Agreement Between Evoked Potentials and Behavioral Thresholds Using LS-Chirp and 1 kHz Tone Burst in Normal-Hearing Adults: A Pilot Study

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ABSTRACT

Background Auditory evoked potentials (AEPs), including the auditory brainstem response (ABR) and cortical auditory evoked potential (CAEP), are widely used to estimate hearing thresholds in individuals unable to provide behavioral responses. However, it remains unclear whether brainstem or cortical activity better reflects perceptual thresholds, and how stimulus characteristics influence this relationship. This study investigated the agreement between evoked potentials and behavioral thresholds using different stimuli and presentation rates.

Methods Two experiments examined agreement between AEPs and behavioral thresholds. Experiment 1 (n = 8 ears) used LS CE-Chirp stimuli at 33.3 stimuli/second. Experiment 2 (n = 12 ears) used 1 kHz tone burst stimuli and examined three conditions: behavioral thresholds at 33.3 stimuli/second (Experiment 2a), behavioral thresholds at 1.0 stimuli/second (Experiment 2b), and standard 1 kHz pure tone audiometry (Experiment 2c). Different adult groups (≥18 years) were recruited for each experiment. Behavioral thresholds were obtained via the Hughson–Westlake method. Thresholds were compared using Wilcoxon signed-rank tests.

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Results Agreement patterns varied systematically with stimulus characteristics. For LS CE-Chirp stimuli at 33.3 stimuli/second, ABR thresholds showed significantly better agreement with behavioral thresholds than CAEP thresholds ($p < 0.05$). For 1 kHz tone burst stimuli at 33.3 stimuli/second, no significant difference was observed between ABR and CAEP agreement with behavioral thresholds ($p > 0.05$). However, at 1.0 stimuli/second, CAEP thresholds demonstrated significantly better agreement with behavioral thresholds than ABR thresholds ($p < 0.05$). Both ABR and CAEP thresholds showed comparable agreement with clinical 1 kHz pure tone audiometry thresholds ($p > 0.05$).

Conclusion These preliminary findings demonstrate that both stimulus type and presentation rate influence threshold estimation, with slower rates favoring cortical-behavioral agreement and faster rates favoring brainstem-behavioral agreement. These context-dependent patterns may guide measurement strategies and support their use in the identification of auditory dysfunction. Further research with larger samples is needed to validate these findings and establish their clinical applicability.

KEYWORDS: ABR, CAEP, LS CE-chirp, 1 kHz tone burst, behavioral hearing thresholds

The auditory evoked potential (AEP), recorded across peripheral and central auditory pathways, is widely used as an objective measure to estimate hearing thresholds. The behavioral hearing threshold, often regarded as the gold standard in clinical audiology, is defined as the lowest intensity at which an individual detects a sound 50% of the time (Katz et al., 2015). While a behavioral measure directly reflects auditory perception, it requires active participation and consistent responses, which are not feasible in populations such as infants, individuals with developmental disabilities, or those with nonorganic hearing loss (Gabr, 2024; Hall, 2016; Lightfoot, 2016; Punch et al., 2016).

In such cases, AEPs provide valuable alternatives for threshold estimation and early detection and intervention of hearing loss by capturing neural activity from the cochlea to the cortex (Hall, 2016). Specifically, the auditory brainstem response (ABR) primarily reflects neural activity from the auditory nerve and brainstem, whereas the cortical auditory evoked potential (CAEP) represents higher-order cortical processing, offering insights into auditory perception (Hood, 1998; Hyde, 1997; Martin et al., 2007).

Recent advancements in stimulus design, particularly the Level-Specific Clause Elberling–Chirp (LS CE-Chirp), have aimed to enhance neural synchrony by compensating for cochlear travel time, thereby improving response amplitude and reliability of evoked responses across frequency ranges (Dau et al., 2000). While LS CE-Chirp has demonstrated advantages in ABR applications, tone burst stimuli remain widely used for their frequency specificity and established clinical utility (Gorga et al., 2006). Previous research has reported that the CAEP threshold obtained with tone burst stimuli may provide more accurate threshold estimation with pure tone audiometry (PTA) thresholds than ABR thresholds, with up to 94% of estimates within 10 to 15 dB of PTA thresholds (Lightfoot & Kennedy, 2006).

However, it remains unclear whether behavioral thresholds are more closely associated with brainstem activity (as captured by ABR) or cortical activity (as reflected in CAEP). This distinction is clinically important, as CAEP responses are thought to better reflect auditory perception and higher-order processing, whereas ABR responses provide a more direct measure of early-stage auditory pathway integrity (Hyde, 1998; Tremblay & Billings, 2011).

Stimulus characteristics, such as duration and presentation rate, may significantly influence ABR and CAEP responses, and thus threshold detection. ABR responses are typically optimized by brief, moderately rapid stimuli (e.g., click and chirp), presented at rates of more than 10 stimuli/second to promote neural synchrony, although excessively fast rates can reduce amplitude and prolong latencies (Dzulkarnain et al., 2013; McKnight et al., 2018). In contrast, CAEP requires longer durations of stimuli (e.g., tone burst and speech) presented at slower rates (~1 stimulus/second) to elicit reliable responses, as rapid presentation may compromise waveform clarity (Lightfoot, 2016; Mukari et al., 2020).

Despite ABR and CAEP having been extensively studied in relation to behavioral thresholds obtained through PTA, no studies to date have directly compared behavioral thresholds measured by PTA with behavioral thresholds measured using stimuli presented via the AEP system. Previous research has demonstrated good agreement between ABR, CAEP, and PTA thresholds. Although this supports the clinical use of ABR and CAEP for estimating PTA thresholds, particularly for applications such as hearing aid fitting, it does not explain which auditory processing level (brainstem vs. cortical) primarily contributes to behavioral threshold detection.

Discrepancies between ABR, CAEP, and PTA thresholds may partly stem from differences in calibration units, such as dB HL used in PTA versus dB nHL used in ABR and CAEP (Canale et al., 2012; Dabbous et al., 2020; Dzulkarnain et al., 2020; Lightfoot & Kennedy, 2006; Lim et al., 2023; Rahne & Ehelebe, 2014; Tan et al., 2025; Xu et al., 2014). In addition, stimulus type differs across methods; PTA typically employs pure tones, whereas ABR and CAEP often utilize clicks, tone bursts, or chirps.

To better understand how different auditory processing levels contribute to behavioral threshold detection, it is important to control for calibration units and stimulus type variables. Standardizing both variables by presenting identical stimuli (e.g., LS-chirp or 1 kHz tone burst) through the AEP system during behavioral testing may provide clearer insights into the relationship between brainstem and cortical responses and perceptual behavioral thresholds. Clarifying the relationship between auditory processing levels and perceptual thresholds may improve threshold estimation accuracy and support the use of objective measures to identify site of lesion by determining which processing level shows better agreement with perceptual hearing thresholds.

Therefore, this study aims to investigate the agreement between CAEP, ABR, and behavioral thresholds in normal-hearing adults by systematically examining the effects of stimulus characteristics (stimulus type, duration, and presentation rate) on threshold detection across different levels of auditory processing. Two experiments were designed to control for previously identified confounding variables (stimulus type, duration, and presentation rate) while exploring the fundamental question of whether brainstem or cortical activity more closely corresponds to behavioral threshold detection.

Experiment 1 examines threshold agreement using LS CE-Chirp stimuli (~5 ms duration) presented at different stimulus rates based on different AEP measurements (33.1/second for ABR, 1/second for CAEP, and 33.1 for the behavioral threshold). The LS CE-Chirp was selected for its ability to compensate for cochlear travel time and enhance neural synchrony, particularly at the brainstem level (Dau et al., 2000). It was hypothesized that ABR thresholds would demonstrate superior agreement with behavioral thresholds compared with CAEP thresholds, either due to the primary contribution of brainstem-level activity to threshold detection or the stimulus-specific advantages of LS CE-Chirp in optimizing brainstem responses.

Experiment 2 was designed to validate and extend findings from Experiment 1 using 1 kHz tone burst stimuli with longer durations (ABR: 5 ms rise/fall times with a brief plateau; CAEP: 20 ms rise/fall times with 50 ms plateau). Additionally, behavioral thresholds were measured at two presentation rates (33.3 and 1.0 stimuli per second) that correspond to the rates typically used for ABR and CAEP testing, respectively. This design allows for direct comparison of behavioral responses using rates that match each evoked potential paradigm. It was hypothesized that if the pattern observed in Experiment 1 persists (i.e., ABR shows better agreement with behavioral thresholds compared with CAEP, or vice versa) despite using longer stimulus durations and controlling for presentation rate, this would provide evidence for which auditory processing level (brainstem or cortical) genuinely contributes to behavioral threshold detection.

Through the control of calibration units and stimulus presentation using identical AEP systems across all measurements, this study aims to clarify the relative contributions of different auditory processing levels to perceptual threshold detection and enhance the clinical application of evoked potentials assessment.

METHODS

Study Design

This cross-sectional study consisted of two experiments to evaluate the agreement between evoked potentials and behavioral hearing assessments. Hearing thresholds were determined for each ear separately (monoaurally) using ABR, CAEP, and behavioral audiometry measurements.

Participants

Ten adult female volunteers with normal hearing were recruited through convenience sampling. Participants ranged in age from 19 to 38 years. Experiment 1 included eight ears from four participants (median age: 34 years, IQR = 3.25 years), and Experiment 2 included 12 ears from six participants (median age: 21.5 years, IQR = 3.00 years). Different participant groups were used in Experiments 1 and 2 due to feasibility constraints, as some participants from Experiment 1 were unavailable to continue in Experiment 2. Both groups consisted of adults above 20 years of age, representing populations with fully mature auditory processing systems. Brainstem auditory pathways mature by approximately 2 years of age and are fully developed by childhood (age: 5–11 years), while cortical auditory functions continue maturing through adolescence (Fitzroy et al., 2015; Rosenhall et al., 1985; Skoe et al., 2015; Wunderlich et al., 2006). Given that both groups consisted of adults with expected mature auditory systems, neurological development would not be expected to influence the findings. This study was approved by the International Islamic University Malaysia Research Ethics Committee, and all participants provided written informed consent.

Inclusion Criteria

1. No abnormalities of the ear canal or tympanic membrane on otoscopic examination.
2. Bilateral normal hearing thresholds (≤20 dB HL) across 0.25 to 8 kHz measured using pure-tone audiometry (PTA).
3. Bilateral Type A tympanograms indicating normal middle-ear function.
4. Ability to cooperate with the study procedures.

Exclusion Criteria

Participants were excluded if they (1) were restless or unable to complete ABR or CAEP testing or (2) reported difficulty hearing in noise, which could indicate possible hidden hearing loss despite normal audiometric thresholds.

Instruments

Three general procedures were used:

1. ABR
2. CAEP
3. Behavioral audiometry testing

General Procedures

ABR TESTING PROCEDURE

Participants were instructed to lie down and remain relaxed to minimize noise and muscle artifacts. After skin preparation with NuPrep gel, electrodes were placed at the high forehead (Fz) as the noninverting electrode, the lower forehead (Fpz) as the ground electrode, and the right and left mastoids (M1/M2) as the inverting electrodes. Electrode impedance was maintained below 5 kΩ to ensure optimal common-mode rejection.

ABRs were recorded using a two-channel recording with alternating polarity at 33.3 stimuli/second. Responses were averaged using Bayesian-weighted averaging until the residual noise level reached 40 nanovolts, with a maximum of 4,000 sweeps. The artifact rejection threshold was set at 40 μV. ABRs were considered present if the signal-to-noise ratio (SNR) exceeded 3. Each recording was repeated twice to confirm repeatability. The ABR threshold was defined as the lowest stimulus intensity that produced a reproducible wave V. Thresholds were compiled in a standardized table across participants to enable comparison with CAEP and behavioral measures, addressing the study objectives.

CAEP TESTING PROCEDURE

For the CAEP assessment, participants were instructed to relax, refrain from excessive movement, and ignore the auditory stimuli. To maintain a calm but wakeful state and minimize attentional effects on cortical responses, they were allowed to watch a muted subtitled movie.

Electrode preparation and placement followed the same ABR procedure, except the noninverting electrode was placed at the vertex (Cz). CAEP was recorded using a two-channel recording with alternating polarity at 1 stimulus/second. Responses were band-pass filtered from 1 to 30 Hz and averaged across 100 stimuli. The artifact rejection was set at 40 μV, and the notch filter was disabled.

Stimuli were initially presented at 60 dB nHL. If a clear response was observed, the intensity was reduced by 20 dB; if no response was observed, it was increased in 5 dB steps to determine the threshold. Each response was recorded twice to verify waveform repeatability and improve SNR. A CAEP threshold was defined as the lowest stimulus level that produced a repeatable waveform with a minimum amplitude of 2 μV and an SNR greater than 2.5. CAEP thresholds were compiled in a standardized table across participants for comparison with ABR and behavioral measures, fulfilling the study objectives.

BEHAVIORAL AUDIOMETRY TESTING PROCEDURE

Behavioral hearing thresholds were obtained using the Hughson–Westlake method with stimuli presented using insert phones. Participants were instructed to raise their hand in response to the presented stimuli. PTA thresholds were recorded on a standard audiogram, while LS CE-Chirp thresholds and 1 kHz tone burst thresholds were recorded on a standardized response sheet. Behavioral thresholds were defined as the lowest intensity level at which a response was reliably observed at least 50% of the time, confirmed by a minimum of two ascending responses.

Experimental Protocol

EXPERIMENT 1: LS CE-CHIRP PROTOCOL

ABR, CAEP, and behavioral audiometry procedures were conducted according to the procedures described in Sections ABR, CAEP, and Behavioral Audiometry using the LS CE-Chirp stimulus. The stimulus characteristics of LS CE-Chirp are summarized in Table 1. Tests were conducted on the same day in a randomized order across participants. It is important to note that for behavioral threshold measurements, the LS CE-Chirp stimulus was presented at a rate of 33.3 stimuli per second. The LS CE-Chirp was presented via the AEP

Table 1 Summary of parameters used in Experiments 1 and 2

Test	Parameter	Experiment 1	Experiment 2
ABR	Stimulus type	LS CE-chirp	1 kHz tone burst
	Stimulus rise and fall time; plateau	0 and 5 ms; 0 ms	5 ms sine wave
	Stimulus rate	33.3 stimuli/s	33.3 stimuli/s
CAEP	Stimulus type	LS CE-chirp	1 kHz tone burst
	Stimulus rise and fall time; plateau	0 and 5 ms; 0 ms	20 ms; 50 ms
	Stimulus rate	1.0 stimuli/s	1.0 stimuli/s
Behavioral threshold	Stimulus type	LS CE-chirp	1 kHz tone Burst
	Stimulus rate	33.3 stimuli/s	33.3 stimuli/s and 1.0 stimuli/s

system to match the stimulus delivery mode used in ABR and CAEP testing.

EXPERIMENT 2: 1 KHZ TONE BURST PROTOCOL

ABR and CAEP were conducted following the procedures described in Sections ABR and CAEP, respectively, using a 1 kHz tone burst stimulus. The stimulus characteristics of the 1 kHz tone burst are summarized in Table 1. Tests were conducted on the same day in a randomized order across participants.

For behavioral audiometry, three threshold measurements were obtained using: (1) a 1 kHz tone burst presented via the AEP system at 33.3 stimuli per second, corresponding to the ABR rate (Experiment 2a); (2) a 1 kHz tone burst at 1 stimulus per second, corresponding to the CAEP rate (Experiment 2b); and (3) standard 1 kHz pure tone audiometry (PTA) using conventional audiometric procedures (Experiment 2c). This approach allowed behavioral thresholds to be obtained under stimulus conditions matched to those used in ABR and CAEP, enabling direct comparisons between evoked potentials and behavioral measures at both brainstem and cortical levels.

Data Analysis

The only variable examined in this study was the hearing threshold. Agreement between AEP (ABR and CAEP) and behavioral thresholds was determined by comparing the thresholds across ABR, CAEP, and behavioral audiometry measurements. Threshold differences were computed as follows:

i. Experiment 1:
- Agreement between CAEP, ABR, and behavioral thresholds using LS CE-Chirp at 33.3 stimuli per second:
  1. ABR threshold: behavioral threshold at 33.3 stimuli/second
  2. CAEP threshold: behavioral threshold at 33.3 stimuli/second

ii. Experiment 2:
- Agreement between CAEP, ABR, and behavioral thresholds using a 1 kHz tone burst at 33.3 stimuli per second:
  1. ABR threshold: behavioral threshold at 33.3 stimuli/second
  2. CAEP threshold: behavioral threshold at 33.3 stimuli/second
- Agreement between CAEP, ABR, and behavioral thresholds using a 1 kHz tone burst at two different stimulus rates (33.3 and 1.0 stimuli per second):
  1. Behavioral threshold 33.3 stimuli/second—behavioral threshold 1.0 stimuli/second
  2. CAEP threshold: behavioral threshold at 1.0 stimuli/second
  3. ABR threshold: behavioral threshold at 33.3 stimuli/second
- Agreement between CAEP, ABR, and behavioral PTA thresholds at 1 kHz:
  1. ABR threshold: behavioral PTA 1 kHz
  2. CAEP threshold: behavioral PTA 1 kHz

Data were coded and entered using Jamovi Version 2.3 (The Jamovi Project 2022). Normality of the data was assessed using the Shapiro–Wilk test and visual inspection of normality plots. Results indicated that the data were not normally distributed. Thus, comparison of median and interquartile ranges (IQR) between paired variables was performed using the nonparametric Wilcoxon signed-rank test. *p*-Values less than 0.05 with a 95% confidence interval were considered statistically significant. Effect sizes will be interpreted according to Cohen's benchmarks: 0.2 = small, 0.5 = medium, 0.8 = large (Cohen, 2013).

RESULTS

Experiment 1: Agreement Between ABR, CAEP, and Behavioral Thresholds Using LS CE-Chirp at 33.3 Stimuli Per Second

The results of Experiment 1, including median and IQR, are presented in Table 2. For the LS CE-Chirp stimulus, the descriptive analysis showed that the CAEP threshold was higher than the ABR threshold, and both the CAEP and ABR thresholds were higher than the behavioral thresholds. Table 3 displays the median and IQR of the comparison between the ABR and CAEP thresholds and the behavioral threshold across different stimuli.

Table 2 Descriptive statistics of all measures included in the analysis

Stimuli	Variables	Median ± IQR (dB nHL)
1. LS CE-chirp ($n = 8$)	Behavioral threshold (33.3/s)	-2.50 ± 6.25
	ABR threshold (33.3/s)	10.0 ± 10.0
	CAEP threshold (1.0/s)	20.0 ± 1.25
2. 1 kHz tone burst ($n = 12$)	Behavioral threshold (33.3/s)	5.00 ± 6.25
	Behavioral threshold (1.0/s)	15.0 ± 5.00
	ABR threshold (33.3/s)	22.5 ± 5.00
	CAEP threshold (1.0/s)	25.0 ± 5.00
3. Pure Tone ($n = 12$)	PTA 1 kHz threshold	10.0 ± 5.00

Table 3 The *p*-values of the post hoc Wilcoxon signed-rank test and the statistic value for the differences between the behavioral threshold, ABR threshold, and CAEP threshold

Experiment	Variables (threshold)	Median difference (IQR)	*p*-Value	Statistic	Effect size
1. LS CE-Chirp ($n = 8$)	ABR- behavioral (33.3 stimuli/s)	7.50 (11.3)	0.010[a]	0.00	−1.00
	CAEP- behavioral (33.3 stimuli/s)	20.0 (11.3)			
2. 1 kHz Tone Burst	ABR- behavioral (33.3 stimuli/s)	15.0 (6.25)	0.516	13.0	−0.278
($n = 12$)	CAEP- behavioral (33.3 stimuli/s)	15.0 (10.0)			
	ABR- behavioral (33.3 stimuli/s)	15.0 (6.25)	0.005[a]	55.0	1.00[a]
	CAEP- behavioral (1.0 stimuli/s)	10.0 (6.25)			
	Behavioral (33.3 stimuli/s) - Behavioral (1.0 stimuli/s)	5.00 (6.25)	0.002[a]	0.00	−1.00
	ABR- PTA 1 kHz	10.0 (5.00)	0.516	13.0	−0.278
	CAEP- PTA 1 kHz	10.0 (5.00)			

[a] $p < 0.05$ or large effect size ($d > 0.8$).

Post hoc analysis using the Wilcoxon signed-rank test revealed that ABR thresholds demonstrated significantly better agreement with behavioral thresholds than CAEP thresholds for the LS CE-Chirp stimulus ($p < 0.05$). This finding suggests two possible interpretations: (1) brainstem-level activity, as reflected by ABR, may play a more dominant role in perceptual threshold detection; and/or (2) stimulus-related factors—such as the temporal and spectral properties of the LS CE-Chirp—may differentially affect the neural encoding observed at the brainstem compared with the cortical level.

Experiment 2a: Agreement Between CAEP, ABR, and Behavioral Threshold using 1 kHz Tone Burst at 33.3 Stimuli Per Second

To further investigate whether the significantly better agreement between ABR and behavioral thresholds observed in Experiment 1 was primarily due to the dominant role of brainstem-level activity in threshold detection, or whether it may have been influenced by stimulus-related factors such as duration or spectral content, Experiment 2 employed a different stimulus with a longer duration: the 1 kHz tone burst. The purpose was to determine whether the better agreement between ABR and behavioral thresholds found with the LS CE-Chirp would also be observed using this alternative stimulus. If a similar pattern to that observed in Experiment 1—where the ABR showed better agreement with the behavioral threshold than the CAEP—emerged in Experiment 2 despite the use of a different stimulus, it would support the hypothesis that brainstem activity plays a more substantial role in perceptual threshold detection than cortical responses. Conversely, if Experiment 2 revealed a different agreement pattern—such as the CAEP showing closer correspondence to the behavioral threshold than the ABR, or no difference in the degree of agreement between the two—it would suggest that stimulus-related characteristics may have contributed to the findings in Experiment 1.

Descriptive analysis for the 1 kHz tone burst revealed a similar trend consistent with that observed for the LS CE-Chirp: CAEP thresholds were slightly higher than ABR thresholds, and both ABR and CAEP thresholds remained higher than behavioral thresholds measured at 33.3 stimuli/second., In contrast to Experiment 1, Wilcoxon signed-rank tests revealed no significant differences between ABR and CAEP thresholds compared with behavioral thresholds at the 33.3 stimuli/second rate ($p > 0.05$; see Table 3). This divergence from Experiment 1 suggests that stimulus-related factors, such as type, duration or/and as stimulus rate, may influence the accuracy of threshold estimation and the relative contributions of brainstem and cortical activity to perceptual threshold detection. However, the finding in this experiment that both ABR and CAEP thresholds showed equivalent agreement with behavioral thresholds raised a further question: what specific stimulus parameter might account for the different patterns observed across Experiments 1 and 2a? To address this, Experiment 2b extended the behavioral threshold measurement using 1kHz tone burst stimuli presented at two rates: 33.3 stimuli/second and 1.0 stimuli/second.

Experiment 2b: Effect of Stimulus Rate on Agreement Between ABR, CAEP, and Behavioral Thresholds Using 1 kHz Tone Burst

The aim of Experiment 2b was to determine whether variations in stimulus rate affect the agreement between CAEP and ABR thresholds with the behavioral threshold. Two possible outcomes were considered: (1) no significant difference between ABR, CAEP, and behavioral thresholds, implying that stimulus type and brainstem-level processing contribute more to perception, or (2) a pattern of better agreement between CAEP threshold and behavioral thresholds, indicating a cortical-level influence of stimulus rate on threshold detection.

Findings revealed that behavioral thresholds at a stimulus rate of 33.3 stimuli/second were significantly lower than those at 1.0 stimuli/second, as shown descriptively in Table 2 and confirmed by post hoc analysis in Table 3 ($p < 0.05$). A Wilcoxon signed-rank test comparing CAEP and ABR thresholds relative to behavioral thresholds at the respective stimulus rates (i.e., CAEP vs. behavioral at 1.0 stimuli/second and ABR versus behavioral at 33.3 stimuli/second) demonstrated a significantly better agreement between CAEP and behavioral thresholds ($p < 0.05$), as presented in Table 3. These results suggest that stimulus rate may influence behavioral threshold detection, with a slower presentation rate associated with higher (poorer) behavioral thresholds. The closer agreement between behavioral thresholds and CAEP thresholds at the slower stimulus rate highlights the role of cortical activity, particularly temporal integration and temporal pattern, in perceptual threshold detection.

Taken together, Experiments 1, 2a, and 2b demonstrate a systematic progression in agreement patterns: ABR showed superior agreement at 33.3/s with LS CE-Chirp (Experiment 1), equivalent agreement at 33.3/s with 1 kHz tone burst (Experiment 2a), while CAEP showed superior agreement at 1.0/s with 1 kHz tone burst (Experiment 2b). This progression reveals that both stimulus type and stimulus rate systematically modulate whether brainstem or cortical activity better predicts behavioral thresholds.

Experiment 2c: Agreement Between CAEP, ABR, and Behavioral Thresholds at 1 kHz Pure-Tone Audiometry

To further validate the agreement pattern from Experiments 1 and 2a and 2b, particularly regarding the predictive value of ABR and CAEP thresholds for behavioral audiometry, an additional analysis compared CAEP and ABR thresholds with standard 1 kHz PTA thresholds. This additional analysis aimed to determine whether behavioral thresholds measured using a longer-duration stimulus (pure tone) align more closely with ABR or CAEP thresholds, or whether no significant differences exist among the three measures, indicating comparable predictive value of objective measurements for perceptual hearing.

Consistent with earlier descriptive findings in Experiment 2, PTA thresholds at 1 kHz were generally lower than both ABR and CAEP thresholds, as shown in Table 2. However, Wilcoxon signed-rank analysis revealed no statistically significant differences between CAEP, ABR, and PTA thresholds at 1 kHz across participants ($p > 0.05$; Table 3). These results suggest that both ABR and CAEP thresholds provide comparable estimates of the 1 kHz PTA threshold, with threshold differences generally within 10 dB.

DISCUSSION

The present study revealed the following key observations based on the limited dataset: (1) ABR threshold demonstrated better agreement with behavioral threshold at 33.3 stimuli per second compared with CAEP thresholds, (2) ABR and CAEP thresholds showed comparable agreement with behavioral thresholds at 33.3 stimuli per second for the 1 kHz tone burst stimulus, and (3) CAEP thresholds exhibited better agreement with behavioral thresholds at 1.0 stimuli per second than ABR thresholds. These findings may be influenced by several factors: (1) the shorter duration of the LS CE-Chirp stimulus, (2) the different contribution of auditory processing levels in threshold detection, with ABR reflecting brainstem activity and CAEP reflecting cortical-level processing, and (3) the slower stimulus rate used for the 1 kHz tone burst stimulus.

Influence of Stimulus Duration and Auditory Generator Level on Threshold Detection

First, the LS CE-Chirp stimulus is designed to align with the tonotopic organization of the cochlea by compensating for cochlear traveling wave delay (Dau et al., 2000). In this design, the low-frequency components are presented first, followed by mid- and high-frequency components, to ensure simultaneous activation across the basilar membrane. This approach enhances neural synchrony and produces larger wave V amplitudes in ABR responses (Dau et al., 2000; Fobel & Dau, 2004). Findings from the present study are consistent with Xu et al., (2014), who reported that ABR thresholds evoked by LS CE-Chirp closely matched behavioral audiograms (within 3–5 dB HL) in young children with hearing loss. Similar agreements between ABR to LS CE-Chirp and adult behavioral thresholds have also been reported across low to mid frequencies (Biagio-de Jager et al., 2020; Cho et al., 2015; Dzulkarnain et al., 2020).

The short duration of the LS CE-Chirp stimulus may preferentially activate fast-conducting auditory nerve fibers projecting via the lateral lemniscus to the inferior colliculus (Dau et al., 2000). This neural activity, reflected in robust wave V responses, suggests a prominent contribution of brainstem-level auditory processing in threshold detection, as observed in Experiment 1 (Don & Eggermont, 1978). In contrast, CAEP threshold estimation is also influenced by stimulus duration and is primarily elicited by stimuli with onsets lasting up to 30 ms (Agung et al., 2006; Beukes et al., 2009; Cody & Klass, 1968; Waber, 1970). Given that the LS CE-Chirp has a total duration of only approximately 5 ms and lacks defined rise and fall times, it may not sufficiently engage cortical generators, potentially explaining the reduced CAEP sensitivity observed in this study (Lightfoot, 2016; Martin et al., 2007; Picton, 2011).

Findings from Experiment 2a support this interpretation. When a longer-duration stimulus (1 kHz tone burst) was used, the discrepancy between behavioral and CAEP thresholds diminished. Both ABR and CAEP thresholds showed comparable agreement with behavioral thresholds at a stimulus rate of 33.3 stimuli/second, suggesting no clear dominance of either brainstem or cortical activity in threshold detection. These results indicate that the agreement pattern observed in Experiment 1 may have been driven, at least in part, by the temporal characteristics of the stimulus—specifically, the shorter duration of the LS CE-Chirp aligning more closely with brainstem-mediated threshold detection mechanisms.

Influence of Stimulus Rate and Auditory Generator Level on Threshold Detection

In addition to stimulus duration, stimulus rate was manipulated in Experiment 2b using the same 1 kHz tone burst stimulus to measure the behavioral threshold. Previous studies have shown that stimulus rate can influence threshold estimation in both ABR and CAEP recordings (Budd et al., 1998; McKnight et al., 2018). For example, a case study by McKnight et al., (2018) investigated the effect of different stimulus rates on ABR responses in children with auditory neuropathy spectrum disorder (ANSD) and hearing loss. The study found that using a slower ABR stimulus rate (5.1 clicks per second) did not significantly improve ABR responses. Whereas CAEP measurements at a slower rate of 0.61 stimuli per second produced more consistent P1 responses aligned with speech perception outcomes.

In AEP measurements, stimulus rate during signal averaging is important to elicit a larger perceivable response. Slower rates in CAEP testing are thought to improve response detectability by reducing neural adaptation and habituation, with an optimal range between 0.5 and 1 Hz (Cody & Klass, 1968; Rapin, 1964). Conversely, higher stimulus rates in tone burst stimulation may induce habituation of the auditory response (Budd et al., 1998).

In the present study, behavioral thresholds in Experiment 2b were measured using a 1 kHz tone burst presented at two rates: a faster rate of 33.3 stimuli per second and a slower rate of 1.0 stimuli per second. Notably, better agreement between CAEP and behavioral threshold was observed at the slower rate. Although thresholds at a slower rate were poorer compared with thresholds at a faster rate, these thresholds at a slower rate showed good agreement with CAEP thresholds.

This pattern may be explained by the interaction between temporal integration and the neural recovery mechanism. At slower rates, temporal integration is reduced due to longer inter-stimulus gaps that reduce neural firing, resulting in poorer behavioral threshold as compared with when the stimulus was presented at a higher stimulus rate (Horváth et al., 2007; Viemeister, 1991; Yabe, 1998). However, the longer refractory periods resulting from longer inter-stimulus gaps allow neurons to recover more effectively between stimuli, improving temporal pattern detection and allowing for slow conducting nerve fiber activation (Andrade et al., 2023; Burkard & Don, 2007; Momtaz & Bidelman, 2024).

From a physiological perspective, the perception of sound at the cortical level may also be influenced by the activity of the nerve fibers. Fast conducting nerve fibers are likely critical for detecting sounds near behavioral threshold in a quiet environment; however, continuous activation of these fibers can lead to synaptic fatigue, limiting their maximum discharge rate to repeated tone burst stimuli. In contrast, slow conducting fibers, which have lower discharge rate and longer recovery times, respond better to transient tone burst stimuli and preserve temporal coding, thereby supporting more accurate cortical-level perception (Costalupes, 1985; Costalupes et al., 1984). These slow-conducting fibers may thus play a predominant role in encoding stimuli at slower rates, potentially explaining better sound perception at a slower rate of stimulation for CAEP recording.

In the present study, the use of a slower stimulus rate in Experiment 2b resulted in better agreement between CAEP and behavioral thresholds. CAEP thresholds demonstrated significantly better agreement with behavioral thresholds when recorded at 1.0 stimuli per second, suggesting that cortical-level auditory processing may contribute more substantially to the thresholds at slower rates. These findings indicate that the temporal characteristics of auditory stimuli, specifically duration and presentation rate, significantly influence the neural generators engaged during threshold detection.

Insight into Behavioral Hearing Threshold with Objective Threshold Measurement

In addition to the findings, further analysis comparing ABR and CAEP thresholds with the standard 1 kHz PTA threshold revealed no significant differences. This observation aligns with the previous research indicating that behavioral PTA thresholds typically differ by approximately 10 dB from both ABR and CAEP (Cardon & Sharma, 2021; Lightfoot & Kennedy, 2006; Ross et al., 1999; Tan et al., 2025).

As noted earlier, CAEP elicited using tone burst stimuli may provide more accurate threshold estimation than traditional ABR, generally within 10 to 15 dB of behavioral thresholds. The N1–P2 response represents an obligatory, exogenous CAEP component, meaning it is largely independent of active cognitive processing, though it can be influenced by the participant's arousal state (Lightfoot, 2016). In the present study, the N1–P2 CAEP waveform components systematically disappeared as the stimulus approached the behavioral threshold, with differences within approximately 10 dB HL. These findings provide additional evidence supporting the reliability of CAEP as an objective predictor of behavioral threshold detection.

CONCLUSION

In conclusion, these preliminary findings may provide insights into the agreement between stimulus characteristics and the behavior of auditory nerve fibers at different levels of the auditory system that contribute to auditory perception. Notably, slower stimulus rates appear to enhance cortical-level processing, whereas shorter stimulus durations preferentially engage brainstem-level activity. These results are particularly relevant for understanding auditory perception across different stimulus characteristics and highlight the potential utility of objective measurements for populations unable to provide reliable behavioral responses, as well as for assessment and diagnosis of auditory dysfunctions. Further investigation with larger sample sizes and inclusion of individuals with auditory disorders is warranted to confirm these mechanisms and to elucidate how different levels of auditory processing contribute to threshold detection in both typical and disordered auditory systems.

SHORT BLURB

This study explores the agreement between ABR, CAEP, and behavioral thresholds using LS CE-Chirp and 1 kHz tone burst stimuli in normal-hearing adults. Findings highlight the effect of stimulus duration and rate on threshold estimation and neural contributions at the brainstem and cortical levels.

ETHICAL APPROVAL

Ethical approval was obtained from the International Islamic University of Malaysia (IIUM) Institutional Research Ethics Committee (reference number: IIUM/504/14/11/2/IREC-2025–131).

AI USE IN MANUSCRIPT

Language editing was assisted using AI tools such as ChatGPT. All content and interpretations remain the sole responsibility of the authors.

CONFLICT OF INTEREST

None declared. Part of the findings from this study was presented at the 7th Malaysian Audiology Scientific Conference (MASCO) 2025.

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