ^c, Amineh Koravand ^{a,*}^a Audiology Program, School of Rehabilitation Sciences, Faculty of Health Sciences, University of Ottawa, Canada^b School of Psychology, Faculty of Social Sciences, University of Ottawa, Canada^c Faculty of Medicine, Memorial University of Newfoundland, Canada

ARTICLE INFO

Keywords:

Cortical auditory responses

T-complex

Noise-induced enhancement

Lateralization

ABSTRACT

Cortical auditory evoked potentials (CAEPs), including the frontocentral (P1–N1–P2) and temporal (T-complex) components, have distinct neural generators. The T-complex appears to mature earlier and remains relatively stable with age. This stability may suggest that the T-complex may better reflect auditory processing in real-life listening conditions compared to frontocentral responses. One critical aspect of real-world listening is the presence of background noise; however, no previous study has examined its impact on the T-complex. The present study investigated the effects of background noise on both T-complex and frontocentral responses in adults during a passive paradigm, using /da/ and a 1-kHz tone pip presented in white and babble noise. In noise compared to quiet, the latency of all components was generally prolonged, and CAEP amplitudes were reduced. However, N1 and Ta amplitudes were enhanced in non-speech noise, and Tb amplitude was enhanced in babble noise. This enhancement pattern was observed only with speech stimuli. Larger CAEP amplitudes in noise may reflect top-down adaptive mechanisms that support speech understanding in adverse conditions. Notably, the larger Tb response to speech in babble noise suggests that the T-complex may index greater adaptation to real-life listening environments compared to frontocentral responses. The differences in CAEPs evoked by noise masked stimuli may highlight the various contributions of different auditory cortical structures to listening in noise. The T-complex also showed rightward lateralization in noise, consistent with findings from the primary auditory cortex.

Introduction

Background noise interrupts everyday communication, requiring our auditory system to focus on relevant information while suppressing irrelevant sounds. Successful perception of speech in noise is dependent on hearing status and sound processing at peripheral, subcortical and cortical levels (Anderson, Skoe, et al., 2010; Bures̄ et al., 2025). Multiple behavioral studies have shown the detrimental effect of noise on speech perception (Dirks et al., 1982; Le Prell & Clavier, 2017; Lee et al., 2015; Meyer et al., 2013; Pittman & Wiley, 2001), though these approaches have limitations. Behavioral measures are influenced by non-auditory factors such as attention and language (Jerger & Musiek, 2000) and cannot directly assess the underlying neurophysiological mechanisms of speech processing in noise. Auditory evoked potentials (AEPs) provide an effective tool to evaluate auditory processing in the presence of background noise (Anderson, Skoe, et al., 2010). Prior research consistently shows that noise degrades auditory subcortical responses, resulting in delayed neural timing and reduced response amplitudes

(Cunningham et al., 2002; Hecox et al., 1989; Parbery-Clark et al., 2011; Russo et al., 2005; Song et al., 2011).

At the cortical level, auditory evoked potentials can be categorized into two responses including frontocentral responses (i.e., P1–N1–P2–N2) and temporal responses (i.e., the T-complex). The P1–N1–P2–N2 sequence reflects auditory processes occurring primarily in the primary auditory cortex, particularly Heschl's gyrus, where the neural generators are tangentially oriented (Lindenberger & Baltes, 1994; Picton et al., 1999; Ponton et al., 2002; Wolpaw & Penry, 1975). The P1 component indexes pre-perceptual encoding of acoustic features such as frequency and timing and is thought to arise from the primary auditory cortex (Čeponienė et al., 2005; Liégeois-Chauvel et al., 1994). The N1 is an onset response generated by multiple sources, including the temporal and frontal lobes, thalamus, and midbrain reticular formation (Näätänen & Picton, 1987). It has both exogenous and endogenous properties, reflecting the presence of an audible sound (Näätänen & Picton, 1987) while becoming more pronounced under attention (Hillyard et al., 1973). The P2 appears to originate mainly from the

* Corresponding author.

E-mail address: amineh.koravand@uottawa.ca (A. Koravand).<https://doi.org/10.1016/j.neuroscience.2026.04.028>

Received 29 September 2025; Accepted 24 April 2026

Available online 27 April 2026

0306-4522/© 2026 The Author(s). Published by Elsevier Inc. on behalf of International Brain Research Organization (IBRO). This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

anterolateral portions of Heschl's gyrus (Ross & Tremblay, 2009) and the insular cortex (Ponton et al., 2000) and is associated with the acoustic and temporal characteristics of stimuli (Näätänen & Picton, 1987). Finally, the N2 is thought to originate from activity in the supratemporal plane of the auditory cortex (Ceponiene et al., 2002). It reflects the physical discrimination of acoustic features and is linked to sensory auditory processing, being modulated by attention, perception, discrimination, and recognition of sounds (Näätänen et al., 1982).

While subcortical responses exhibit consistent changes in the presence of background noise, cortical auditory evoked potentials (CAEP; P1-N1-P2-N2), show less consistent effect. Most studies report that noise degrades CAEPs, resulting in smaller amplitude and prolonged latency (Androulidakis & Jones, 2006; Billings et al., 2013; Billings et al., 2009; Kaplan-Neeman et al., 2006; Russo et al., 2009; Whiting et al., 1998). However, a few studies report that N1 amplitude is increased in noise (Alain et al., 2009; Duquette-Laplante et al., 2024; Papesh et al., 2015; Parbery-Clark et al., 2011), a pattern not observed for P1 and P2. It may suggest that the structures of the central auditory system that generate these waveforms may contribute differently to the processing of sound in noise.

The methodological differences likely account for the discrepancies in N1 findings. The enhanced N1 was recorded in studies employing binaural stimuli presentations at relatively fast rates (Alain et al., 2009; Parbery-Clark et al., 2011), whereas smaller N1 amplitude in noise were reported in studies using monaural presentations at slower rates (Billings et al., 2009; Kaplan-Neeman et al., 2006). However, this distinction is not fully supported, as Papesh et al. (2015) reported CAEP in both monaural and binaural conditions (Papesh et al., 2015). Another possible explanation for the noise-induced enhancement is the modulation of auditory efferent system in the presence of background noise (Guinan, 2006; Huffman & Henson, 1990). Efferent pathways may facilitate the intelligibility of speech in noise through inhibition (Chintanpalli et al., 2012; Huffman & Henson, 1990; Scharf et al., 1997). This top-down inhibition may reduce the baseline level of spontaneous and/or excitatory activities that prolong the neural response to transient auditory events in noise (Alain et al., 2009; Haider et al., 2013). Animal studies have shown that the efferent stimulation can enhance auditory neurons responses leading to increase the signal-to-noise ratio for evoked potentials when stimuli are presented in noise (Kawase & Liberman, 1993; Tomchik & Lu, 2006). Hypothetically, it may be speculated that efferent system may be more sensitive to speech stimuli, allowing more efficient adaptation in noise and yielding stronger auditory responses to speech compared to non-speech stimuli.

More research on CAEPs in noise using speech and non-speech stimuli in various noises is needed to clarify whether stimulus type influences noise-induced enhancement. To our knowledge, only one study has examined the effect of both stimuli type (speech vs., non-speech) and noise type (non-speech noise vs. 8-talker babble noise) (Duquette-Laplante et al., 2024). This study observed an N1 enhancement only when speech stimuli was delivered in the presence of non-speech noise. The author suggested that the speech stimuli were more salient than tonal stimuli in non-speech noise (Duquette-Laplante et al., 2024). However, because most of the CAEPs waves were not identifiable in 8-talker babble noise, comparison between non-speech stimuli and speech noise was not possible (Duquette-Laplante et al., 2024). Babble noise with fewer talkers, for example 4-talker appears to be more efficient in CAEP research, as studies have reported identifiable waveforms under this condition (Benítez-Barrera et al., 2021; Billings et al., 2011; B. R. Zendel et al., 2015). Although direct comparisons between non-speech noise and 4 talker babble have not been made, it is plausible that the N1 would be larger in the presence of non-speech noise and there would be no similar effect in babble noise.

Therefore, further studies on CAEPs are needed to examine the effect of noise type using speech and non-speech stimuli. Moreover, existing research on CAEPs in noise has not addressed how background noise impacts temporal auditory evoked responses change. The T-complex, or

temporal response, including Na-Ta-Tb sequence correspond to processes in secondary auditory areas, specifically the lateral superior temporal gyrus, where dipole sources are radially oriented (Lindenberger & Balthes, 1994; Uhlén et al., 1996; Wolpaw & Penry, 1975). The Na-Ta-Tb responses occur between 50–200 ms, are typically observed at electrodes located at T7 and T8, and exhibit negative, positive and negative polarity, respectively. In addition to the different neural generators between the T-complex and frontocentral responses, these two responses mature at distinct ages (Albrecht et al., 2000; Billings et al., 2011; Pang & Taylor, 2000). Notably, developmental research has shown that the T-complex matures earlier than frontocentral responses and remains relatively stable with age (Bishop et al., 2011; Ponton et al., 2002; Tonnquist-Uhlen et al., 2003). The T-complex can be modulated by changes in stimulus intensity, interstimulus interval (ISI) and Stimulus Onset Asynchrony (SOA) (Clunies-Ross et al., 2018; Jarmo A. Hämäläinen et al., 2011). Verbal stimuli elicit a larger amplitude and/or shorter latency of the T-complex compared to non-verbal stimuli (Bishop et al., 2012; Groen et al., 2008; Hine & Debenner, 2007), and it also represents the spectral-temporal attributes of speech stimuli (Silva et al., 2020; Wagner et al., 2016). Additionally, some studies have reported hemispheric differences, with distinct modulation patterns observed at left (T7) versus right (T8) temporal sites, suggesting that the T-complex reflects differential processing in the two hemispheres of the secondary auditory cortex (Clunies-Ross et al., 2015; Clunies-Ross et al., 2018).

Like frontocentral responses, the T-complex can be affected by stimulus features, however, to the best of our knowledge, no study evaluated noise-induced changes in the T-complex or compared these patterns to noise-induced changes in frontocentral responses. Consequently, the effect of noise on auditory processes in secondary auditory areas indexed by the T-complex areas remains unclear.

The aim of this study was to evaluate the effect of noise on the T-complex and to compare these effects with those observed in the frontocentral responses. In addition, this study assessed whether CAEPs are differentially modulated by stimulus type (speech vs. non-speech) and noise type (non-speech noise vs. 4-talker babble).

Considering the different neural generators of the T-complex and P1-N1-P2-N2 sequence, an examination of the T-complex under noisy conditions and comparing it to the auditory frontal responses may provide more insight into the neurophysiological underpinnings of auditory processing within different areas of the auditory cortex (i.e., primary and secondary auditory cortex). Moreover, such findings may have clinical relevance, as they could inform our understanding of how noise affects processing in secondary auditory areas in populations with communication disorders, such as people with auditory processing disorder, whose main complaint is difficulty understanding speech in noisy environments.

Hypotheses

Given the greater stability of T-complex responses throughout life, it is hypothesized that the T-complex may better represent the auditory processing in real-life noisy listening conditions than frontocentral responses. This suggests that the T-complex may better represent auditory information in the presence of noise. Moreover, if the larger auditory responses in noise reflect the top-down adaptive mechanisms acting on speech processing, then the noise-induced enhancement in CAEPs is expected to occur primarily in response to speech stimuli rather than non-speech stimuli. Additionally, given the distinct stimulus-induced modulation patterns of the T-complex at electrodes T7 and T8, differential effects of noise on the T-complex are anticipated between these two sites.

Method

Participants

Twenty students aged 18 to 30 years ($M = 28$, $SD = 4.6$; 9 males) participated in this study.

Inclusion and exclusion criteria

All participants had normal audiometric thresholds (≤ 15 dB HL) at octave frequencies from 500 Hz to 8 kHz, bilaterally, based on the American National Standards Institute (1996) protocol. Tympanograms were normal, showing an admittance curve with a single peak between +50 and -100 daPa using a 226-Hz probe tone. Participants were right-handed and fluent in English for both speaking and listening, as determined by the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007). No history of otological or neurological disorders was reported by any of the adult participants. In addition, participants with musical training were excluded, as previous studies have shown that music practice can enhance speech-in-noise perception and increase the amplitude of CAEPs in the presence of background noise compared to quiet (Anderson et al., 2013; Benjamin Rich Zendel et al., 2015).

Procedure

During the experiment, after familiarization with the testing equipment and procedures, participants were seated in a sound-attenuated room to complete the tasks. They were instructed to ignore the auditory stimuli and focus their attention on a silent, subtitled movie.

Stimuli

Participants completed two experiments as part of this study; here we report the results of studies that explored the effect of noise on CAEP using non-speech stimuli, and the effect of noise on CAEP using a speech stimulus. The second study explored the manipulation of voice onset time of a speech stimulus, and the results will be reported elsewhere. Two experiments were conducted in one day, starting with the first experiment followed by the second experiment.

The non-speech stimulus was a pure tone 1 kHz with 250 ms duration and 10 ms rise and fall time, created in Audacity software (Audacity Team, 1999). The speech stimulus was a natural /da/, it was originally recorded by a male voice and used in the study of Dubno & Schaefer (1992). The speech stimuli had the same duration (250 ms) and rise-fall time (10 ms) as non-speech stimuli. Stimuli were presented using insert earphones (EARTone 3A) in three listening conditions including quiet, in the presence of babble noise and in the presence of non-speech noise in experiment 1, there were three blocks of 1 kHz in three listening conditions including quiet, non-speech noise and babble noise. In the experiment 2, considering the goal of the study, each block included /da/ and /ta/, and three blocks in total were delivered in three listening conditions. The order of listening conditions was random between subjects. Non-speech noise (similar to white noise but swas band-pass limited to have equal energy from 250-6000 Hz was created and extracted from Audacity software (Audacity Team, 1999). English four-talker babble noise was the same as Zendel et al, 2015 (Benjamin Rich Zendel et al., 2015). Since hearing in noise is typically a binaural process, it is important to implement test measures that increase the ecological validity, or the extent to which the results can generalize to real-life listening situations. The stimuli were delivered in a passive non-oddball, homogenous paradigm, because Oddball paradigms introduce cognitive variables such as attention and stimulus context effects, which complicate the interpretation of earlier CAEP components (Billings et al., 2011). Stimuli were equalized for root mean square (rms) amplitude and then played at 80 dB SPL. For noisy conditions, signal-to-

noise ratio was kept as +5 dB, by reducing the intensity of noise to 75 dB SPL. The SNR = +5dB, because it seems that CAEPs are still recognizable in this level of noise, as previous studies could detect reliable responses at SNR = +5dB (Bidelman & Howell, 2016; Billings et al., 2017; Billings et al., 2009; Cunningham et al., 2002; Duquette-Laplante et al., 2024). Interstimulus interval (ISI) was randomly between 1100–1250 ms. The number of presentations of each stimulus was 300 in each block, for each listening condition, which were delivered by E-prime software. The whole project including the two paradigms took around two hours, 30 min for non-speech experiment and 60 min for speech stimuli experiment with few short breaks between the blocks and experiments to decrease fatigue.

Electrophysiological recording

The electrical responses were recorded from 32 active silver/silver chloride electrodes attached to an electrode cap (Brain Products GmbH, Munich, Germany). The electrodes were placed over frontal, central, parietal, temporal, and occipital areas of the scalp, using 10–20 standard system. A ground electrode was placed on the forehead. Vertical eye movements and blink artefacts were recorded from an electrode placed on the infra-orbital ridge of the left eye. The tip of the nose served as an online reference for all channels, including the electro-oculogram (EOG). Interelectrode impedances were kept between 25 and 50k Ω . The EEG signals were digitized continuously at a sampling rate of 500 Hz and stored on a hard disk for later analyses.

Electrophysiological data analysis

The data were analysed using Brain Products' Analyzer2 software. The signals were digitally filtered using a low-pass filter set at 20 Hz (24 dB/octave roll-off). A common average reference was calculated as off-line reference (Clunies-Ross et al., 2018). Eye movements and blink artefacts were corrected in the EEG using Independent Component Analysis (ICA) (Chaumon et al., 2015; Makeig et al., 1996). To achieve this, vertical and horizontal EOG activity was computed. Vertical EOG was derived by subtracting the inferior orbital channel from FP2, while horizontal eye movements were obtained by subtracting FT9 from FT10 (Duda-Milloy et al., 2019). The ICA model assumes that the observed electrophysiological signals represent a linear mixture of neural sources and artifacts that are mutually statistically independent. Using blind source separation, the algorithm was trained to identify each participant's ocular artifact signature, which was then removed from the EEG traces. Epochs were excluded if they had amplitudes exceeding ± 100 μ V at any site. Less than 10% of trials were excluded. Moreover, the EEG was visually inspected to ensure adequate artifact rejection. Epochs were segmented from 100 ms pre-stimulus onset to 600 ms post-stimulus onset. Segmented waveforms were baseline corrected around the 100 ms pre-stimulus interval and averaged based on condition. Although both Cz and Fz were selected for the detection of frontocentral responses (P1-N1-P2), only the responses at Cz are reported as there were more robust responses at Cz compared to Fz (Näätänen & Picton, 1987). Additionally, the amplitude of the N1 at Cz has been considered the strongest predictor of individual speech-in-noise perception thresholds (Billings et al., 2013). The T-complex was extracted from the temporal regions, T7 and T8 (Wolpaw & Penry, 1975). Tonquist-Uhlen and colleagues (2003) also suggest that T7 and T8 are optimal for measuring the T-complex since they reflect little activity from the sources underlying the P1, N1 and P2. Regarding T-complex components, as Na was not detected clearly in most of the participants, only Ta and Tb are reported in the results.

A peak detection procedure was performed for each participant to measure peak latency for each component. Regarding amplitude measurements a mean amplitude method was applied. Mean amplitude rather than peak amplitude is less affected by noise, leading to more efficient responses (Clayson et al., 2013; Luck, 2012). The mean

amplitudes were calculated based on an interval between two points (25 ms) on either side of the peak (i.e., a 50 ms window) for each peak. This time window was based on the grand averaged ERPs at sites Cz, T7 and T8 (Anderson, Chandrasekaran, et al., 2010; J. A. Hämäläinen et al., 2011). The latency intervals over which each of the mean amplitudes were calculated are reported in Table 1.

Statistical analysis

Statistical analyses were conducted using JASP (Jeffreys’s Amazing Statistics Program). Repeated-measures analyses of variance (ANOVAs) were performed to compare the amplitude and latency of the CAEPs. Prior to analysis, data were screened to ensure that the assumptions of ANOVA were met. The normality of residuals was assessed using Q–Q plots generated in JASP, which indicated that the residuals were approximately normally distributed, as the points closely followed the diagonal line without substantial deviations. When Mauchly’s test of sphericity was violated, the Greenhouse–Geisser correction was automatically applied to adjust the degrees of freedom.

A 2 (Stimuli: tone, speech) by 3 (Listening condition: no noise (quiet), non-speech noise, babble noise) repeated measures ANOVA was used to calculate separately latency and amplitude of P1, N1 and P2. A 2 (Electrode location: T7, T8) by 2 (Stimuli: tone, speech) by 3 (Listening condition: no noise (quiet), non-speech noise (marked as W), babble noise) repeated measures ANOVA was used to calculate separately latency and amplitude of Ta and Tb. The level of significance was set at 5% and statistically significant values were addressed as ($p < 0.05$).

In addition, an exploratory analysis was conducted to examine whether individual factors such as age or sex moderated noise-related effects. For this purpose, age was included as a continuous covariate and sex as a between-subjects factor, along with their interactions with listening condition and stimulus type. These analyses were considered exploratory, as the study was not designed or powered to assess individual-difference effects, and the age range was restricted to adults only.

Results

The following sections describe the primary effects of listening conditions, stimulus type and electrode location on auditory evoked potentials. Exploratory analyses examining whether age or sex moderated the primary effects did not show reliable interaction effects for P1, N1, P2, or T-complex measures (all p -values > 0.05).

Amplitude

Temporal responses, Ta peak

Repeated-measures ANOVA (Table 2) revealed no significant main effect of listening condition, $F(2, 38) = 1.896, p = 0.164, \eta^2 = 0.009$. However, significant main effects were found for stimuli, $F(1, 19) = 7.559, p = 0.013, \eta^2 = 0.032$, and electrode location, $F(1, 19) = 9.849, p = 0.005, \eta^2 = 0.070$. These effects were qualified by a significant three-

Table 1

Latency intervals over which each of the mean amplitudes were calculated.

Peak-site	The latency interval based on Listening condition- Stimuli					
	Q-1 kHz	Q-da	W-1 kHz	W-da	B-1 kHz	B-da
P1	43–93 ms	43–93 ms	47–97 ms	67–117 ms	47–97 ms	77–137 ms
N1	89–139 ms	91–141 ms	93–143 ms	123–173 ms	97–147 ms	195–245 ms
P2	149–199 ms	163–213 ms	167–217 ms	195–245 ms	161–211 ms	319–369 ms
Ta-T7	89–139 ms	93–143 ms	95–145 ms	127–177 ms	99–149 ms	197–247 ms
Tb-T7	143–193 ms	155–205 ms	153–203 ms	185–235 ms	155–205 ms	329–379 ms
Ta-T8	91–141 ms	87–137 ms	99–149 ms	125–175 ms	95–145 ms	195–245 ms
Tb-T8	143–193 ms	161–211 ms	157–207 ms	191–241 ms	159–209 ms	317–367 ms

Q: Quiet, W: Non-speech noise, B: Babble noise.

Table 2

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) and Electrode (T7 and T8) on amplitude of Ta.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	1.311 ^a	2 ^a	0.656 ^a	1.896 ^a	0.164 ^a	0.009
Residuals	13.145	38	0.346			
Stimuli	4.923	1	4.923	7.559	0.013	0.032
Residuals	12.373	19	0.651			
Location	10.668	1	10.668	9.849	0.005	0.070
Residuals	20.580	19	1.083			
Listening condition * Stimuli	33.084	2	16.542	61.811	< 0.001	0.218
Residuals	10.170	38	0.268			
Listening condition * Location	6.372	2	3.186	13.704	< 0.001	0.042
Residuals	8.834	38	0.232			
Stimuli * Location	11.061	1	11.061	25.569	< 0.001	0.073
Residuals	8.220	19	0.433			
Listening condition * Stimuli * Location	4.387 ^a	2 ^a	2.194 ^a	12.452 ^a	< 0.001 ^a	0.029
Residuals	6.695	38	0.176			

Note. Type III Sum of Squares.

^a Mauchly’s test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

way interaction among listening condition, stimuli, and electrode location, $F(2, 38) = 13.704, p < 0.001, \eta^2 = 0.042$. All two-way interactions were also significant: listening condition \times stimuli, $F(1, 38) = 61.811, p < 0.001, \eta^2 = 0.218$; listening condition \times electrode location, $F(1, 38) = 13.704, p < 0.001, \eta^2 = 0.042$; and stimuli \times electrode location, $F(1, 19) = 25.569, p < 0.001, \eta^2 = 0.073$. Given the significant three-way interaction, follow-up two-way ANOVAs were conducted separately for each stimulus, electrode, and listening condition.

A two-way ANOVA was done to evaluate the interaction between Listening condition and Electrode for each Stimulus, separately (Tables 3 and 4).

The results showed that the Electrode \times Listening condition interaction depended on stimulus type and was significant only for the 1-kHz tone (Fig. 1). Follow-up t -tests with Bonferroni correction confirmed that Ta was significantly larger at T8 than at T7 in non-speech noise ($p < 0.001$) and babble noise ($p < 0.001$). However, no such difference was observed in quiet ($p = 1.000$).

A two-way ANOVA was done to evaluate the interaction between Listening condition and Stimuli for each Electrode, separately (Tables 5 and 6).

The Listening condition \times Stimuli interaction was significant at both T7 and T8 (Fig. 1). Follow-up t -tests with Bonferroni correction showed that at T7, for the 1-kHz tone, Ta amplitude was smaller in non-speech

Table 3

The two-way ANOVA to assess the interaction between Listening condition and Electrode, with 1 kHz.

Cases	Sum of Squares	df	Mean Square	F	p
Listening condition	19.482	2	9.741	35.803	< 0.001
Residuals	10.339	38	0.272		
Electrode	21.728	1	21.728	26.549	< 0.001
Residuals	15.549	19	0.818		
Listening condition * Electrode	10.265	2	5.133	20.470	< 0.001
Residuals	9.528	38	0.251		

Note. Type III Sum of Squares.

Table 4

The two-way ANOVA to assess the interaction between Listening condition and Electrode, with da.

Cases	Sum of Squares	df	Mean Square	F	p
Listening condition	14.913	2	7.456	21.837	< 0.001
Residuals	12.976	38	0.341		
Electrode	0.002	1	0.002	0.003	0.960
Residuals	13.250	19	0.697		
Listening condition * Electrode	0.494	2	0.247	1.565	0.222
Residuals	6.001	38	0.158		

Note. Type III Sum of Squares.

noise ($p < 0.001$) and babble noise ($p < 0.001$). At the same electrode, for /da/, Ta amplitude was larger in non-speech noise ($p < 0.001$), with no significant effect of babble noise ($p = 0.24$). At T8, for the 1-kHz tone, there was no significant effect of either non-speech noise ($p = 0.352$) or babble noise ($p = 0.163$). For /da/ at T8, Ta amplitude was larger in non-speech noise ($p < 0.001$) and marginally larger in babble noise ($p = 0.054$).

A two-way ANOVA was done to evaluate the interaction between Electrode and Stimuli for each Listening condition, separately (Tables 7–9).

The Electrode \times Stimuli interaction was significant only under noisy conditions (Fig. 1). Follow-up t -tests showed that for the 1-kHz tone, Ta amplitude was significantly larger at T8 than at T7 in both non-speech noise and babble noise ($p < 0.001$), whereas no significant electrode effect was observed for /da/ ($p > 0.05$).

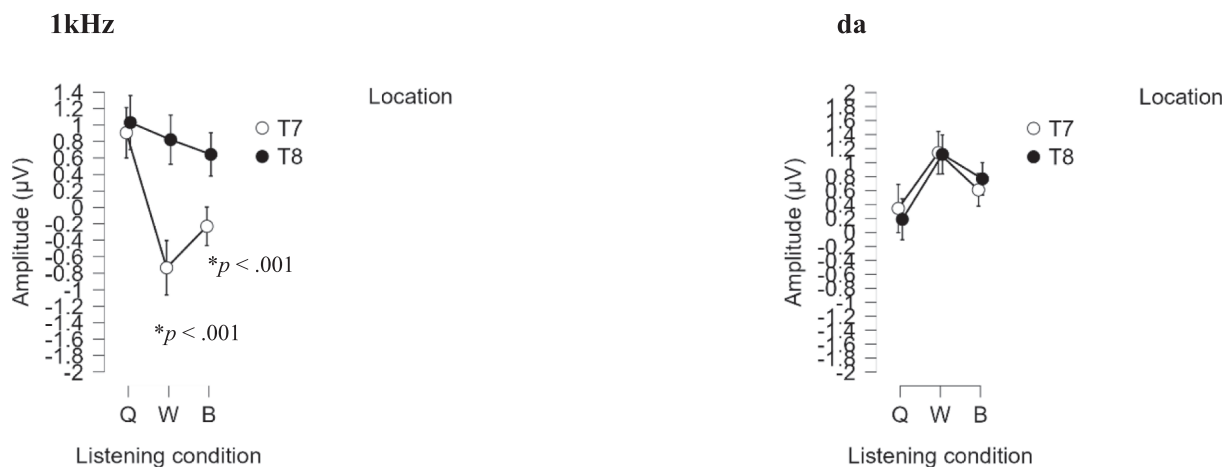


Fig. 1. The mean amplitude of Ta, to da and 1 kHz, in quiet (Q), non-speech noise (W) and babble noise (B), at T7 and T8. The most significant conditions have been marked with star symbol: *.

Temporal responses, Tb peak

Repeated-measures ANOVA (Table 10) revealed significant main effects of listening condition, $F(2, 38) = 24.749, p < 0.001, \eta^2 = 0.213$; stimuli, $F(1, 19) = 20.752, p < 0.001, \eta^2 = 0.076$; and location, $F(1, 19) = 10.437, p = 0.004, \eta^2 = 0.063$. Significant interactions were also observed between listening condition and stimuli, $F(2, 38) = 7.752, p = 0.020, \eta^2 = 0.024$, and between stimuli and location, $F(2, 38) = 5.587, p = 0.029, \eta^2 = 0.024$. Follow-up t -tests with Bonferroni correction showed that for the 1-kHz tone, there was no significant difference in Tb amplitude between non-speech noise and quiet ($p = 1.000$). However, Tb amplitude was significantly smaller in babble noise compared to quiet ($p < 0.030$; Fig. 2). For /da/, Tb amplitude was significantly different between non-speech noise and quiet ($p = 0.025$), babble noise and quiet ($p < 0.001$), and babble noise and non-speech noise ($p < 0.001$; Fig. 2).

Follow-up t -tests showed that the effect of location was significant only for /da/ ($p < 0.001$; Fig. 2). With speech stimuli, Tb amplitude was larger at T8 than at T7 across all listening conditions. Notably, in quiet, Tb amplitude was larger at T7 than at T8, whereas in both noise conditions it was larger at T8 than at T7. The mean differences were 0.59, 0.40, and 0.70 μV in quiet, non-speech noise, and babble noise, respectively. In addition, the effect of stimulus type depended on location, being significant only at T8 ($p < 0.001$) and not at T7 ($p = 1.000$).

Frontocentral responses, P1 peak

Repeated-measures ANOVA (Table 11) revealed a significant main effect of listening condition, $F(2, 38) = 14.221, p < 0.001, \eta^2 = 0.229$. No significant main effect of stimuli was observed, $F(1, 19) = 0.459, p =$

Table 5

The two-way ANOVA to assess the interaction between Listening condition and Electrode, at T7.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	4.896	2	2.448	7.308	0.002	0.060
Residuals	12.730	38	0.335			
Stimuli	15.371	1	15.371	43.391	< 0.001	0.188
Residuals	6.731	19	0.354			
Listening condition * Stimuli	29.954 ^a	2 ^a	14.977 ^a	47.896 ^a	< 0.001 ^a	0.367
Residuals	11.883	38	0.313			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

Table 6

The two-way ANOVA to assess the interaction between Listening condition and Electrode, at T8.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	2.787 ^a	2 ^a	1.394 ^a	5.725 ^a	0.007 ^a	0.071
Residuals	9.249	38	0.243			
Stimuli	0.613	1	0.613	0.840	0.371	0.016
Residuals	13.862	19	0.730			
Listening condition * Stimuli	7.517	2	3.759	28.669	< 0.001	0.193
Residuals	4.982	38	0.131			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

Table 7

The two-way ANOVA to assess the interaction between Electrode and Stimuli, Q.

Cases	Sum of Squares	df	Mean Square	F	p
Stimuli	9.919	1	9.919	23.322	< 0.001
Residuals	8.081	19	0.425		
Electrode	0.005	1	0.005	0.007	0.936
Residuals	14.717	19	0.775		
Stimuli * Electrode	0.390	1	0.390	1.858	0.189
Residuals	3.991	19	0.210		

Note. Type III Sum of Squares.

Table 8

The two-way ANOVA to assess the interaction between Electrode and Stimuli, W.

Cases	Sum of Squares	df	Mean Square	F	p
Stimuli	23.478	1	23.478	41.784	< 0.001
Residuals	10.676	19	0.562		
Electrode	11.723	1	11.723	21.699	< 0.001
Residuals	10.265	19	0.540		
Stimuli * Electrode	12.495	1	12.495	36.734	< 0.001
Residuals	6.463	19	0.340		

Note. Type III Sum of Squares.

Table 9

The two-way ANOVA to assess the interaction between electrode and stimuli, B.

Cases	Sum of Squares	df	Mean Square	F	p
Stimuli	4.610	1	4.610	23.134	< 0.001
Residuals	3.786	19	0.199		
Electrode	5.312	1	5.312	22.769	< 0.001
Residuals	4.432	19	0.233		
Stimuli * Electrode	2.563	1	2.563	10.919	0.004
Residuals	4.460	19	0.235		

Note. Type III Sum of Squares.

0.506, $\eta^2 = 0.005$, and the interaction between listening condition and stimuli was not significant, $F(2, 38) = 1.180$, $p = 0.318$, $\eta^2 = 0.016$. Follow-up *t*-tests with Bonferroni correction showed that P1 amplitude was significantly smaller in non-speech noise than in quiet ($p < 0.001$) and in non-speech noise than in babble noise ($p < 0.001$). No significant effect of babble noise was observed (Fig. 3).

Frontocentral responses, N1 peak

Repeated-measures ANOVA (Table 12) revealed a significant main effect of listening condition, $F(2, 38) = 13.196$, $p < 0.001$, $\eta^2 = 0.180$. No significant main effect of stimuli was observed, $F(1, 19) = 0.540$, $p = 0.471$, $\eta^2 = 0.006$. However, the interaction between stimuli and listening condition was significant, $F(2, 38) = 31.763$, $p < 0.001$, $\eta^2 =$

Table 10

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) and Electrode (T7 and T8) on amplitude of Tb.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	25.300	2	12.650	24.749	< 0.001	0.213
Residuals	19.423	38	0.511			
Stimuli	9.065	1	9.065	20.752	< 0.001	0.076
Residuals	8.299	19	0.437			
Location	7.456	1	7.456	10.437	0.004	0.063
Residuals	13.573	19	0.714			
Listening condition * Stimuli	2.827	2	1.414	7.752	0.002	0.024
Residuals	6.930	38	0.182			
Listening condition * Location	0.588	2	0.294	1.778	0.183	0.005
Residuals	6.280	38	0.165			
Stimuli * Location	2.800	1	2.800	5.587	0.029	0.024
Residuals	9.524	19	0.501			
Listening condition * Stimuli * Location	0.317	2	0.159	0.946	0.397	0.003
Residuals	6.372	38	0.168			

Note. Type III Sum of Squares.

Effect sizes were reported as η^2 and interpreted using conventional benchmarks (.01 = small,.06 = medium,.14 = large).

0.223. Follow-up *t*-tests with Bonferroni correction showed that for the 1-kHz tone, N1 amplitude was significantly smaller in non-speech noise than in quiet ($p = 0.008$), in babble noise than in quiet ($p < 0.001$), and in babble noise than in non-speech noise ($p = 0.003$; Fig. 6). For /da/, N1 amplitude was significantly larger in non-speech noise than in quiet ($p < 0.001$) and in babble noise ($p = 0.002$). However, no significant difference was found between babble noise and quiet ($p = 1.000$; Fig. 4).

Frontocentral responses, P2 peak

Repeated-measures ANOVA (Table 13) revealed a significant main effect of listening condition, $F(2, 38) = 34.414$, $p < 0.001$, $\eta^2 = 0.530$. No significant main effect of stimuli was observed, $F(1, 19) = 0.040$, $p = 0.844$, $\eta^2 = 0.0001$, and the interaction between factors was not significant, $F(2, 38) = 2.458$, $p = 0.099$, $\eta^2 = 0.012$. Follow-up *t*-tests with Bonferroni correction showed that P2 amplitude was significantly smaller in non-speech noise than in quiet ($p = 0.003$), in babble noise than in quiet ($p < 0.001$), and in babble noise than in non-speech noise ($p < 0.001$; Fig. 5).

Latency

Temporal responses, Ta peak

Repeated-measures ANOVA (Table 14) revealed significant main effects of listening condition, $F(2, 38) = 146.499$, $p < 0.001$, $\eta^2 = 0.328$, and stimuli, $F(1, 19) = 417.083$, $p < 0.001$, $\eta^2 = 0.277$. No significant effect of location (T7 vs. T8) was observed, $F(1, 19) = 0.010$, $p = 0.900$, $\eta^2 = 0.001$. Significant interactions were found between listening condition and stimuli, $F(2, 38) = 83.397$, $p = 0.043$, $\eta^2 = 0.203$, and between listening condition and location, $F(2, 38) = 3.435$, $p < 0.001$, $\eta^2 = 0.003$. Follow-up *t*-tests with Bonferroni correction confirmed the effect of listening condition, showing longer latency in non-speech noise versus quiet, babble noise versus quiet, and babble noise versus non-speech noise for both stimuli ($p < 0.01$; Fig. 8). However, no significant differences were observed between T7 and T8 in any listening condition ($p > 0.05$; Fig. 6).

Temporal responses, Tb peak

Repeated-measures ANOVA (Table 15) revealed significant main effects of listening condition (quiet, non-speech noise, and babble

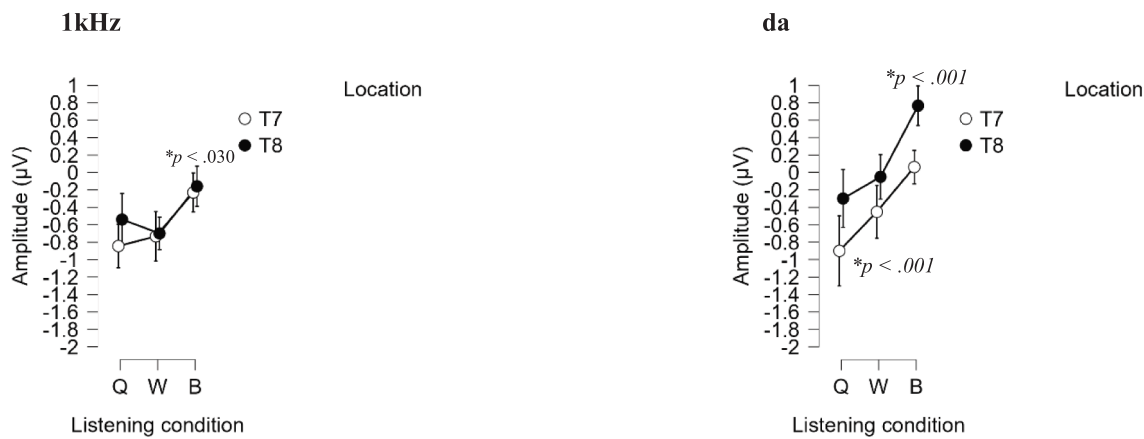


Fig. 2. The mean amplitude of Tb, to da and 1 kHz, in Quiet, Non-speech noise, and Babble noise, at T7 and T8. The most significant conditions have been marked with star symbol: *.

Table 11

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on amplitude of P1.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	3.336	2	1.668	14.221	< 0.001	0.229
Residuals	4.457	38	0.117			
Stimuli	0.069	1	0.069	0.459	0.506	0.005
Residuals	2.835	19	0.149			
Listening condition * Stimuli	0.226	2	0.113	1.180	0.318	0.016
Residuals	3.639	38	0.096			

Note. Type III Sum of Squares.

noise), $F(2, 38) = 334.004, p < 0.001, \eta^2 = 0.356$, and stimuli, $F(1, 19) = 454.589, p < 0.001, \eta^2 = 0.293$. No significant main effect of location (T7 vs. T8) was observed, $F(1, 19) = 2.392, p = 0.138, \eta^2 = 0.001$. The only significant interaction was between listening condition and stimuli, $F(2, 38) = 371.992, p < 0.001, \eta^2 = 0.295$. Follow-up *t*-tests with Bonferroni correction confirmed the effect of listening condition for both stimuli ($p < 0.01$), showing longer latency in non-speech noise

versus quiet, babble noise versus quiet, and babble noise versus non-speech noise (Fig. 7).

Frontocentral responses, P1 peak

Repeated-measures ANOVA (Table 16) revealed significant main effects of listening condition, $F(2, 38) = 83.045, p < 0.001, \eta^2 = 0.327$, and stimuli, $F(1, 19) = 281.426, p < 0.001, \eta^2 = 0.301$, as well as a

Table 12

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on amplitude of N1.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	7.012	2	3.506	13.196	< 0.001	0.180
Residuals	10.097	38	0.266			
Stimuli	0.219	1	0.219	0.540	0.471	0.006
Residuals	7.692	19	0.405			
Listening condition * Stimuli	8.680	2	4.340	31.763	< 0.001	0.223
Residuals	5.192	38	0.137			

Note. Type III Sum of Squares.

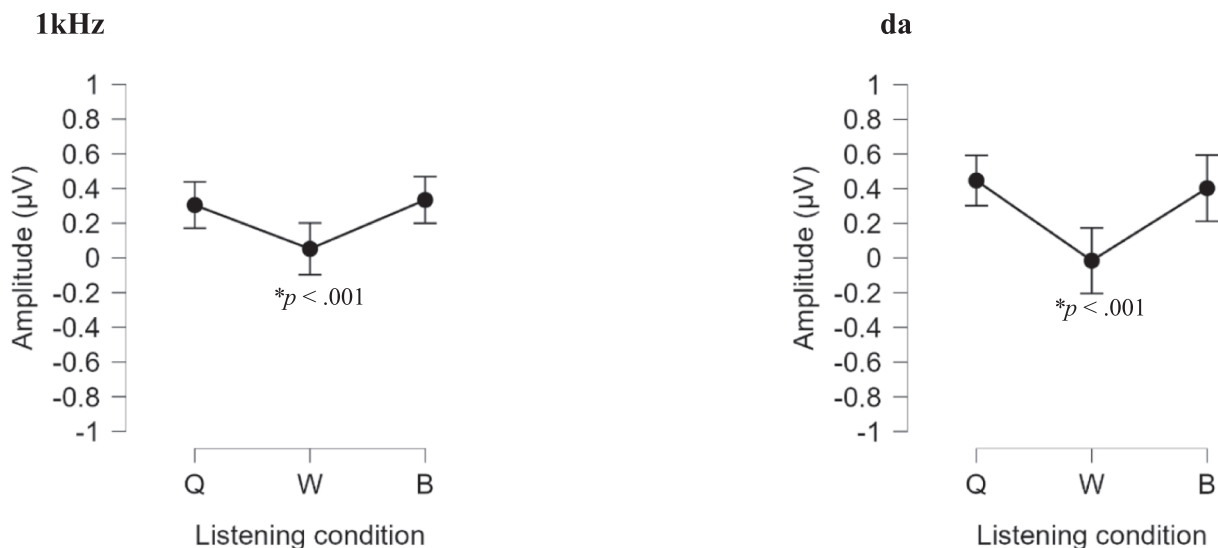


Fig. 3. The mean amplitude of P1, to da and 1 kHz, in quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.

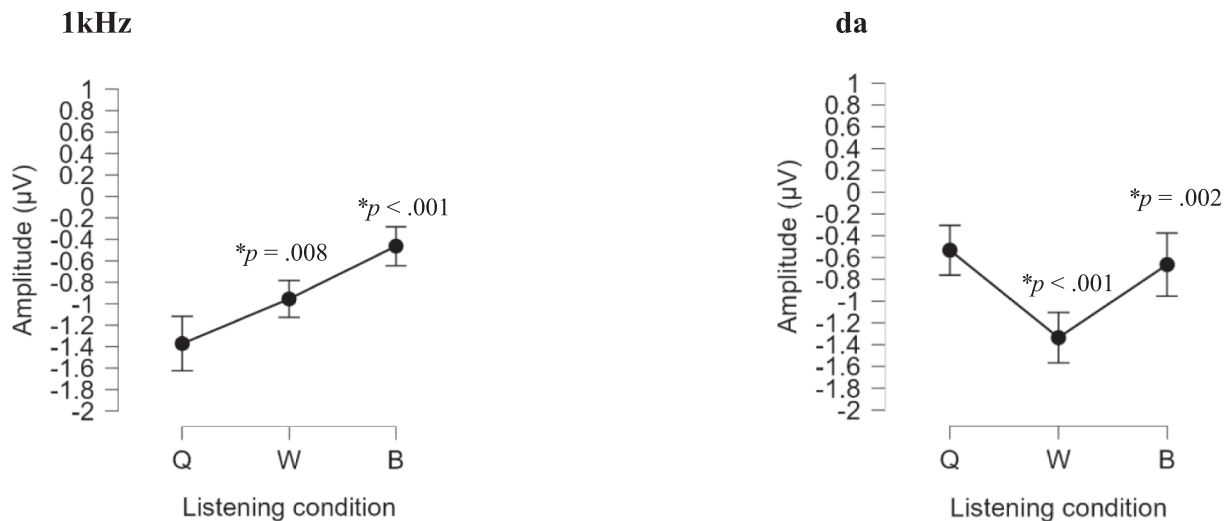


Fig. 4. The mean amplitude of N1, to da and 1 kHz, in quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.+.

Table 13

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on amplitude of P2.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	40.564 ^a	2 ^a	20.282 ^a	34.414 ^a	< 0.001 ^a	0.536
Residuals	22.396	38	0.589			
Stimuli	0.010	1	0.010	0.040	0.844	1.371 × 10 ⁻⁴
Residuals	4.981	19	0.262			
Listening condition * Stimuli	0.887	2	0.444	2.458	0.099	0.012
Residuals	6.857	38	0.180			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

significant interaction between stimuli and listening condition, $F(2, 38) = 27.299, p < 0.001, \eta^2 = 0.163$. Follow-up *t*-tests with Bonferroni correction showed significantly longer latency in non-speech noise versus quiet, babble noise versus quiet, and babble noise versus non-

speech noise for /da/ ($p < 0.001$). For the 1-kHz tone, P1 latency was marginally longer in non-speech noise than in quiet ($p = 0.070$; Fig. 8).

Frontocentral responses, N1 peak

Repeated-measures ANOVA (Table 17) revealed significant main effects of listening condition, $F(2, 38) = 199.449, p < 0.001, \eta^2 = 0.390$, and stimuli, $F(1, 19) = 286.171, p < 0.001, \eta^2 = 0.287$, as well as a significant interaction between stimuli and listening condition, $F(2, 38) = 142.724, p < 0.001, \eta^2 = 0.234$. Follow-up *t*-tests with Bonferroni correction confirmed the effect of listening condition, showing longer latency in non-speech noise versus quiet, babble noise versus quiet, and babble noise versus non-speech noise for both stimuli ($p < 0.01$; Fig. 9).

Frontocentral responses, P2 peak

Repeated-measures ANOVA (Table 18) revealed significant main effects of listening condition, $F(2, 38) = 177.444, p < 0.001, \eta^2 = 0.358$, and stimulus type, $F(1, 19) = 157.026, p < 0.001, \eta^2 = 0.277$, as well as a significant interaction between stimulus type and listening condition, $F(2, 38) = 153.546, p < 0.001, \eta^2 = 0.261$. Follow-up *t*-tests with Bonferroni correction confirmed the effect of listening condition. For /da/, P2 latency was significantly longer in non-speech noise versus quiet, babble noise versus quiet, and babble noise versus non-speech noise (p

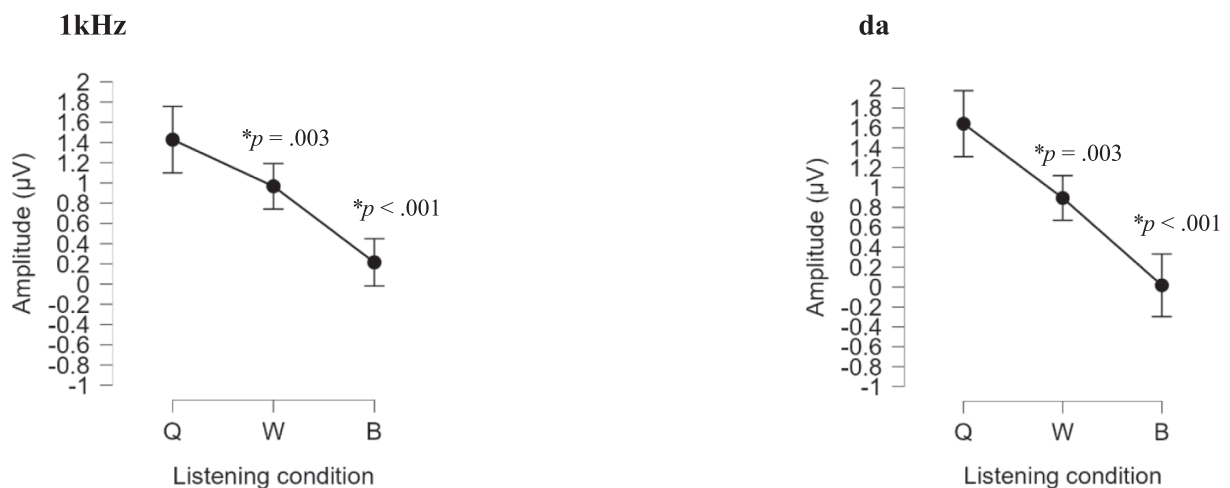


Fig. 5. The mean amplitude of P2, to da and 1 kHz, in quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.

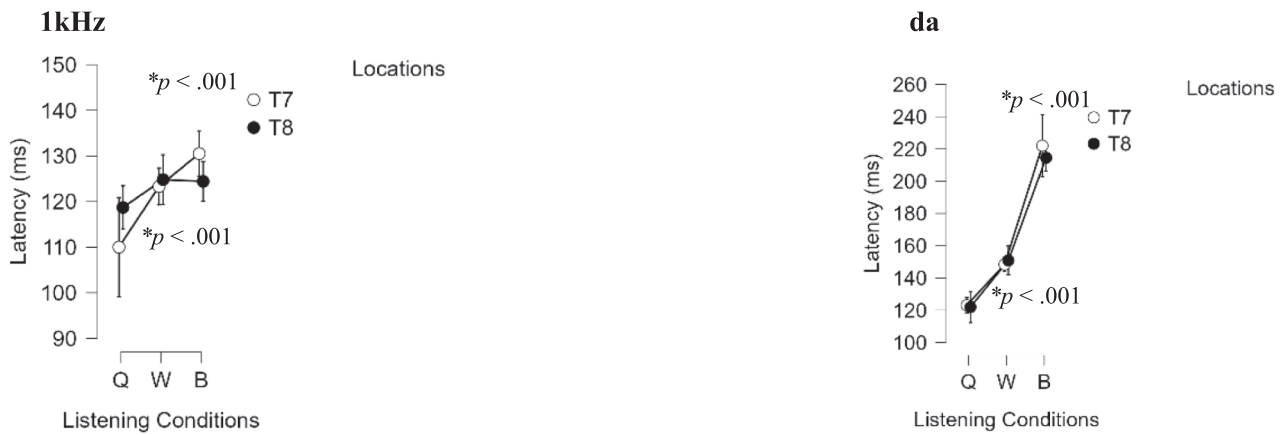


Fig. 6. The average of Ta latency to 1 kHz and da, in quiet (Q), non-speech noise (W) and babble noise (B), at T7 and T8. The most significant conditions have been marked with star symbol: *.

Table 14

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) and Electrode (T7 and T8) on latency of Ta.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	12,2533.104 ^a	2 ^a	61,266.552 ^a	14,6.499 ^a	< 0.001 ^a	0.328
Residuals	15,891.751	38	41,8.204			
Stimuli	10,3369.448	1	10,3369.448	41,7.083	< 0.001	0.277
Residuals	47,08.941	19	24,7.839			
Locations	6.393	1	6.393	0.014	0.906	1.712 × 10 ⁻⁵
Residuals	84,38.050	19	44,4.108			
Listening condition * Stimuli	75,866.829 ^a	2 ^a	37,933.415 ^a	83.397 ^a	< 0.001 ^a	0.203
Residuals	17,284.339	38	45,4.851			
Listening condition* Locations	12,79.774	2	63,9.887	3.435	0.043	0.003
Residuals	70,79.021	38	18,6.290			
Stimuli * Locations	17,1.417	1	17,1.417	0.389	0.540	4.590 × 10 ⁻⁴
Residuals	83,65.412	19	44,0.285			
Listening condition * Stimuli * Locations	32,2.063	2	16,1.032	0.751	0.479	8.624 × 10 ⁻⁴
Residuals	81,47.965	38	21,4.420			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated (p < 0.05).

Table 15

The results of Repeated Measures ANOVA evaluating the effect Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) and Electrode (T7 and T8) on latency of Tb.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening Condition	25,9640.558 ^a	2 ^a	12,9820.279 ^a	33,4.004 ^a	< 0.001 ^a	0.356
Residuals	14,769.775	38	38,8.678			
Stimuli	21,3785.704	1	21,3785.704	45,4.589	< 0.001	0.293
Residuals	89,35.379	19	47,0.283			
Location	88,5.504	1	88,5.504	2.392	0.138	0.001
Residuals	70,33.579	19	37,0.188			
Listening Condition * Stimuli	19,3382.408	2	96,691.204	37,1.992	< 0.001	0.265
Residuals	98,77.258	38	25,9.928			
Listening Condition * Location	66,0.058	2	33,0.029	1.589	0.217	9.040 × 10 ⁻⁴
Residuals	78,91.608	38	20,7.674			
Stimuli * Location	45,6.504	1	45,6.504	1.537	0.230	6.252 × 10 ⁻⁴
Residuals	56,42.246	19	29,6.960			
Listening Condition * Stimuli * Locations	38,6.808 ^a	2 ^a	19,3.404 ^a	1.082 ^a	0.349 ^a	5.298 × 10 ⁻⁴
Residuals	67,92.192	38	17,8.742			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated (p < 0.05).

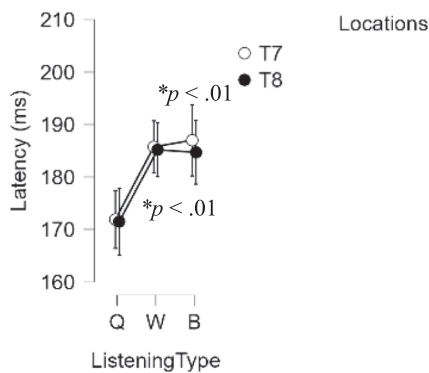
< 0.001; Fig. 12). For the 1-kHz tone, latency was significantly longer in non-speech noise versus quiet and in babble noise versus quiet (p < 0.001), with no significant difference between non-speech noise and babble noise (p = 1.000; Fig. 10).

Discussion

The aim of this study was to evaluate the effect of noise on cortical

auditory evoked potentials, particularly by comparing noise-induced changes between temporal and frontocentral components using various types of noise and stimuli. Given the different neural generators and developmental trajectories of these responses, we hypothesized that temporal and central responses would show distinct patterns. Consistent with our expectation, the effect of noise on temporal responses differed from that on frontocentral responses (Fig. 11). Our second hypothesis predicted that noise-induced enhancement of N1 would be observed

1kHz



da

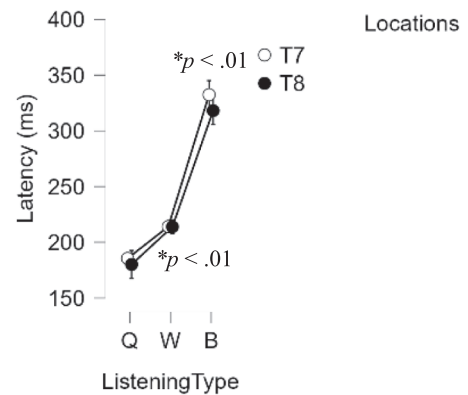


Fig. 7. The average of Tb latency to 1 kHz and da, in quiet (Q), non-speech noise (W) and babble noise (B), at T7 and T8. The most significant conditions have been marked with star symbol: *.

Table 16

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on latency of P1.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	11,908.717	2	59,54.358	83.045	< 0.001	0.327
Residuals	27,24.617	38	71.700			
Stimuli	10,982.533	1	10,982.533	28,1.426	< 0.001	0.301
Residuals	74,1.467	19	39.025			
Listening condition * Stimuli	59,41.017	2	29,70.508	27.299	< 0.001	0.163
Residuals	41,34.983	38	10,8.815			

Note. Type III Sum of Squares.

only with speech stimuli, not with non-speech stimuli, as speculated (Figurer 11A). The current study also showed larger Ta and Tb amplitudes in noise for speech stimuli. Supporting our third hypothesis, the

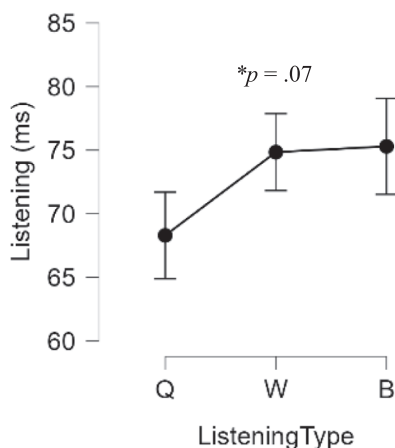
results revealed different patterns of T-complex modulation between electrodes T7 and T8 under certain conditions (Fig. 11A). Specifically, with non-speech stimuli, Ta amplitude was larger in noise at T8 than at T7 (Fig. 11B), whereas with speech stimuli, Tb amplitude increased in noise only at T8 (Fig. 11A). (See Table 19).

Pattern of changes in the temporal and frontocentral responses

Changes of amplitude

The results showed that noise-induced modulations in CAEP amplitude included both suppression and enhancement patterns, depending on the type of noise and the stimulus. The amplitudes of Ta and Tb were affected by background noise. Ta was reduced when non-speech stimuli were presented in noise compared to quiet. In contrast, Ta was enhanced in noise when the target stimulus was /da/, reaching significance in non-speech noise but not in babble noise. Tb was reduced in non-speech noise (not significant) but was significantly enhanced in babble noise when the target stimulus was /da/. The different Tb amplitude patterns observed in babble versus white noise may reflect differences in auditory scene analysis (ASA) demands (Bregman, 1990). ASA refers to object

1kHz



da

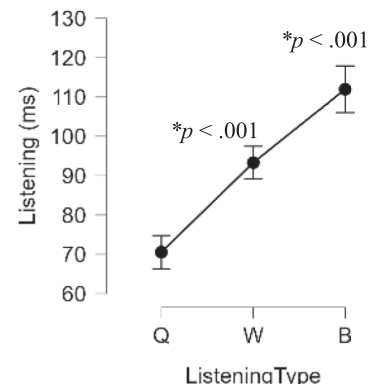


Fig. 8. The average of P1 latency to 1 kHz and da, in quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.

Table 17

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on latency of N1.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	61,255.017 ^a	2 ^a	30,627.508 ^a	19,9.449 ^a	< 0.001 ^a	0.390
Residuals	58,35.317	38	15,3.561			
Stimuli	44,969.408	1	44,969.408	26,8.171	< 0.001	0.287
Residuals	31,86.092	19	16,7.689			
Listening condition * Stimuli	36,791.217	2 ^a	18,395.608 ^a	14,2.724 ^a	< 0.001 ^a	0.234
Residuals	48,97.783	38	12,8.889			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

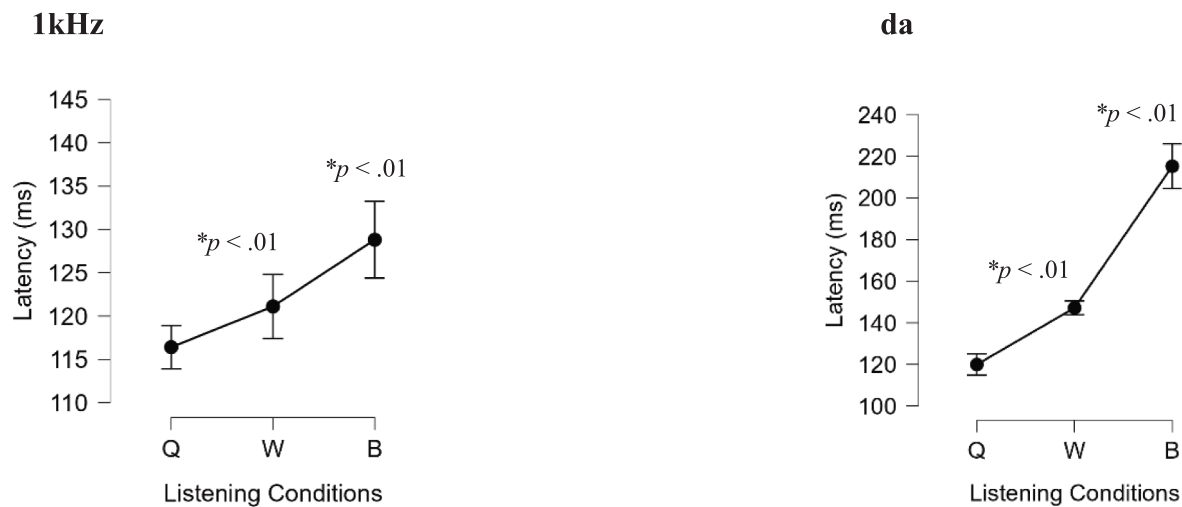


Fig. 9. The average of N1 latency to 1 kHz and da, in quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.

Table 18

The results of Repeated Measures ANOVA evaluating the effect of Listening conditions (Q, W, B), Stimuli (1 kHz and /da/) on latency of P2.

Cases	Sum of Squares	df	Mean Square	F	p	η^2
Listening condition	12,2802.450 ^a	2 ^a	61,401.225 ^a	17,7.444 ^a	< 0.001 ^a	0.358
Residuals	13,149.217	38	34,6.032			
Stimuli	95,034.408	1	95,034.408	15,7.026	< 0.001	0.277
Residuals	11,499.092	19	605.215			
Listening condition * Stimuli	89,694.117 ^a	2 ^a	44,847.058 ^a	15,3.546 ^a	< 0.001 ^a	0.261
Residuals	11,098.883	38	29,2.076			

Note. Type III Sum of Squares.

^a Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < 0.05$).

formation, segregation of speech streams and extracting meaning during a noisy environment (Bregman, 1990; Cunningham et al., 2002; Schnupp et al., 2010; Shinn-Cunningham & Best, 2008). Informational masking, such as babble noise, reflects the competing speech sounds that not only physically interfere with the target speech but also impair the separating of the sound of the speaker from the background speech (Douglas S Brungart et al., 2001). It is assumed that informational masking is more detrimental to speech understanding than energetic masking like white noise (Douglas S Brungart et al., 2001), due to failures of subject's attention leading to lower ability to attend to and segregate out the target speech in the presence of other similar speech sounds (D. S. Brungart et al., 2001; Shinn-Cunningham, 2008). So, it may be plausible to speculate that babble noise requires greater cortical processing to separate the target speech signal from the background that might be observed as a larger amplitude of Tb in babble noise than white noise in current study. To our knowledge, this is the first study to report the effects of noise on Ta and Tb components, with no previous results available for direct comparison. More research is needed to confirm these findings.

Among the central responses, the amplitudes of P1 and P2 showed a reduction pattern in noise. Suppression of frontocentral auditory evoked potential amplitudes has been reported in several previous studies (Androulidakis & Jones, 2006; Billings et al., 2017; Billings et al., 2009; McCullagh et al., 2012; Whiting et al., 1998). It has been suggested that the addition of background noise suppresses neural discharge and reduces the synchronized firing of neural populations, leading to a decrease in the magnitude of auditory responses (Cunningham et al., 2002; Kaplan-Neeman et al., 2006; McCullagh et al., 2012).

In the current study, changes in P1 were dependent on the type of noise. P1 amplitude was reduced in non-speech noise but not in babble noise. Reports on P1 amplitude in the literature are inconsistent, with some studies showing decreases in P1 under noise conditions (Bertoli et al., 2005; Papesh et al., 2015), although other studies have reported no change in P1 amplitude under noise conditions (Billings et al., 2009; Gott & Hughes, 1989). It has been suggested that variability in P1 amplitude modulation in noise may stem from individual differences as well as methodological differences in the acquisition and analysis of CAEP data across studies (Papesh et al., 2015). However, none of the

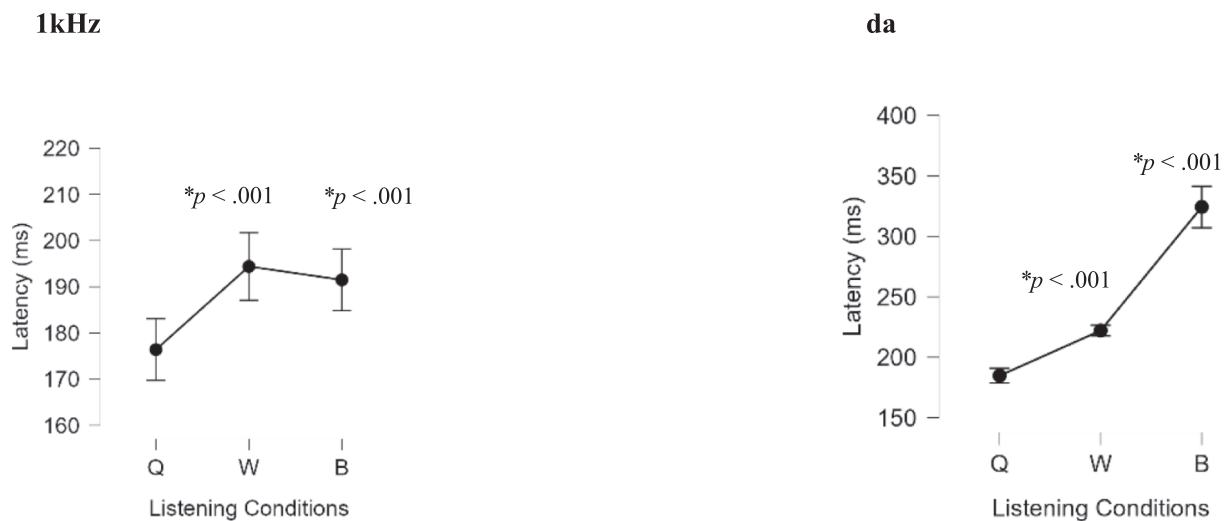


Fig. 10. The average of P2 latency to 1 kHz and da, quiet (Q), non-speech noise (W) and babble noise (B). The most significant conditions have been marked with star symbol: *.

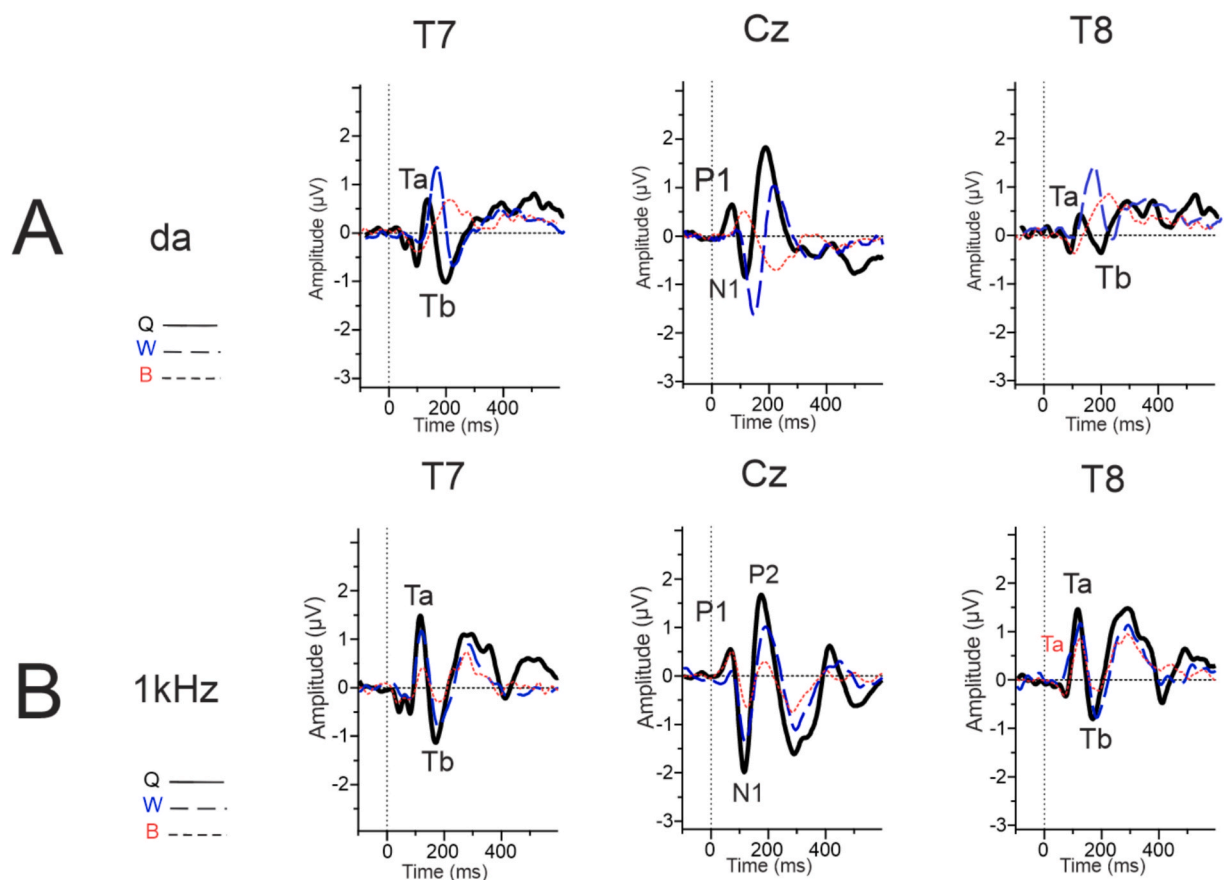


Fig. 11. Grand average of Auditory Cortical Responses to da (A) and 1 kHz (B), recorded at electrode Cz, T7 and T8, in quiet (black curve), non-speech noise (blue curve) and babble noise (red curve). A, with da, mostly the latency of all CAEPs was prolonged in noise. The amplitude of P1 and P2 were reduced. However, the amplitude of N1, Ta and Tb were reduced and increased in noise. Also, the Tb’s amplitude was larger at T8, than T7. B, with 1 kHz, the latency was prolonged, and the amplitude was reduced for most of the AEPs in noise. Also, the Ta’s amplitude was larger at electrode T8, than responses at electrode T7, in noisy conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

previous studies have reported such effect of noise type on P1 amplitude. In the current study, a reduction was observed only in the non-speech noise condition, suggesting that noise type influences the strength of the P1 response. This may indicate that the neural generators of P1 are more resistant to, and better adapted to, speech noise than to non-speech

noise, thereby maintaining the representation of auditory stimuli. Also, the non-significant changes in the results might be observed because of the small sample size ($n = 20$) of the current study. So, further research using the same paradigm with larger sample size is needed to confirm this interpretation.

Table 19
Summary of findings.

Component	Amplitude modulation in noise	Latency modulation in noise
P1	There was a reduction pattern in amplitude of P1 in noises, significantly only with speech stimulus in non-speech noise.	Longer latency in noises, it was significant only with speech stimuli.
N1	There were a reduction and an enhancement pattern in noises. The amplitude of N1 was decreased using 1 kHz, but it was increased using speech, significantly in non-speech noise.	Longer latency in noises.
P2	There was a reduction pattern in amplitude of P2, significantly in babble noise using both stimuli. In non-speech noise, the P2 amplitude was decreased significantly with speech.	Longer latency in noises, significantly with speech stimulus.
Ta	At T7 and with 1 kHz, there was a significant reduction pattern in noises, with /da/ there was a significant enhancement pattern in non-speech noise and no significant change in babble noise. At T8, no significant change on Ta with 1 kHz, and significantly larger amplitude in noises with /da/. Also, only with 1 kHz, there was significantly larger amplitude of Ta at electrode T8 than Ta recorded at electrode T7, in noises. No effect of location on Ta in quiet.	Longer latency in noises, significantly with speech stimulus.
Tb	In non-speech noise, there was reduction pattern in amplitude of Tb, non significantly using 1 kHz and significant using speech. In babble noise, the amplitude of Tb increased with speech stimuli only at T8 and decreased with 1 kHz at both electrodes T7 and T8.	Longer latency in noises, significantly with speech stimulus.

P2 amplitude was reduced in the presence of both babble and non-speech noise, for both speech and non-speech stimuli. This suppression of P2 amplitude is consistent with previous findings in the literature (Billings et al., 2009; Kaplan-Neeman et al., 2006; McCullagh et al., 2012; Papesh et al., 2015; Whiting et al., 1998). The majority of studies have demonstrated that P2 amplitude is consistently reduced, regardless of methodological differences, stimulus type, or noise type (Billings et al., 2009; Kaplan-Neeman et al., 2006; Whiting et al., 1998).

N1 was reduced for non-speech stimuli in noise but was enhanced for speech stimuli in the presence of non-speech noise. Consistent with expectations, the current findings replicate those of Duquette-Laplante et al. (2024), who reported decreased N1 amplitude for non-speech and increased amplitude for speech stimuli in noise. Additional parameters, such as binaural versus monaural presentation, fast versus slow stimulation rates (90 ms vs. 2000 ms), and the inclusion of low-frequency components (e.g., 1–30 Hz vs. 3–30 Hz high-pass filtering), may also contribute to the enhancement of N1 amplitude (Alain et al., 2009; Baltzell & Billings, 2014; Billings et al., 2009; Papesh et al., 2015). The current study demonstrated that stimulus type interacts with background noise to influence cortical responses. Specifically, background noise reduced N1 amplitude when the stimulus was a tone, whereas non-speech noise enhanced the N1 response when the stimulus was /da/. Moreover, N1 amplitude was not affected by babble noise when the stimulus was a 1-kHz tone, possibly because 1 kHz is a salient frequency within babble noise. This finding does not fully support previous explanations for the enhanced N1 observed with speech stimuli in non-speech noise but instead suggests that stimulus type; speech versus non-speech, plays a critical role in modulating changes in amplitude.

In addition to Duquette-Laplante et al. (2024), who reported enhanced N1 amplitude in noise with speech stimuli, two out of three other studies have also demonstrated this enhancement (Alain et al., 2009; Papesh et al., 2015; Parbery-Clark et al., 2011), used speech stimuli (Papesh et al., 2015; Parbery-Clark et al., 2011). Considering the consistency between the current study and previous research, speech stimuli appear to be an additional factor contributing to increased N1 amplitude in the presence of background noise. A possible explanation may lie in reports suggesting that modulation of the efferent auditory system in noise differs depending on stimulus type (Namasivayam et al., 2013; Namasivayam et al., 2015). It has been demonstrated that speech stimuli may exhibit greater release from suppression than tones (Namasivayam et al., 2015). As such, speech stimuli may trigger the efferent system in noise differently and/or more efficiently than non-speech stimuli (Bidelman & Howell, 2016). However, more research is needed to confirm this hypothesis.

Changes of latency

The results showed longer latencies for both frontocentral and temporal responses in noise compared to quiet. This finding replicates previous reports demonstrating delayed auditory evoked potentials in the presence of background noise (Billings et al., 2011; Billings et al., 2009; Benjamin Rich Zendel et al., 2015). Noise degrades the neural synchronization, leading to slower transmission and longer latency of auditory response (Anderson, Skoe, et al., 2010; Billings et al., 2009).

The comparison between temporal and frontocentral responses

This study, as one the first addressing the effect of noise on the T-complex components, has shown remarkable and novel finding of noise-induced changes on temporal responses, which were distinct from frontocentral responses. Most frontocentral responses were suppressed in noise, with N1 being the only component to show enhancement, which reached significance only in non-speech noise. However, both temporal components showed larger responses under certain noisy conditions, with Tb in particular exhibiting significant amplitude increases, most prominently in the presence of babble noise.

Babble noise is probably the closest noise to real-life listening environments. This result may support the idea of the T-complex indexing greater adaptation to real-life listening situations than the frontocentral responses. It may highlight the robust function of the T-complex in processing auditory information at the secondary auditory areas in noisy listening conditions compared to the frontal responses at the primary auditory cortex. As this is the first study reporting this result, more research is needed to confirm the distinctive processing of auditory information in noise occurring in primary and secondary auditory areas.

Effect of location (T7 vs. T8)

One of the interesting and novel findings of this study was the difference in noise-induced modulations between the right and left hemispheres. Both Ta and Tb showed significantly larger responses at T8 compared to T7 in at least one noisy listening condition, indicating greater activity in the right hemisphere than in the left under noise. No such hemispheric difference was observed in quiet, suggesting that this auditory lateralization is induced by noise. Rightward lateralization in noise has also been reported in the literature and is thought to reflect greater right-hemisphere involvement in processing auditory signals under degraded listening conditions (Shtyrov et al., 1998; Shtyrov et al., 1999; Wong et al., 2009). Greater activity in the right hemisphere is likely the result of additional compensatory processing that supports the understanding of impoverished speech (Bidelman & Dexter, 2015; Du et al., 2014). An additional explanatory framework for the observed lateralization involves hemispheric specialization in auditory speech processing (Poeppl, 2003; Zatorre & Belin, 2001). Classically, the spectro-temporal asymmetry model posits that the left hemisphere is

specialized for rapid temporal features characteristic of speech, whereas the right hemisphere preferentially processes spectral information, maybe tonal processing and music perception (Belin et al., 1998; Liégeois-Chauvel et al., 1999; Zatorre & Belin, 2001). However, this classical dichotomy has been refined by the *Asymmetric Sampling in Time* (AST) hypothesis, which proposes that speech processing is bilaterally organized, with hemispheric differences emerging from distinct temporal integration windows rather than strict domain specialization (Poeppel, 2003). According to the AST framework, the left hemisphere is preferentially tuned to fast temporal modulations, whereas the right hemisphere is more sensitive to slower temporal fluctuations that extend over longer integration windows (Abrams et al., 2008; Arnal et al., 2015; Giraud & Poeppel, 2012; Poeppel, 2003). Within this conceptualization, the noise-induced rightward lateralization observed in the present study is theoretically meaningful rather than incidental. Degraded listening conditions alter the acoustic structure of speech by reducing access to rapidly changing cues and increasing reliance on slower, more robust temporal information (Russo et al., 2004). Indeed, cortical neurons exhibit adaptive synchronization in noise, shifting their tracking toward lower temporal modulation rates (Ding & Simon, 2013; Kachlicka et al., 2022). From this perspective, the enhanced right-hemisphere response in noise may reflect an adaptive reweighting of cortical processing strategies, whereby the auditory system preferentially recruits neural mechanisms optimized for slower temporal integration. Previous CAEP studies have demonstrated rightward lateralization in auditory responses such as the mismatch negativity (MMN) (Shtyrov et al., 1998), N1 (Bidelman & Howell, 2016), or N400 (Benjamin Rich Zendel et al., 2015). This is the first study to report rightward lateralization in noise as indexed by the T-complex. Given that these responses are primarily generated in secondary auditory areas, this finding extends previous studies that demonstrated rightward lateralization in noise within the primary auditory cortex (Bidelman & Dexter, 2015; Bidelman & Howell, 2016).

Moreover, the current study showed that rightward lateralization of Ta was observed only with tones in noisy conditions, whereas rightward lateralization of Tb emerged with speech stimuli in noise. This may indicate that stimulus type influences auditory processing in noise and that speech and non-speech stimuli are processed differently within secondary auditory areas. Further research is needed to confirm this finding.

The novel results of this study showed the distinct noise-induced changes between temporal and frontocentral responses. This discrepancy may suggest the distinct roles of different auditory cortex structures in listening ability in noise. The stimuli and noise type interaction can affect the amplitude modulation of AEPs. Importantly, the Tb saw increased amplitude when noise was babble and stimuli was speech. It can show special adaptation of auditory processing for perception of speech in real-life noisy conditions. Furthermore, T-complex generators supported the rightward lateralization of cortical auditory processing in noise. This outcome can be utilized for clinical application purposes to evaluate the effect of noise at secondary auditory areas in clinical populations with communication disorders, such as people with auditory processing disorder. Future studies in normal-hearing children can bring more information regarding the effect of noise on T-complex. Also, according to the distinct results between temporal and frontocentral responses, it may be promising to examine the pattern of changes of these two responses in noise, in population who have listening difficulties in noise, like individuals with auditory processing disorder. Regarding the methodology, more research using various SNR with speech and non-speech stimuli can demonstrate if the increasing change of amplitude is observed in more favorable or effortful listening conditions.

Future directions

Future studies in normal-hearing children can bring more information regarding the effect of noise on T-complex. Also, according to the

distinct results between temporal and frontocentral responses, it may be promising to examine the pattern of changes of these two responses in noise, in population who have listening difficulties in noise, like individuals with auditory processing disorder. Regarding the methodology, more research using various SNR with speech and non-speech stimuli can demonstrate if the increasing change of amplitude is observed in more favorable or effortful listening conditions.

Declaration of generative AI and AI-assisted technologies in the writing process

No AI tools or services were used during the preparation of this work.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Zohreh Ahmadi: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shanna Kousaie:** Writing – review & editing. **Benjamin Rich Zendel:** Writing – review & editing. **Amineh Koravand:** Writing – review & editing, Visualization, Supervision, Software, Resources, Methodology, Investigation.

Ethics approval

The University of Ottawa Research Ethics Board approved this study, Ethic file number=H-07-24-10451. All participants received and signed a written consent form.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the participants for investing time in this study. Also, authors acknowledge Olivia Chanel Zupicic-Grsic and Félix Harvey for their valuable collaboration and contributions during the execution of this project and express their sincere gratitude to Dr. Kenneth Campbell for his expert guidance and generous support in setting up and refining the experimental procedures.

References

- Abrams, D.A., Nicol, T., Zecker, S., Kraus, N., 2008. Right-hemisphere auditory cortex is dominant for coding syllable patterns in speech. *J. Neurosci.* 28 (15), 3958–3965. <https://doi.org/10.1523/jneurosci.0187-08.2008>.
- Alain, C., Quan, J., McDonald, K., Van Roon, P., 2009. Noise-induced increase in human auditory evoked neuromagnetic fields. *Eur. J. Neurosci.* 30 (1), 132–142.
- Albrecht, R., Suchodoletz, W., Uwer, R., 2000. The development of auditory evoked dipole source activity from childhood to adulthood. *Clin. Neurophysiol.* 111 (12), 2268–2276. [https://doi.org/10.1016/s1388-2457\(00\)00464-8](https://doi.org/10.1016/s1388-2457(00)00464-8).
- Anderson, S., Chandrasekaran, B., Yi, H.G., Kraus, N., 2010. Cortical-evoked potentials reflect speech-in-noise perception in children. *Eur. J. Neurosci.* 32 (8), 1407–1413. <https://doi.org/10.1111/j.1460-9568.2010.07409.x>.
- Anderson, S., Skoe, E., Chandrasekaran, B., Kraus, N., 2010. Neural timing is linked to speech perception in noise. *J. Neurosci.* 30 (14), 4922–4926. <https://doi.org/10.1523/jneurosci.0107-10.2010>.

- Anderson, S., White-Schwoch, T., Parbery-Clark, A., Kraus, N., 2013. A dynamic auditory-cognitive system supports speech-in-noise perception in older adults. *Hear. Res.* 300, 18–32. <https://doi.org/10.1016/j.heares.2013.03.006>.
- Androulidakis, A.G., Jones, S.J., 2006. Detection of signals in modulated and unmodulated noise observed using auditory evoked potentials. *Clin. Neurophysiol.* 117 (8), 1783–1793. <https://doi.org/10.1016/j.clinph.2006.04.011>.
- Arnal, L.H., Poeppel, D., Giraud, A.-L., 2015. Chapter 5 - temporal coding in the auditory cortex. In: Aminoff, M.J., Boller, F., Swaab, D.F. (Eds.), *Handbook of Clinical Neurology*. Elsevier, pp. 85–98. <https://doi.org/10.1016/B978-0-444-62630-1.00005-6>.
- Baltzell, L.S., Billings, C.J., 2014. Sensitivity of offset and onset cortical auditory evoked potentials to signals in noise. *Clin. Neurophysiol.* 125 (2), 370–380. <https://doi.org/10.1016/j.clinph.2013.08.003>.
- Belin, P., Zilbovicius, M., Crozier, S., Thivard, L., Fontaine, A., Masure, M.C., Samson, Y., 1998. Lateralization of speech and auditory temporal processing. *J. Cogn. Neurosci.* 10 (4), 536–540. <https://doi.org/10.1162/089892998562834>.
- Benítez-Barrera, C.R., Key, A.P., Ricketts, T.A., Tharpe, A.M., 2021. Central auditory system responses from children while listening to speech in noise. *Hear. Res.* 403, 108165. <https://doi.org/10.1016/j.heares.2020.108165>.
- Bertoli, S., Smurzynski, J., Probst, R., 2005. Effects of age, age-related hearing loss, and contralateral cafeteria noise on the discrimination of small frequency changes: psychoacoustic and electrophysiological measures. *J. Assoc. Res. Otolaryngol.* 6 (3), 207–222. <https://doi.org/10.1007/s10162-005-5029-6>.
- Bidelman, G.M., Dexter, L., 2015. Bilinguals at the “cocktail party”: dissociable neural activity in auditory-linguistic brain regions reveals neurobiological basis for nonnative listeners’ speech-in-noise recognition deficits. *Brain Lang.* 143, 32–41. <https://doi.org/10.1016/j.bandl.2015.02.002>.
- Bidelman, G.M., Howell, M., 2016. Functional changes in inter- and intra-hemispheric cortical processing underlying degraded speech perception. *Neuroimage* 124 (Pt A), 581–590. <https://doi.org/10.1016/j.neuroimage.2015.09.020>.
- Billings, C.J., Bennett, K.O., Molis, M.R., Leek, M.R., 2011. Cortical encoding of signals in noise: effects of stimulus type and recording paradigm. *Ear Hear.* 32 (1), 53–60. <https://doi.org/10.1097/AUD.0b013e3181ec5c46>.
- Billings, C.J., Grush, L.D., Maamor, N., 2017. Acoustic change complex in background noise: phoneme level and timing effects. *Physiol. Rep.* 5 (20). <https://doi.org/10.14814/phy2.13464>.
- Billings, C.J., McMillan, G.P., Penman, T.M., Gille, S.M., 2013. Predicting perception in noise using cortical auditory evoked potentials. *J. Assoc. Res. Otolaryngol.* 14 (6), 891–903. <https://doi.org/10.1007/s10162-013-0415-y>.
- Billings, C.J., Tremblay, K.L., Stecker, G.C., Tolin, W.M., 2009. Human evoked cortical activity to signal-to-noise ratio and absolute signal level. *Hear. Res.* 254 (1), 15–24. <https://doi.org/10.1016/j.heares.2009.04.002>.
- Bishop, D.V., Anderson, M., Reid, C., Fox, A.M., 2011. Auditory development between 7 and 11 years: an event-related potential (ERP) study. *PLoS One* 6 (5), e18993. <https://doi.org/10.1371/journal.pone.0018993>.
- Bishop, D.V., Hardiman, M.J., Barry, J.G., 2012. Auditory deficit as a consequence rather than endophenotype of specific language impairment: electrophysiological evidence. *PLoS One* 7 (5), e35851. <https://doi.org/10.1371/journal.pone.0035851>.
- Bregman, A.S., 1990. *Auditory scene analysis: the perceptual organization of sound*. The MIT Press, 10.7551/mitpress/1486.001.0001.
- Brungart, D.S., Simpson, B.D., Ericson, M.A., Scott, K.R., 2001. Informational and energetic masking effects in the perception of multiple simultaneous talkers. *J. Acoust. Soc. Am.* 110 (5 Pt 1), 2527–2538. <https://doi.org/10.1121/1.1408946>.
- Brungart, D.S., Simpson, B.D., Ericson, M.A., Scott, K.R., 2001. Informational and energetic masking effects in the perception of multiple simultaneous talkers. *J. Acoust. Soc. Am.* 110 (5), 2527–2538.
- Bureš, Z., Voráček, J., Capková, D., Fuksa, J., Vencovský, V., Svobodová, V., Tóthová, D., Vojtová, M., Cha, S., Syka, J., Profant, O., 2025. Development of audiometric parameters throughout the lifespan. II: relationships between parameters. *Hear. Res.* 464, 109309. <https://doi.org/10.1016/j.heares.2025.109309>.
- Čeponienė, R., Alku, P., Westerfield, M., Torki, M., Townsend, J., 2005. ERPs differentiate syllable and nonphonetic sound processing in children and adults. *Psychophysiology* 42 (4), 391–406. <https://doi.org/10.1111/j.1469-8986.2005.00305.x>.
- Ceponiene, R., Rinne, T., Näätänen, R., 2002. Maturation of cortical sound processing as indexed by event-related potentials. *Clin. Neurophysiol.* 113 (6), 870–882. [https://doi.org/10.1016/s1388-2457\(02\)00078-0](https://doi.org/10.1016/s1388-2457(02)00078-0).
- Chaumon, M., Bishop, D.V., Busch, N.A., 2015. A practical guide to the selection of independent components of the electroencephalogram for artifact correction. *J. Neurosci. Methods* 250, 47–63.
- Chintanpalli, A., Jennings, S.G., Heinz, M.G., Strickland, E.A., 2012. Modeling the anti-masking effects of the olivocochlear reflex in auditory nerve responses to tones in sustained noise. *J. Assoc. Res. Otolaryngol.* 13 (2), 219–235. <https://doi.org/10.1007/s10162-011-0310-3>.
- Clayson, P.E., Baldwin, S.A., Larson, M.J., 2013. How does noise affect amplitude and latency measurement of event-related potentials (ERPs)? A methodological critique and simulation study. *Psychophysiology* 50 (2), 174–186. <https://doi.org/10.1111/psyp.12001>.
- Clunies-Ross, K.L., Brydges, C.R., Nguyen, A.T., Fox, A.M., 2015. Hemispheric asymmetries in auditory temporal integration: a study of event-related potentials. *Neuropsychologia* 68, 201–208.
- Clunies-Ross, K.L., Campbell, C., Ohan, J.L., Anderson, M., Reid, C., Fox, A.M., 2018. Hemispheric asymmetries in rapid temporal processing at age 7 predict subsequent phonemic decoding 2 years later: a longitudinal event-related potential (ERP) study. *Neuropsychologia* 111, 252–260. <https://doi.org/10.1016/j.neuropsychologia.2018.01.035>.
- Cunningham, J., Nicol, T., King, C., Zecker, S.G., Kraus, N., 2002. Effects of noise and cue enhancement on neural responses to speech in auditory midbrain, thalamus and cortex. *Hear. Res.* 169 (1–2), 97–111. [https://doi.org/10.1016/s0378-5955\(02\)00344-1](https://doi.org/10.1016/s0378-5955(02)00344-1).
- Ding, N., Simon, J.Z., 2013. Adaptive temporal encoding leads to a background-insensitive cortical representation of speech. *J. Neurosci.* 33 (13), 5728. <https://doi.org/10.1523/JNEUROSCI.5297-12.2013>.
- Dirks, D.D., Morgan, D.E., Dubno, J.R., 1982. A procedure for quantifying the effects of noise on speech recognition. *J. Speech Hear. Disord.* 47 (2), 114–123. <https://doi.org/10.1044/jshd.4702.114>.
- Du, Y., Buchsbaum, B.R., Grady, C.L., Alain, C., 2014. Noise differentially impacts phoneme representations in the auditory and speech motor systems. *Proc. Natl. Acad. Sci.* 111 (19), 7126–7131. <https://doi.org/10.1073/pnas.1318738111>.
- Duda-Milloy, V., Tavakoli, P., Campbell, K., Benoit, D.L., Koravand, A., 2019. A time-efficient multi-deviant paradigm to determine the effects of gap duration on the mismatch negativity. *Hear. Res.* 377, 34–43.
- Duquette-Laplante, F., Jutras, B., Néron, N., Fortin, S., Koravand, A., 2024. Exploring the differences between an immature and a mature human auditory system through auditory late responses in quiet and in noise. *Neuroscience* 545, 171–184. <https://doi.org/10.1016/j.neuroscience.2024.03.018>.
- Giraud, A.-L., Poeppel, D., 2012. Cortical oscillations and speech processing: emerging computational principles and operations. *Nat. Neurosci.* 15 (4), 511–517.
- Gott, P.S., Hughes, E.C., 1989. Effect of noise masking on the brain-stem and middle-latency auditory evoked potentials: central and peripheral components. *Electroencephalogr. Clin. Neurophysiol.* 74 (2), 131–138. [https://doi.org/10.1016/0168-5597\(89\)90018-x](https://doi.org/10.1016/0168-5597(89)90018-x).
- Groen, M.A., Alku, P., Bishop, D.V.M., 2008. Lateralisation of auditory processing in down syndrome: a study of T-complex peaks Ta and Tb. *Biol. Psychol.* 79 (2), 148–157. <https://doi.org/10.1016/j.biopsycho.2008.04.003>.
- Guinan Jr., J.J., 2006. Olivocochlear efferents: anatomy, physiology, function, and the measurement of efferent effects in humans. *Ear Hear.* 27 (6), 589–607. <https://doi.org/10.1097/01.aud.0000240507.83072.e7>.
- Haider, B., Häusser, M., Carandini, M., 2013. Inhibition dominates sensory responses in the awake cortex. *Nature* 493 (7430), 97–100. <https://doi.org/10.1038/nature11665>.
- Hämäläinen, J.A., Fosker, T., Szücs, D., Goswami, U., 2011. N1, P2 and T-complex of the auditory brain event-related potentials to tones with varying rise times in adults with and without dyslexia. *Int. J. Psychophysiol.* 81 (1), 51–59. <https://doi.org/10.1016/j.ijpsycho.2011.04.005>.
- Hecox, K.E., Patterson, J., Birman, M., 1989. Effect of broadband noise on the human brain stem auditory evoked response. *Ear Hear.* 10 (6). https://journals.lww.com/ear-hearing/fulltext/1989/12000/effect_of_broadband_noise_on_the_human_brain_stem.5.aspx.
- Hillyard, S.A., Hink, R.F., Schwent, V.L., Picton, T.W., 1973. Electrical signs of selective attention in the human brain. *Science* 182 (4108), 177–180. <https://doi.org/10.1126/science.182.4108.177>.
- Hine, J., Debener, S., 2007. Late auditory evoked potentials asymmetry revisited. *Clin. Neurophysiol.* 118 (6), 1274–1285. <https://doi.org/10.1016/j.clinph.2007.03.012>.
- Huffman, R.F., Henson Jr., O.W., 1990. The descending auditory pathway and acoustic motor systems: connections with the inferior colliculus. *Brain Res. Brain Res. Rev.* 15 (3), 295–323. [https://doi.org/10.1016/0165-0173\(90\)90005-9](https://doi.org/10.1016/0165-0173(90)90005-9).
- Jerger, J., & Musiek, F. (2000). Report of the Consensus Conference on the Diagnosis of Auditory Processing Disorders in School-Aged Children. *J Am Acad Audiol*, 11(9), 467-474.
- Kachlicka, M., Laffere, A., Dick, F., Tierney, A., 2022. Slow phase-locked modulations support selective attention to sound. *Neuroimage* 252, 119024. <https://doi.org/10.1016/j.neuroimage.2022.119024>.
- Kaplan-Neeman, R., Kishon-Rabin, L., Henkin, Y., Muchnik, C., 2006. Identification of syllables in noise: electrophysiological and behavioral correlates. *J. Acoust. Soc. Am.* 120 (2), 926–933. <https://doi.org/10.1121/1.2217567>.
- Kawase, T., Liberman, M.C., 1993. Antimasking effects of the olivocochlear reflex. I. Enhancement of compound action potentials to masked tones. *J. Neurophysiol.* 70 (6), 2519–2532. <https://doi.org/10.1152/jn.1993.70.6.2519>.
- Le Prell, C.G., Clavier, O.H., 2017. Effects of noise on speech recognition: challenges for communication by service members. *Hear. Res.* 349, 76–89. <https://doi.org/10.1016/j.heares.2016.10.004>.
- Lee, J.Y., Lee, J.T., Heo, H.J., Choi, C.H., Choi, S.H., Lee, K., 2015. Speech recognition in real-life background noise by young and middle-aged adults with normal hearing. *J. Audiol. Otol.* 19 (1), 39–44. <https://doi.org/10.7874/jao.2015.19.1.39>.
- Liégeois-Chauvel, C., de Graaf, J.B., Laguitton, V., Chauvel, P., 1999. Specialization of left auditory cortex for speech perception in man depends on temporal coding. *Cereb. Cortex* 9 (5), 484–496. <https://doi.org/10.1093/cercor/9.5.484>.
- Liégeois-Chauvel, C., Musolino, A., Badier, J.M., Marquis, P., Chauvel, P., 1994. Evoked potentials recorded from the auditory cortex in man: evaluation and topography of the middle latency components. *Electroencephalogr. Clin. Neurophysiol.* 92 (3), 204–214. [https://doi.org/10.1016/0168-5597\(94\)90064-7](https://doi.org/10.1016/0168-5597(94)90064-7).
- Lindenberger, U., Baltes, P.B., 1994. Sensory functioning and intelligence in old age: a strong connection. *Psychol. Aging* 9 (3), 339–355. <https://doi.org/10.1037/0882-7974.9.3.339>.
- Luck, S.J., 2012. *An introduction to the event-related potential technique*. MIT Press.
- Makeig, S., Jung, T.-P., Ghahremani, D., Sejnowski, T.J., 1996. Independent component analysis of simulated ERP data. *Institute for Neural Computation*. University of California: technical report INC-9606.
- Marian, V., Blumenfeld, H.K., Kaushanskaya, M., 2007. The language experience and proficiency questionnaire (LEAP-Q): assessing language profiles in bilinguals and

- multilinguals. *J. Speech Lang. Hear. Res.* 50 (4), 940–967. [https://doi.org/10.1044/1092-4388\(2007/067\)](https://doi.org/10.1044/1092-4388(2007/067)).
- McCullagh, J., Musiek, F.E., Shinn, J.B., 2012. Auditory cortical processing in noise in normal-hearing young adults. *Audiological Medicine* 10 (3), 114–121.
- Meyer, J., Dentel, L., Meunier, F., 2013. Speech recognition in natural background noise. *PLoS One* 8 (11), e79279. <https://doi.org/10.1371/journal.pone.0079279>.
- Näätänen, R., Picton, T., 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology* 24 (4), 375–425. <https://doi.org/10.1111/j.1469-8986.1987.tb00311.x>.
- Näätänen, R., Simpson, M., Loveless, N.E., 1982. Stimulus deviance and evoked potentials. *Biol. Psychol.* 14 (1), 53–98. [https://doi.org/10.1016/0301-0511\(82\)90017-5](https://doi.org/10.1016/0301-0511(82)90017-5).
- Namasivayam, A.K., Le, D.J., Hard, J., Lewis, S.E., Neufeld, C., van Lieshout, P., 2013. Peripheral auditory tuning for vowels. *J. Integr. Neurosci.* 12 (04), 461–474. <https://doi.org/10.1142/S0219635213500283>.
- Namasivayam, A.K., Wong, W.Y., Sharma, D., van Lieshout, P., 2015. Visual speech gestures modulate efferent auditory system. *J. Integr. Neurosci.* 14 (1), 73–83. <https://doi.org/10.1142/s0219635215500016>.
- Pang, E.W., Taylor, M.J., 2000. Tracking the development of the N1 from age 3 to adulthood: an examination of speech and non-speech stimuli. *Clin. Neurophysiol.* 111 (3), 388–397. [https://doi.org/10.1016/s1388-2457\(99\)00259-x](https://doi.org/10.1016/s1388-2457(99)00259-x).
- Papesh, M.A., Billings, C.J., Baltzell, L.S., 2015. Background noise can enhance cortical auditory evoked potentials under certain conditions. *Clin. Neurophysiol.* 126 (7), 1319–1330. <https://doi.org/10.1016/j.clinph.2014.10.017>.
- Parbery-Clark, A., Marmel, F., Bair, J., Kraus, N., 2011. What subcortical-cortical relationships tell us about processing speech in noise. *Eur. J. Neurosci.* 33 (3), 549–557. <https://doi.org/10.1111/j.1460-9568.2010.07546.x>.
- Picton, T.W., Alain, C., Woods, D.L., John, M.S., Scherg, M., Valdes-Sosa, P., Bosch-Bayard, J., Trujillo, N.J., 1999. Intracerebral sources of human auditory-evoked potentials. *Audiol. Neurootol.* 4 (2), 64–79. <https://doi.org/10.1159/000013823>.
- Pittman, A.L., Wiley, T.L., 2001. Recognition of speech produced in noise. *J. Speech Lang. Hear. Res.* 44 (3), 487–496. [https://doi.org/10.1044/1092-4388\(2001/038\)](https://doi.org/10.1044/1092-4388(2001/038)).
- Poeppl, D., 2003. The analysis of speech in different temporal integration windows: cerebral lateralization as 'asymmetric sampling in time'. *Speech Comm.* 41 (1), 245–255.
- Ponton, C., Eggermont, J.J., Khosla, D., Kwong, B., Don, M., 2002. Maturation of human central auditory system activity: separating auditory evoked potentials by dipole source modeling. *Clin. Neurophysiol.* 113 (3), 407–420. [https://doi.org/10.1016/s1388-2457\(01\)00733-7](https://doi.org/10.1016/s1388-2457(01)00733-7).
- Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2000. Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. *Clin. Neurophysiol.* 111 (2), 220–236. [https://doi.org/10.1016/s1388-2457\(99\)00236-9](https://doi.org/10.1016/s1388-2457(99)00236-9).
- Ross, B., Tremblay, K., 2009. Stimulus experience modifies auditory neuromagnetic responses in young and older listeners. *Hear. Res.* 248 (1–2), 48–59. <https://doi.org/10.1016/j.heares.2008.11.012>.
- Russo, N., Nicol, T., Musacchia, G., Kraus, N., 2004. Brainstem responses to speech syllables. *Clin. Neurophysiol.* 115 (9), 2021–2030. <https://doi.org/10.1016/j.clinph.2004.04.003>.
- Russo, N., Zecker, S., Trommer, B., Chen, J., Kraus, N., 2009. Effects of background noise on cortical encoding of speech in autism spectrum disorders. *J. Autism Dev. Disord.* 39 (8), 1185–1196. <https://doi.org/10.1007/s10803-009-0737-0>.
- Russo, N.M., Nicol, T.G., Zecker, S.G., Hayes, E.A., Kraus, N., 2005. Auditory training improves neural timing in the human brainstem. *Behav. Brain Res.* 156 (1), 95–103. <https://doi.org/10.1016/j.bbr.2004.05.012>.
- Scharf, B., Magnan, J., Chays, A., 1997. On the role of the olivocochlear bundle in hearing: 16 case studies. *Hear. Res.* 103 (1–2), 101–122. [https://doi.org/10.1016/s0378-5955\(96\)00168-2](https://doi.org/10.1016/s0378-5955(96)00168-2).
- Schnupp, J., Nelken, I., King, A.J., 2010. Auditory scene analysis. In: *Auditory Neuroscience: Making Sense of Sound*. The MIT Press, p. 0. <https://doi.org/10.7551/mitpress/7942.003.0007>.
- Shinn-Cunningham, B.G., 2008. Object-based auditory and visual attention. *Trends Cogn. Sci.* 12 (5), 182–186. <https://doi.org/10.1016/j.tics.2008.02.003>.
- Shinn-Cunningham, B.G., Best, V., 2008. Selective attention in normal and impaired hearing. *Trends Amplif.* 12 (4), 283–299. <https://doi.org/10.1177/1084713808325306>.
- Shtyrov, Y., Kujala, T., Ahveninen, J., Tervaniemi, M., Alku, P., Ilmoniemi, R.J., Näätänen, R., 1998. Background acoustic noise and the hemispheric lateralization of speech processing in the human brain: magnetic mismatch negativity study. *Neurosci. Lett.* 251 (2), 141–144. [https://doi.org/10.1016/s0304-3940\(98\)00529-1](https://doi.org/10.1016/s0304-3940(98)00529-1).
- Shtyrov, Y., Kujala, T., Ilmoniemi, R.J., Näätänen, R., 1999. Noise affects speech-signal processing differently in the cerebral hemispheres. *Neuroreport* 10 (10), 2189–2192. <https://doi.org/10.1097/00001756-199907130-00034>.
- Silva, D.M.R., Rothe-Neves, R., Melges, D.B., 2020. Long-latency event-related responses to vowels: N1-P2 decomposition by two-step principal component analysis. *Int. J. Psychophysiol.* 148, 93–102. <https://doi.org/10.1016/j.ijpsycho.2019.11.010>.
- Song, J.H., Skoe, E., Banai, K., Kraus, N., 2011. Perception of speech in noise: neural correlates. *J. Cogn. Neurosci.* 23 (9), 2268–2279. <https://doi.org/10.1162/jocn.2010.21556>.
- Tomchik, S.M., Lu, Z., 2006. Modulation of auditory signal-to-noise ratios by efferent stimulation. *J. Neurophysiol.* 95 (6), 3562–3570. <https://doi.org/10.1152/jn.00063.2006>.
- Tonnquist-Uhlen, I., Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2003. Maturation of human central auditory system activity: the T-complex. *Clin. Neurophysiol.* 114 (4), 685–701. [https://doi.org/10.1016/s1388-2457\(03\)00005-1](https://doi.org/10.1016/s1388-2457(03)00005-1).
- Uhlén, I.T., Borg, E., Persson, H.E., Spens, K.E., 1996. Topography of auditory evoked cortical potentials in children with severe language impairment: the N1 component. *Electroencephalogr. Clin. Neurophysiol.* 100 (3), 250–260. [https://doi.org/10.1016/0168-5597\(95\)00256-1](https://doi.org/10.1016/0168-5597(95)00256-1).
- Wagner, M., Roychoudhury, A., Campanelli, L., Shafer, V.L., Martin, B., Steinschneider, M., 2016. Representation of spectro-temporal features of spoken words within the P1-N1-P2 and T-complex of the auditory evoked potentials (AEP). *Neurosci. Lett.* 614, 119–126. <https://doi.org/10.1016/j.neulet.2015.12.020>.
- Whiting, K.A., Martin, B.A., Stapells, D.R., 1998. The effects of broadband noise masking on cortical event-related potentials to speech sounds /ba/ and /da. *Ear Hear.* 19 (3). https://journals.lww.com/ear-hearing/fulltext/1998/06000/the_effects_of_broadband_noise_masking_on_cortical.5.aspx.
- Wolpaw, J.R., Penry, J.K., 1975. A temporal component of the auditory evoked response. *Electroencephalogr. Clin. Neurophysiol.* 39 (6), 609–620. [https://doi.org/10.1016/0013-4694\(75\)90073-5](https://doi.org/10.1016/0013-4694(75)90073-5).
- Wong, P.C., Jin, J.X., Gunasekera, G.M., Abel, R., Lee, E.R., Dhar, S., 2009. Aging and cortical mechanisms of speech perception in noise. *Neuropsychologia* 47 (3), 693–703. <https://doi.org/10.1016/j.neuropsychologia.2008.11.032>.
- Zatorre, R.J., Belin, P., 2001. Spectral and temporal processing in human auditory cortex. *Cereb. Cortex* 11 (10), 946–953. <https://doi.org/10.1093/cercor/11.10.946>.
- Zendel, B.R., Tremblay, C.-D., Belleville, S., Peretz, I., 2015. The impact of musicianship on the cortical mechanisms related to separating speech from background noise. *J. Cogn. Neurosci.* 27 (5), 1044–1059.