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Objective measures of auditory temporal resolution with ABR

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ABSTRACT

Objective: To develop a reliable objective method to measure temporal resolution thresholds using Auditory Brainstem Response (ABR) with statistical response detection methods.
Design: The ABR paradigms "Two Clicks (2C)" and "Temporal Notched Noise with Click (TNNC)" were evaluated for measuring objective temporal resolution thresholds. Statistical methods were used for ABR detection. Test-retest reliability of both ABR paradigms was also assessed. For comparison, a Gaps in Noise test and psychometric TNNC paradigm measured behavioural thresholds from the same subjects.
Study sample: 23 normal-hearing participants in the main study, and an additional 10 in the test-retest experiment, aged 20–35 years.
Results: Objective temporal resolution thresholds averaged 4.04 ms for the 2C paradigm and 3.21 ms for the TNNC paradigm. Group-level data showed reduced ABR amplitude and detection as gap durations approached threshold, whilst individual ABR amplitudes fluctuated across gap durations. Behavioural thresholds averaged 1.49 and 2.22 ms. In the test-retest experiment, TNNC showed moderate repeatability, while 2C had slight, non-significant repeatability (measured by Cohen's Kappa).
Conclusions: While these objective approaches show promise for measuring temporal resolution at a group level, their application in individuals remains challenging due to high variability across subjects. The TNNC paradigm demonstrated better performance in terms of ABR repeatability.

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Temporal resolution; suprathreshold hearing; auditory brainstem response; forward and backward masking; two clicks; paired clicks

1. Introduction

Speech comprehension difficulties are commonly reported among older individuals, regardless of whether they have hearing loss or not, particularly in challenging listening situations such as speech-in-noise (Moore and Füllgrabe 2020). These challenges have been associated with a decline in suprathreshold auditory processing, specifically affecting auditory temporal resolution (Cesur and Derinsu 2017). Temporal resolution is the minimum period between two auditory stimuli that can be perceived. It refers to the ability to detect small temporal-acoustic changes that occur in a sound within a certain time period (Gelfand 2017). Detection of rapid temporal acoustic information is essential not only for prosodic and duration discrimination but also for accurate speech decoding, including voice onset time and speech perception in both quiet and noisy environments (Lorenzi and Moore 2007; Moon and Hong 2014; Moore 2008). Conventional audiometric tests such as pure-tone-audiometry do not accurately predict an individual's ability to comprehend speech or their temporal resolution thresholds. The current paper aims to describe and test improved objective, electrophysiological methods for the detection of temporal resolution.

Temporal information consists of two key elements: temporal envelope, which represents slow fluctuations in amplitude over time, and temporal fine structure, which captures the rapid oscillations occurring near the centre frequency of each band (Moore 2008). Both elements are important for speech identification: in quiet environments, it may be possible to use either envelope or fine structure cues to identify words (with envelope cues generally more prominent), but in background noise, both cues are essential for clear speech perception (Lorenzi and Moore 2007). Additionally, a study on the optimal combination of neural correlates of envelope and fine structure cues found that model predictions best matched human performance when envelope coding was given greater emphasis than temporal fine structure (Moon et al. 2014). Gap and amplitude modulation detection are two common methods used to measure temporal resolution based on envelope cues (Dimitrijevic et al. 2016; Shen and Richards 2013).

Previous studies on measurements of temporal resolution mainly focused on subjective, behavioural gap detection which provides the description of temporal resolution based on a single threshold; this was initially proposed by Garner (1947). This is now a well-established paradigm that measures the listener's ability to perceive a brief silent gap that separates two consecutive stimuli, and the stimulus is often noise. The behavioural gap detection threshold, which is known to vary depending on the person and stimulus-related factors, has been reported in the range of 2–3 ms for broadband noises in normal-hearing people (Moore 2012; Phillips 1999). The standard Gaps in Noise (GiN) test developed by Musiek et al. (2005) is now probably the most widely used gap detection method that does not employ multiple alternative forced-choice approaches. In the standard GiN test, the threshold is determined as the minimum gap duration at which the participant achieves more than 65% correct responses. Studies have reported average GiN thresholds for individuals with normal-hearing to range from 3.79 to 6.52 ms (Gallun et al.

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2012; Jafari et al. 2016; Lavasani et al. 2016; Rabelo, Weihing, and Schochat 2015).

Impairments in temporal resolution have been associated with various conditions, including sensorineural hearing loss, ageing, and central auditory processing disorder (ASHA 2005; Chermak and Musiek 2013; Vercammen et al. 2018). The assessment of such conditions often uses gap detection paradigms. Nevertheless, the application of such subjective paradigms may not represent the optimal approach for evaluating temporal resolution ability, as they require focused attention and cooperation. Furthermore, these paradigms pose challenges for specific demographic groups, such as infants and individuals with difficulties related to comprehension of instructions and sustaining attention. There is a need for an objective method that can quantitatively assess temporal resolution without relying on individuals' behavioural responses. Such methods could not only provide thresholds but also offer valuable insights into suprathreshold hearing, potentially enhancing our understanding of auditory processing.

To address this issue, recent studies on humans and animals have explored various objective assessment tools to measure temporal resolution threshold based on auditory evoked potentials (AEPs) (Bidelman and Bhagat 2017; Bidelman and Khaja 2014; Lee et al. 2020; Poth et al. 2001; Werner et al. 2001). AEPs represent activity within the auditory system in response to sound and contribute to the early detection and diagnosis of auditory dysfunction (Hall 2017). Proposed methodologies for objectively evaluating temporal resolution have typically been adapted from behavioural approaches. This includes the utilisation of AEPs in tasks such as gap detection, forward and backward masking, and modulation detection (Leigh-Paffenroth and Fowler 2006; Marler and Champlin 2005; Mussoi and Brown 2019; Palmer and Musiek 2014; Purcell et al. 2004).

Among AEPs, the auditory brainstem response (ABR) is the most reliable and widely used measure in both clinical and research settings to evaluate auditory function. Both Poth et al. (2001) and Werner et al. (2001) adapted GiN to ABR in order to acquire objective temporal resolution thresholds. Variables of interest include the occurrence or the amplitude of the response to the onset of the noise presented after a silent gap. Studies have reported that average objective thresholds are similar to behavioural thresholds (Bidelman and Bhagat 2017; Poth et al. 2001; Werner et al. 2001). Subsequent studies have extended these findings, demonstrating an increase in the latency (Cheng and Champlin 2021) and a decrease in the amplitude (Duda-Milloy et al. 2019) of wave V of the ABR as the gap duration decreases.

Another stimulus commonly used to assess the objective temporal resolution of the peripheral auditory system is paired clicks. Bidelman and Bhagat (2017) used a gap detection paradigm involving paired clicks instead of noise bursts and reported temporal thresholds of approximately 3–4 ms across both ABR paired click measures and behavioural gap detection. They also examined cochlear function using stimulus-frequency otoacoustic emissions and found similar temporal threshold to ABR and behavioural findings. They concluded that similar temporal resolution thresholds across behavioural, cochlear and brainstem measurements suggest human temporal resolution, established in the cochlea would be seen at progressively higher levels of the hearing pathway (Bidelman and Bhagat 2017). These findings highlight the close link between cochlear function and temporal processing. More recently, Lee et al. (2020) investigated the relationship between temporal resolution and noise-induced cochlear synaptopathy in rats, again using paired click stimuli. The study found that as the number of cochlear synapses was reduced, the amplitude of the ABR peak I component diminished, accompanied by a decline in temporal resolution (Lee et al. 2020). These results suggest that deterioration in temporal resolution may serve as a sensitive marker of hidden hearing loss or cochlear synaptopathy, and that ABR measures elicited by paired click stimuli hold promise as a measure of synaptic health and temporal processing.

Previous studies often relied on visual inspection of averaged waveforms to determine the presence of ABR responses. However, Lv, Simpson, and Bell (2007) demonstrated that, even among experienced audiologists, hearing thresholds in normal-hearing participants can vary depending on the clinician performing the assessment. The application of objective ABR detection techniques based on quantitative measures of response strength, such as F_{sp} and Hotelling's T^2 test, offers a standardised alternative that minimises subjective variability. Chesnaye et al. (2018) demonstrated that these objective methods achieve high sensitivity with low false positives, thus providing a reliable and efficient alternative to visual detection. Whilst several methods have been proposed for the objective, electrophysiological measurement of temporal resolution, these approaches have not generally been applied in the same subjects, making comparison of results difficult. Thus, it remains unclear which method for assessing objective temporal resolution should be recommended.

The present study aims to develop a reliable ABR approach to measure temporal resolution thresholds. Following a preliminary study exploring a number of experimental paradigms, a detailed comparison of two promising alternatives, "Two Clicks (2C)" and "Temporal Notched Noise with Click (TNNC)," was conducted. Well-established conventional statistical detection methods were adapted to enhance ABR detection and avoid the subjectivity of visual inspection. By comparing the performance of these objective tests with behavioural tests in normal hearing subjects, our study seeks to establish a robust method for determining temporal resolution thresholds using ABRs. Lastly, this study aims to investigate the test-retest reliability of the recommended objective paradigms.

2. Materials and methods

An initial pilot study compared five stimulus paradigms to see which elicited most reliable ABRs. The stimuli included Gaps in Noise (GiN), Two Clicks (2C), Temporal Notched Noise with Click (TNNC), Gaps in Frozen Noise (i.e. noise that is identically repeated in all stimuli), and Gaps in Frozen Noise with 50 ms Interstimulus Interval (ISI). From the pilot study, the 2C and TNNC paradigms elicited significantly higher ABR detection rates, especially for short gaps and so were selected for further evaluation, whereas the others showed inconsistent or minimal responses at short gap durations.

2.1. Participants

23 young adults (17 males, 6 females, age 27.7 ± 3.63) were included in the main study and test-retest ABR measurements were recorded from an additional 10 young adults (4 males and 6 females, mean age of 29.3 years, ranging from 24 to 33 years). Recruitment criteria required participants to be aged 18–40 years and to have normal-hearing (20 dB HL or better at frequencies 0.25 through 8 kHz by pure tone audiometry). All participants reported no history of neurological or hearing disorders. All participants provided informed, written consent. Ethical approval for the study was granted by the University of Southampton's Ethics and Research Governance Office (ERGO) under submission number ERGO/FEPS/67134.

2.2. ABR stimuli and recording

As illustrated in Figure 1, the Two Clicks (2C) paradigm uses paired clicks (Burkard and Deegan 1984) with varying inter-click gaps to assess temporal resolution using ABR. Initially, single-click ABRs were recorded as a baseline. In the 2C paradigm, each epoch consists of two clicks separated by gap durations of 1, 2, 4, 6, 8 and 20 ms respectively. The first click is fixed at 10 ms within the epoch, while the timing of the second click varies depending on the gap duration. The two clicks are expected to elicit two separate ABRs. As the gap between clicks reduces, the response to the second click will be reduced due to temporal inhibition from the first click. For gap durations less than the participant's temporal threshold, responses to the second click are expected to be absent (or undetectable). The objective temporal resolution threshold was therefore defined as the minimum gap duration at which the participant had a statistically significant (present) response. Clicks were calibrated following the peak-to-peak equivalent signal level procedure outlined in BS EN ISO 389-6 (2007) with dBZ weighting. The output of the audiometer was compared to the peak-to-peak value of a calibration piston (94 dB SPL at 1 kHz). Clicks were calibrated in p.e. SPL and then converted to dB HL and presented at 70 dB HL.

The Temporal Notched Noise with Click (TNNC) paradigm was employed to assess temporal resolution by incorporating both forward and backward masking effects into ABR recordings. This paradigm was selected because it produces clearer ABR responses compared to traditional gap-in-noise paradigms with no click (as established in pilot work). As illustrated in Figure 1, this stimulus was designed as follows: 10 ms random white noise, a gap with a click in the middle and then another segment of random white noise. The gap duration defined here is the time between the offset of the first noise and the click (to be equivalent to measurements made with the 2C paradigm). As the gap duration is reduced, masking effects are expected to reduce the ABR response to the click. The objective temporal resolution threshold is deemed to be the minimum gap duration at which the ABR ceases to be detected. Each epoch had a total length of 51 ms, with gap durations set to 0.5, 1, 2, 4, 6, 8, or 15 ms. Between gaps, the noise was continuous (i.e. no noise onset after 51 ms). For the TNNC paradigm, the optimal masking level (click-to-noise ratio ≈ −3.8 dB, calculated as the level difference between the click and the maximum noise amplitude) was determined in a preliminary study by embedding clicks into continuous noise without gaps and gradually reducing the click level until no ABR was detected. The TNNC stimuli were calibrated in dBA and presented at 70 dBA.

During the test, the participant reclined on a couch and was asked to relax with eyes closed. All stimuli were generated in MATLAB® (MATLAB R2020a, The MathWorks Inc., Natick, MA, USA) software and presented monoaurally from the CED Signal 7 software through a Cambridge Electronic Design (CED, Cambridge, UK) micro 1401 data acquisition unit and routed through a GSI 16 Audiometer (Grason-Stadler Milford, USA) to EAR-TONE 3 A insert phones placed in the participant's ears. ABR signals were amplified with a Digitimer 360 isolated 8-channel patient amplifier (Digitimer Limited, Hertfordshire, UK) with electrodes placed at the vertex (active electrode), the nape of the neck (reference) and mid-forehead (ground) and routed back to the micro 1401 and sampled at 10 kHz. The ABR filter cut-offs were 0.1 and 3 kHz. Electrode impedances remained below 5 kΩ throughout the recording.

A total of 6100 epochs were recorded for each stimulus and an artefact rejection method was applied by discarding epochs where the maximum absolute value exceeded 20 µV. For the test-retest experiment, two identical ABR test sessions were conducted at intervals of 1–7 days.

2.3. Behavioural evaluation

To investigate the correlation between electrophysiological and behavioural results, participants were tested using two different psychophysical methods. The first method was a GiN test; the second was the TNNC paradigm. The study aimed to determine whether these two methods produced similar gap-detection thresholds with each other and if these thresholds were similarly related to the ABR gap-detection threshold. The TNNC paradigm was identical to the one used in ABR, specifically chosen to compare the subjective measurements with the objective findings. The GiN test used here differed from the TNNC only by the absence of a click.

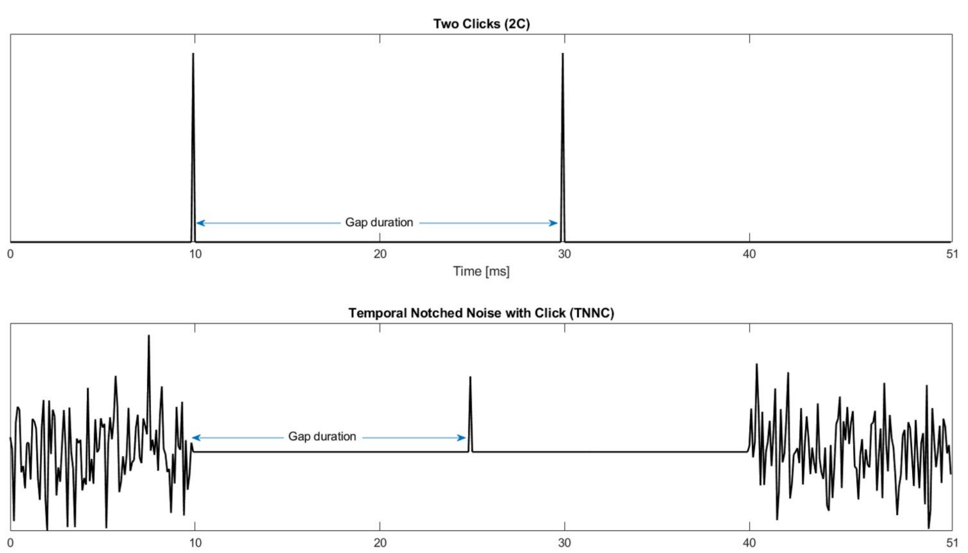

Figure 1. A schematic illustration of ABR stimulation paradigms explored in the study. Two Clicks (fist click at 10 ms + gap + second click) and Temporal Notched Noise with Click (10 ms white noise + gap + click + gap + white noise).

The stimuli were generated using MATLAB (version R2020a) and were passed through a GSI 16 Audiometer (Grason-Stadler Milford, USA) to EAR-TONE 3A insert phones (E.A.R Auditory Systems, Aearo Company, Indianapolis, IN). All stimuli were delivered monaurally and levels were controlled using the calibration procedural approach as per BS EN ISO 389-6:2007.

Psychophysical testing was conducted using three alternative forced choice (3-AFC) procedure for stimulus presentation. In each 3-AFC trial, three 51 ms white noise bursts at 70 dB A were presented, separated by an interval of 1000 ms. A silent gap was temporally placed in one randomly chosen of the three noise bursts (odd stimulus). For the TNNC paradigm, there was a click centred in this gap. The participants were asked to identify the odd stimulus (first, second or third). An adaptive gap detection algorithm using a single staircase was applied according to a one-up, two-down rule with a fixed step size of 1 ms, beginning with 8 ms gaps. Testing was continued until 8 reversals were obtained, which corresponded to about 30 trials. The gap detection threshold was calculated as the average of the last 6 reversals to exclude early, unstable responses.

2.4. Data analysis

As the gap durations shorten, the ABRs in response to the first and second clicks of the 2C stimuli overlapped and became difficult to distinguish. In order to isolate the response to the second click, the response to the single click stimulus was therefore subtracted from the response to the two clicks (see Figure 2). The response detection algorithm (see below) was then applied to this difference signal.

For the TNNC paradigm, the ABR to the click formed the input to the response detection algorithm. It is important to note that this is a compound response, including the onset and potentially offset responses to the noise with short gaps. The rationale behind using this approach is that the click provides the clearest ABR. As the gap becomes shorter, all responses will become smaller allowing to determine a threshold for the TNNC stimulus. Thus, subtraction was not needed for this paradigm.

Analysis of all collected data was performed offline by using MATLAB® (MATLAB R2020a, The MathWorks Inc., Natick, MA, USA). For both paradigms, the analysis window was 10 ms, starting 5 ms after the target stimulus onset (the second click for 2C or the click in the notch for TNNC), which should include a wave V in both cases.

In contrast to previous works that used visual detection for ABR identification, this study applied two robust statistical detection methods, F_{sp} and Hotelling's T^2, along with a bootstrap resampling approach to enhance reliability and objectivity in ABR measurement.

The F_{sp} detection statistic, introduced by Elberling and Don (1984), is based on the ratio of the variance of the averaged ABR response to the estimated variance of background EEG noise (an F statistic). This approach assumes that if a true response is present, the F statistic will exceed a critical threshold (e.g. 1.75 for 2000 sweeps; Lv, Simpson, and Bell (2007)). F_{sp} thus allows for an objective criterion that can be compared to a null distribution (no response present).

The Hotelling's T^2 (HT^2) test, a multivariate extension of the t-test, was applied to evaluate whether the ABR waveform differs significantly from zero. It splits the ABR waveform into time voltage means (averaged across short time segments) and compares the mean vector of those bins to the covariance of the bins

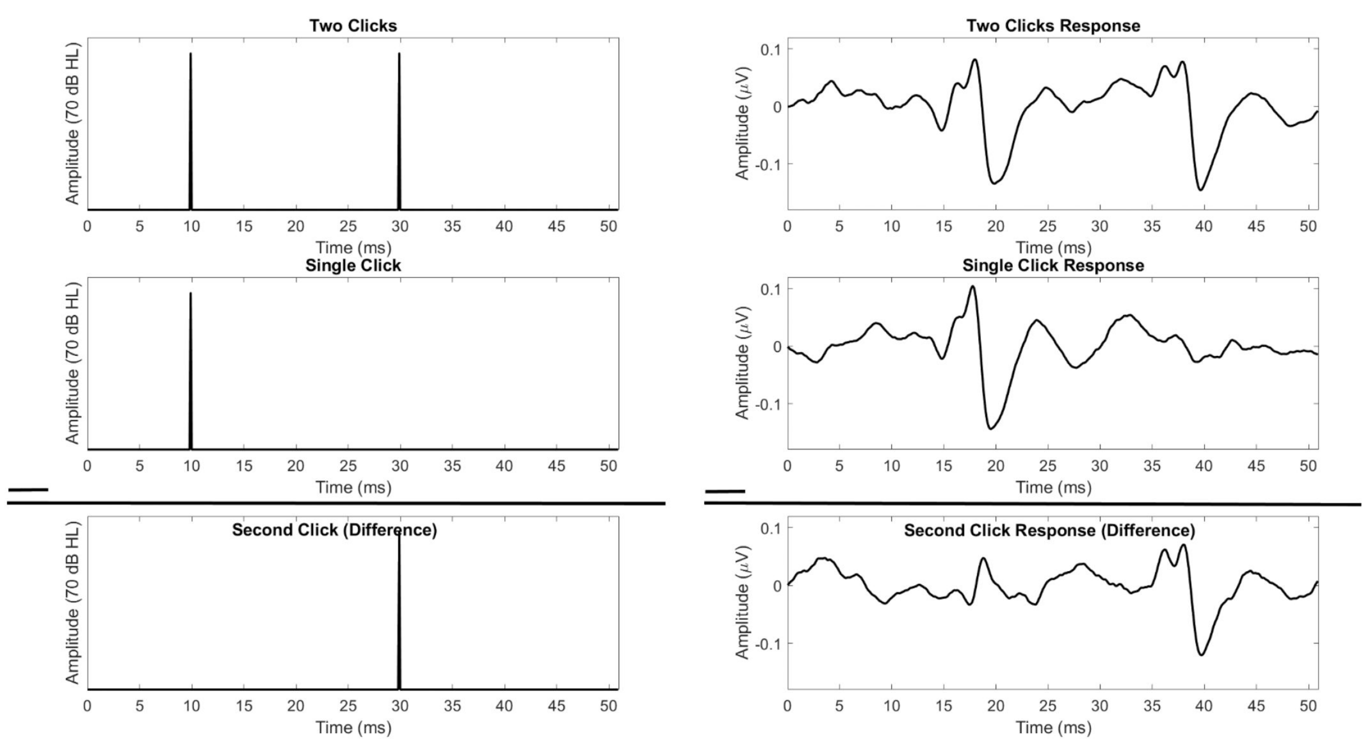

Figure 2. An illustration of the subtraction of a single click response from ABR to the Two Clicks paradigm. The top windows display the Two Clicks paradigm and its corresponding click-evoked peaks. The middle windows show the response to a single click stimulus and its ABR. The bottom windows represent the difference between the first and the second rows (consisting of only the second click and the ABR to the second click). After subtraction, the response to the first click has been largely removed.

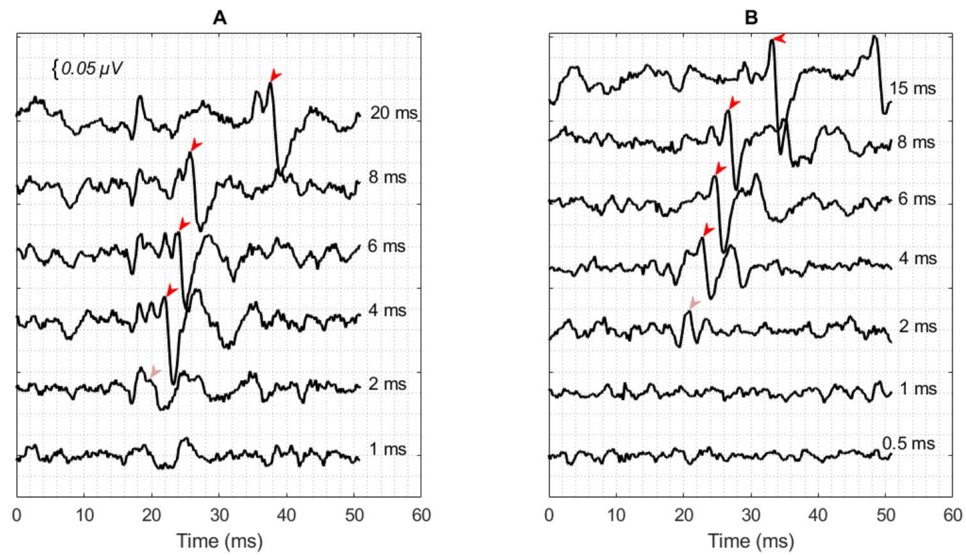

Figure 3. Grand averages of ABRs from 23 participants for each gap duration. Arrows indicate wave V; a pale arrow indicates that the peak is somewhat ambiguous. A: 2C paradigm with the response to the first click largely removed by subtracting the participant's single-click response from the two-click response in order to just leave the response to the second click. The first click was at a latency of 10 ms and the second click at 11, 12, 14, 16, 18, and 30 ms, respectively, presented from bottom to top. B: ABRs to the TNNC paradigm. Noise stopped at a latency of 10 ms and clicks were located at 10.5, 11, 12, 14, 16, 18, and 25 ms, for the gap durations from 0.5 to 15 ms, respectively, presented in order from bottom to top.

across epochs to produce an F value (Chesnaye et al. 2018). HT^2 tests for statistically significant deviations across multiple time points, while accounting for correlations among these points.

To further enhance reliability, we used the bootstrap resampling method (Efron and LePage 1992). For ABR detection, the bootstrap method creates a "null distribution" for both F_{sp} and HT^2 by resampling EEG segments that are randomly distributed with respect to the stimulus, thus simulating a no-response condition (Chesnaye et al. 2018; Lv, Simpson, and Bell 2007). In this study, 500 resamples were generated, each used to calculate F_{sp} and HT^2 values under the null hypothesis of no response. This resampling distribution allowed for robust hypothesis testing by comparing the actual ABR statistic to the null distribution from the subject (rather than using an assumed critical value across subjects), providing p-values. Significance was determined at a threshold of $\alpha = 0.05$ (Wilcox 2010).

IBM SPSS Statistics software version 28.1.1.0 (IBM© Corp., Armonk, NY) was used for further statistical analyses. A Friedman test was used with the Wilcoxon post hoc test to examine the effect of gap duration on amplitude. The correlation between subjective and objective gap detection thresholds was analysed with Pearson correlation analysis. For the test-retest experiment, the Intraclass Correlation Coefficient (ICC) was used to assess the between-session repeatability of threshold measurements and both F_{sp} and HT^2 values. Cohen's Kappa analysis was applied to measure agreement between sessions in detecting individual responses at different gap durations.

3. Results

The number of epochs remaining after artefact rejection was 5372.88 ± 871.70 for the 2C paradigm and 5954.72 ± 264.21 for the TNNC paradigm. There were no statistically significant differences in sensitivity between F_{sp} and HT^2 detection methods (for TNNC $p = 0.804$; for 2C $p = 0.832$).

Grand averages of 23 participants' ABRs to the two paradigms are shown in Figure 3 for each gap duration. Note that the grand averages of the 2C responses shown in Figure 3(A) are isolated/subtracted second-click responses. Visual analysis of Figure 3(A) suggests that ABRs to the second click are evident at a gap duration of 4 ms or above with the 2C paradigm.

In Figure 3(B), it appears that for TNNC a clear brainstem response to the click is produced for a gap duration of 4 ms or more. For this paradigm, our focus was the response to the click. A response to the noise onset after the gap is sometimes seen but is not consistent across participants (it is clearly evident in Figure 3(B) at the 15 ms gap condition). Thus, both paradigms provide similar gap thresholds at the group level.

3.1. Presence of responses (detection rate)

3.1.1. 2C Paradigm

All 23 participants had responses to the first click under all conditions and to the second click following a silent gap of 20 ms (without subtraction). Figure 4(A) presents the percentage of participants with significant isolated/subtracted second click responses, analysed using HT^2 with bootstrap, as a function of gap duration. For a 4 ms gap duration, there were significant second-click responses in 18 out of the 23 participants. Cochran's Q test revealed a significant effect of gap duration on detection percentage ($Q(5) = 61.216$, $p < 0.001$). Additionally, McNemar's post-hoc test demonstrated a significant increase in response rate from 2 ms to 4 ms gaps ($p < 0.001$), but not for other pairs of successively increasing gap durations.

3.1.2. TNNC paradigm

Figure 4(B) shows the percentage of participants with measurable responses using HT^2 with bootstrap, as a function of gap duration. All 23 participants exhibited significant responses to the click positioned after the 15 ms silent gap. Cochran's Q test revealed a significant effect of gap duration on detection percentage (Q(6) = 90.097, $p < 0.001$). Post-hoc analysis using McNemar's test demonstrated significant increases in response rates between several gap durations: from 1 to 2 ms ($p = 0.016$), 2 to 4 ms ($p = 0.016$), and 4 to 6 ms ($p = 0.031$).

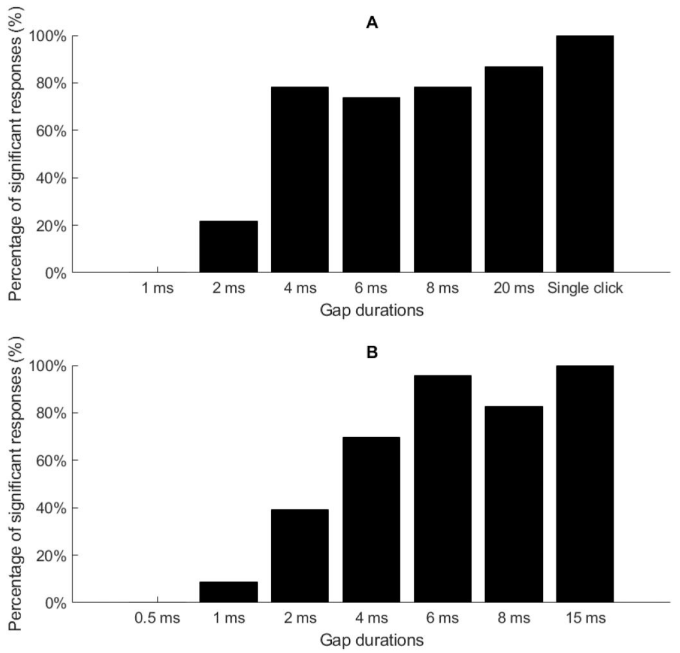

Figure 4. A: The percentage of participants with a significant response across gap durations in ABRs to the 2C paradigm and a single click analysed using Hotelling's T^2 with bootstrap in 23 participants. B: The percentage of participants with a significant response across gap durations in ABRs to the TNNC paradigm.

3.2. Response amplitude

Amplitudes were calculated using the peak-to-peak amplitude estimation, taking the difference between the highest peak and the lowest trough within the analysis window.

3.2.1. 2C Paradigm

Figure 5(A) presents ABR wave V amplitudes and latencies to the second click (subtracted) for individual participants as a function of gap duration. Generally, response amplitudes decreased as the gap duration shortened. A Friedman test revealed a statistically significant difference in amplitude across gap durations ($\chi^2(5) = 65.410$, $p < 0.001$). Wilcoxon post-hoc tests revealed a statistically significant difference between amplitudes at the 2 and 4 ms gap duration conditions ($p < 0.001$). However, no statistically significant differences were found between amplitudes for other consecutive gap durations in paired analyses using the Wilcoxon test ($p > 0.05$). Additionally, Figure 5(A) shows noticeable fluctuations in individual amplitude results. Although a decreasing trend in amplitude was observed in the grand average with decreasing gap duration, this trend was not evident in all individuals' data.

3.2.2. TNNC paradigm

Figure 5(B) illustrates wave V amplitudes and latencies to the click at the centre of the gap for each participant as a function of gap duration. Overall, response amplitudes decreased with decreasing gap duration. A Friedman test revealed a statistically significant difference in amplitude across gap conditions ($\chi^2(6) = 102.988$, $p < 0.001$). Paired analyses for consecutive gap durations were conducted to compare the amplitudes and Wilcoxon post-hoc test revealed statistically significant differences between amplitudes for the 15 and 8 ms gap durations ($p < 0.001$) and for

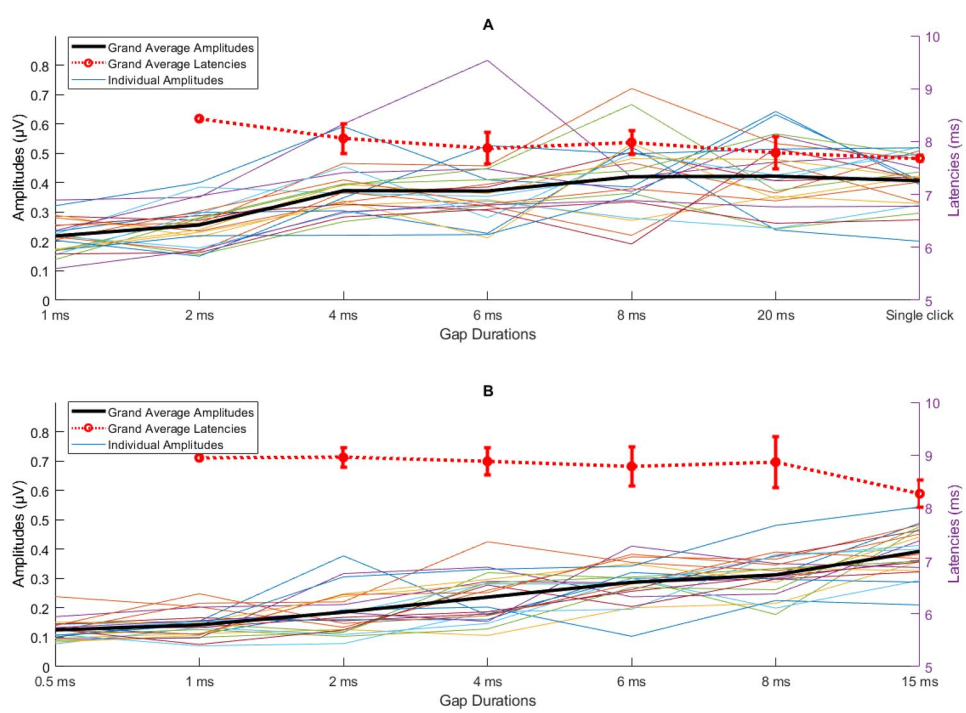

Figure 5. The solid black lines represent the grand average of the amplitudes and fainter lines indicate individual subject amplitudes. The dotted red lines show the average latencies of significant responses with standard error bars (No error bars are given when less than 3 participants had significant responses and for the lowest gap durations, no average value is provided, as no significant responses were observed.). The left Y-axis shows amplitude values in uV, while the right Y-axis shows latencies in ms. A: The amplitudes and latencies of the ABRs to the second click in the 2C paradigm of the 23 participants. B: The amplitudes and latencies of the ABRs to the click in the TNNC paradigm of the 23 participants.

the 4 and 2 ms gap durations ($p = 0.002$). However, no statistically significant differences were found for other consecutive gap durations in paired analyses using the Wilcoxon test ($p > 0.05$). Additionally, Figure 5(B) shows noticeable fluctuations in individual amplitude results. Although a decreasing trend in amplitude was observed in the grand average with decreasing gap duration, this trend was not consistently observed in individual data.

3.3. Response latency

When a significant response was present, the values of the latencies at which the peak occurred were recorded manually and are shown in Figure 5. Conditions with 1 ms gap durations are not included due to insufficient data for latency analysis.

3.3.1. 2C Paradigm

Wave V latencies to the first click did not change significantly across gap durations. Although a Friedman test indicated differences across conditions ($p < 0.001$) with a trend for latency to decrease with gap duration, this was not significant on post-hoc testing with Bonferroni correction. Figure 5(A) plots the mean wave V latencies to the second click as a function of gap duration. Generally, latencies to the second click increased as the gap duration decreased. A Friedman test showed a significant change in latency across gaps ($\chi^2(5) = 78.715$, $p < 0.001$). This indicates that the size of the gap significantly affected response times. Paired analyses of consecutive gap durations with Wilcoxon post-hoc test revealed a statistically significant delay between 6 and 4 ms ($p = 0.006$) and between 4 and 2 ms ($p < 0.001$).

3.3.2. TNNC paradigm

In Figure 5(B), the mean wave V latencies to the click in the TNNC paradigm for each participant are displayed as a function of gap duration. Friedman test revealed a statistically significant difference in latency across gap conditions ($\chi^2(4) = 50.094$, $p < 0.001$). Although latencies of responses to the click slightly increased as the gap duration decreased, Wilcoxon post-hoc test revealed a statistically significant delay only between 15 and 8 ms ($p < 0.001$) in paired analyses of consecutive gap durations.

3.4. Behavioural and objective thresholds

Figure 6(A) presents individual behavioural gap thresholds. For the Psychometric GiN test, the average gap threshold was 2.22 ± 0.44 ms (range: 1.57 to 3.17 ms), whereas for the Psychometric TNNC paradigm, it averaged 1.49 ± 0.62 ms (range: 1 to 6.31 ms). While the average values are similar, a Pearson correlation test between the Psychometric GiN test and the Psychometric TNNC revealed no statistically significant correlation ($r = 0.194$, $p = 0.375$). Given that in healthy volunteers the range of values is narrow, low correlation however might be expected.

Objective gap thresholds obtained with ABR paradigms are shown in Figure 6(B). The average gap threshold for the 2C paradigm was 4.04 ± 1.22 ms (range: 1 to 6 ms), whereas for the TNNC paradigm, it averaged 3.21 ± 1.85 ms (range: 1 to 8 ms). While the average values are similar, a Pearson correlation test between the ABR paradigms again showed no statistically significant correlation ($r = 0.336$, $p = 0.118$).

Figure 6(C and D) illustrate correlations between behavioural and ABR gap thresholds. There was no significant correlation found between the 2C paradigm and the Psychometric GiN test ($r = 0.185$, $p = 0.397$), nor between behavioural and objective measures of the TNNC ($r = 0.238$, $p = 0.274$).

3.5. Test-retest reliability

3.5.1. 2C Paradigm

The average objective thresholds were 2.6 ± 1.34 ms for the first and 2.8 ± 1.03 ms for the second test session with the 2C paradigm in ABR. The test-retest reliability of individual thresholds evaluated using the ICC. Results indicated similar average values but no significant correlation in temporal resolution thresholds between test sessions (ICC = 0.416, $p = 0.233$). The relatively narrow range of values in this normal-hearing population may have contributed to this.

Figure 7 shows the correlations of F_{sp} and HT^2 values of significant ABRs across the test sessions. F_{sp} values demonstrated excellent reliability across sessions (Figure 7(A); ICC = 0.957, $p < 0.0005$), as did HT^2 values (Figure 7(B); ICC = 0.937, $p < 0.001$).

Cohen's Kappa analysis was employed to assess consistency in response detection between sessions, resulting in non-significant agreement ($\kappa = 0.188$, $p = 0.146$) in detection performance over repeated tests.

3.5.2. TNNC paradigm

For the TNNC paradigm, the average objective thresholds were 3.2 ± 1.68 ms for the first and 3.5 ± 2.17 ms for the second test session. Individual threshold reliability between test sessions was also assessed using ICC. No statistically significant correlation in objective temporal resolution thresholds was observed across sessions (ICC = 0.603, $p = 0.105$), with data again exhibiting a narrow spread. Figure 7(B and C) demonstrate the correlations of F_{sp} and HT^2 values of significant ABRs to the TNNC paradigm across the test sessions. F_{sp} and HT^2 values indicated high reliability across sessions (ICC = 0.854, ICC = 0.856 respectively, both $p < 0.001$).

Cohen's Kappa analysis demonstrated moderate agreement between sessions ($\kappa = 0.447$, $p < 0.001$), indicating moderate consistency (repeatability) in response presence across repeated tests.

4. Discussion

This study aimed to develop and compare reliable ABR approaches for objectively measuring temporal resolution thresholds. Our findings demonstrate that both the 2C and TNNC paradigms can provide objective measures of gap detection thresholds that are broadly consistent with those reported by standard behavioural methods in the literature (Giannela Samelli and Schochat 2008; Musiek et al. 2005).

Our findings reveal mean temporal resolution thresholds of 4.04 and 3.21 ms, with 2C and TNNC paradigms respectively. These results are consistent with previous studies of temporal resolution using human scalp-recorded ABRs, which have reported thresholds ranging from 2.4 to 4 ms (Bidelman and Khaja 2014; Poth et al. 2001; Werner et al. 2001).

The average psychophysical gap thresholds in this study (~2 ms) were in general lower than those derived with ABRs. As in hearing threshold measurements (e.g. in pure tone audiometry), our study found lower temporal resolution thresholds with

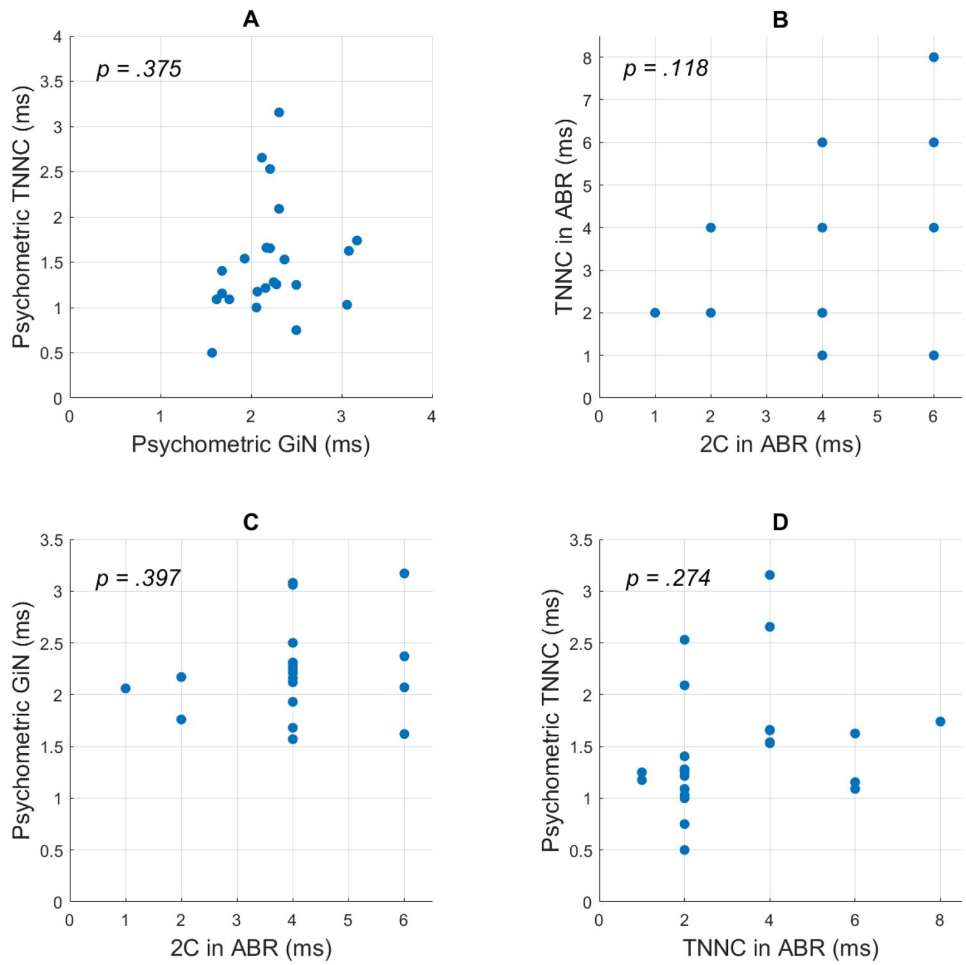

Figure 6. A: Behavioural gap thresholds of each participant with the Psychometric Gaps in Noise tests and the Psychometric Temporal Notched Noise with Click. B: Objective gap thresholds in ABR with the Two Clicks and the Temporal Notched Noise with Click. C: Objective gap thresholds in ABR with the Two Clicks and the behavioural gap thresholds with the Psychometric Gaps in Noise tests. D: Objective gap thresholds in ABR with the Temporal Notched Noise with Click and the behavioural gap thresholds with the Psychometric Temporal Notched Noise with Click. No significant correlations were found between any of the test pairs.

behavioural methods. This difference in thresholds doesn't necessarily limit clinical or research applications, as results can be interpreted relative to normal population values by using correction factors.

Our behavioural gap thresholds align with findings by Moore (2012), Phillips (1999), but are lower than the 4–5 ms thresholds reported in standard GiN test studies (Giannela Samelli and Schochat 2008; John, HallIII, and Kreisman 2012; Musiek et al. 2005). Hoover, Pasquesi, and Souza (2015) noted that adaptive procedures yield lower thresholds with less variability for normal-hearing young adults compared to standard GiN tests, which rely on a certain percentage of correct responses rather than an adaptive procedure or an AFC method. No significant correlation was found between the two psychometric tests used. While adaptive procedures are considered the "gold standard" for assessing subjective gap sensitivity (Hoover, Pasquesi, and Souza 2015), the lack of correlation observed may be attributed to individual differences in the response to two paradigms, variability in thresholds over time, or random measurement errors. Specifically, the gap sizes, stimulus types, or procedure (e.g. one-up, two-down step size) used in these tests could have influenced the results. This finding highlights the challenge of accurately assessing temporal resolution and the potential need for alternative objective methods. Additionally, it raises the possibility that a single measure of "temporal resolution" is inadequate to reflect the complex psychoacoustic processes involved (Elmer et al. 2023).

In addition to objective threshold measurement, ABR amplitudes and the number of measurable responses generally decreased as the gap duration decreased for both paradigms. This pattern in amplitude aligns with previous studies using noise and paired click paradigms (Bidelman and Khaja 2014; Duda-Milloy et al. 2019; Poth et al. 2001). As gap duration reduced, the latencies of ABRs to the second click within the 2C paradigm rose but this was only significant between 4 and 2 ms gap durations. For TNNC, differences were only significant between 15 to 8 ms. Cheng and Champlin (2021) used paired clicks and Poth et al. (2001) used noise as the stimulus in ABR studies of temporal resolution and also found that ABR latencies increased as the duration of the gap decreased.

An aim of our study was to overcome one limitation of previous works using ABR for the assessment of temporal resolution, in that others have relied on visual inspection of the ABR. As an alternative, we used statistical detection methods to evaluate the presence of responses, enhancing the objectivity of the ABR assessment. F_{sp}, and HT^2 objective detection methods have been reported in previous studies to be promising for automatically detecting ABRs (Chesnaye et al. 2018, 2021; Lv, Simpson, and Bell 2007) with HT^2 providing better detection sensitivity and test-time compared to alternative approaches including F_{sp}

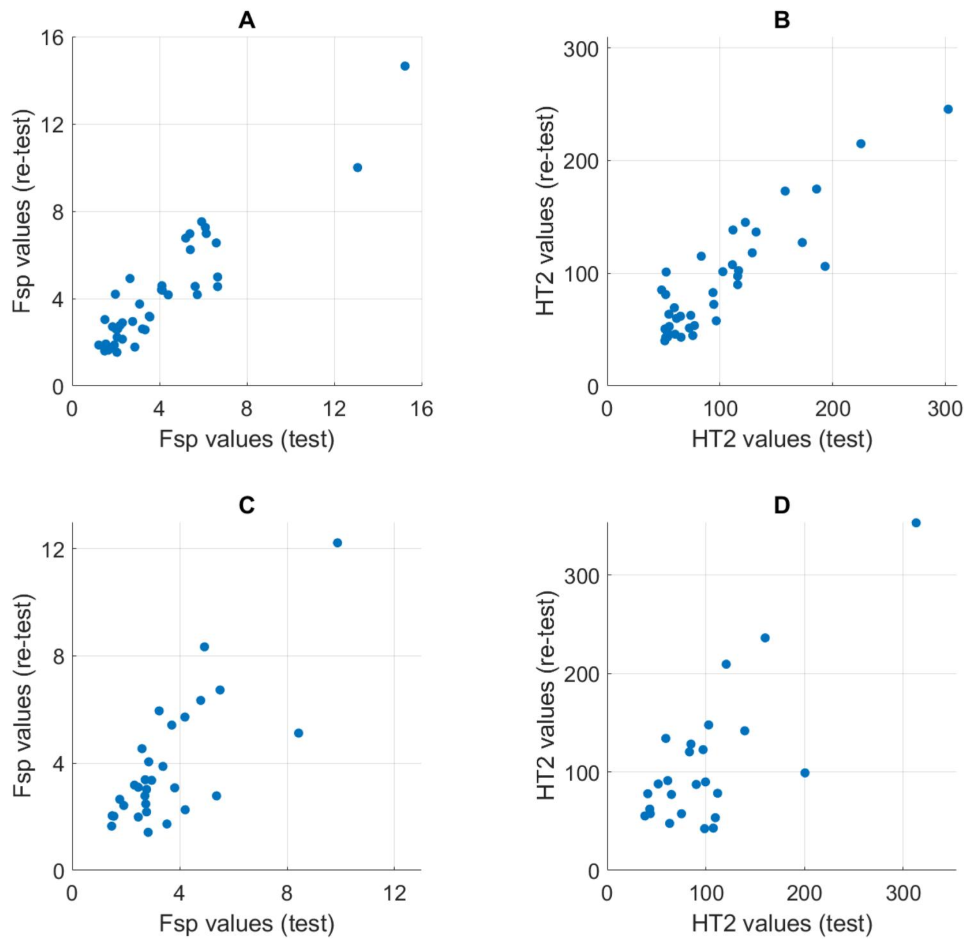

Figure 7. A: F_{sp} values of ABRs to the Two Clicks in test and re-test sessions. B: Hotelling's T^2 (HT2) values of ABRs to the Two Clicks in test and re-test sessions. C: F_{sp} values of ABRs to the Temporal Notched Noise with Click in test and re-test sessions. D: Hotelling's T^2 (HT2) values of ABRs to the Temporal Notched Noise with Click in test and re-test sessions.

(Chesnaye et al. 2018). In the current study, we compared F_{sp} and HT^2 approaches, using bootstrapping to determine statistical significance of responses and found that both methods showed good consistency for response detection without significant differences.

Experimental paradigms were developed with the aim of keeping measurement times acceptable for potential clinical application. We used a shorter generated stimulus duration (approximately 50 ms) compared to previous studies: Poth et al. (2001) used epoch durations up to 164 ms; Werner et al. (2001) used an 80 ms including ISI. However, more averaging than previously reported was applied to obtain acceptable response quality. This meant that the ABR test duration for both 2C and TNNC paradigms exceeded 30 minutes each, due to the large number of epochs recorded and the testing of multiple gap durations. Such recording durations could represent a challenge for the clinical application of the methods.

Test duration could potentially be shortened further by implementing a descending procedure, for example, starting with an easily detectable gap duration and progressively decreasing it until no response is present, rather than recording all predefined gap durations and/or with using adaptive step sizes. Another alternative approach might be a sequential test procedure, such as proposed in Stürzebecher and Cebulla (2013) or Chesnaye et al. (2020). Based on the current encouraging results, such a follow-on study should be carried out.

When responses were present, there was high correlation in the F_{sp} and HT^2 values across sessions for both paradigms (see Figure 7 and corresponding ICC values). Test-retest reliability analysis revealed better overall reliability and consistency in response presence for TNNC compared to the 2C paradigm, so TNNC may have better utility for clinical and research applications. However, neither paradigm demonstrated strongly repeatable temporal resolution threshold measurement across the small cohort of normal hearing individuals.

Whilst both electrophysiological and behavioural methods assess temporal processing, they reflect different aspects of the auditory system. ABR primarily captures peripheral auditory function through early neural responses, yet behavioural temporal resolution measurements also depend on central auditory mechanisms, which reflect complex sound features over time (Zatorre and Belin 2001). This difference may contribute to the lack of correlation between ABR-derived temporal resolution thresholds and behavioural thresholds.

A further potential challenge for the clinical application of the current methods is the individual variability seen in responses. Whilst group trends can be clearly seen, such as the reduction in ABR amplitude as gap duration reduces (see Figure 5, solid line showing group average results), individual amplitude measurements are variable and do not show clear trends with gap duration (see fainter lines indicating individual subject amplitudes in Figure 5). The variability in individual recordings may also explain why we did not see a significant correlation between ABR gap thresholds and behavioural thresholds in the current study. The variability in individual responses will be a challenge for defining individual temporal resolution thresholds for clinical applications.

One specific issue is that the subtraction process used in the 2C paradigm is likely to increase noise levels compared to the TNNC approach. In theory, when one ABR is subtracted from another, noise level increases by 3 dB. Additionally, it is important to consider the residual ABR responses observed in the paired-click paradigm after response subtraction. The amplitude of response to the first click in a pair was lower compared to single-click responses, leaving a residual peak after subtraction. This pattern aligns with findings from Burkard and Deegan (1984), who noted that second click could induce adaptation in the first click ABR (in the following epoch). The residual activity after subtraction suggests incomplete adaptation, which may contribute to residual peaks and potential false positives at shorter gap durations. The TNNC paradigm demonstrated better response detection reliability than the 2C paradigm between test and retest. Hence the TNNC approach may be better suited for clinical measurement.

Our study focused on individuals with normal-hearing. Further research is needed to evaluate the performance of these paradigms in populations with reduced temporal resolution, such as older adults or individuals with auditory processing disorders. Such studies would be crucial for assessing the clinical efficacy of these methods in identifying and monitoring temporal processing deficits, as well as distinguishing individuals with impaired temporal resolution from healthy controls. If the efficacy of the paradigms can be demonstrated, then potential clinical applications could include objective detection of temporal processing deficits and tailoring auditory rehabilitation strategies to individual needs, thereby potentially improving speech perception.

Our findings suggest that the 2C and the TNNC paradigm (with better repeatability) in ABR could be useful tools for determining objective gap detection in humans, at least on a group level. Detection of responses on an individual basis and definition of individual objective thresholds appears more challenging.

5. Conclusions

This study demonstrates the potential of ABR-based paradigms, particularly the TNNC, for objectively assessing temporal resolution thresholds. We found average objective gap thresholds of approximately 4 ms with the 2C paradigm and 3.2 ms with the TNNC paradigm, and around 2 ms with psychophysical methods, broadly consistent with literature using both behavioural and electrophysiological methods.

The integration of objective statistical detection methods represents a significant step towards fully automated evaluation of temporal processing abilities. While these methods show promise for group-level analyses, further refinement is needed to enhance their reliability for individual assessment.

These findings contribute to ongoing efforts to improve the diagnosis and treatment of suprathreshold hearing impairments. Further work is needed to validate the reliability and diagnostic potential of objective temporal resolution measures in patients with hearing loss or auditory processing disorders. Demonstrating such reliability could potentially lead to tailoring of therapeutic approaches and hearing aid characteristics such as compression times to individuals.

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References

American Speech-Language-Hearing Association. 2005. *(Central) Auditory Processing Disorders* [Technical Report]. American Speech-Language-Hearing Association. www.asha.org/policy

Bidelman, G. M., and S. P. Bhagat. 2017. "Cochlear, Brainstem, and Psychophysical Responses Show Spectrotemporal Tradeoff in Human Auditory Processing." *Neuroreport* 28 (1):17–22. https://doi.org/10.1097/WNR.0000000000000714.

Bidelman, G. M., and A. S. Khaja. 2014. "Spectrotemporal Resolution Tradeoff in Auditory Processing as Revealed by Human Auditory Brainstem Responses and Psychophysical Indices." *Neuroscience Letters* 572:53–57. https://doi.org/10.1016/j.neulet.2014.04.037.

Burkard, R., and D. Deegan. 1984. "Brainstem Evoked Responses to Paired-Click Stimuli: The Use of Digital Response Subtraction." *Audiology: official Organ of the International Society of Audiology* 23 (1):85–98. https://doi.org/10.3109/00206098409072824.

Cesur, S., and E. U. Derinsu. 2017. "Effect of Aging on Temporal Resolution." *Turkish Journal of Geriatrics/Türk Geriatri Dergisi* 20 (3):178–186.

Cheng, F.-Y., and C. A. Champlin. 2021. "Auditory Brainstem Responses to Successive Sounds: Effects of Gap Duration and Depth." *Audiology Research* 11 (1):38–46. https://doi.org/10.3390/audiolres11010005.

Chermak, G. D., and F. E. Musiek. 2013. *Handbook of Central Auditory Processing Disorder, Volume II: Comprehensive Intervention*. Vol. 2. San Diego: Plural Publishing.

Chesnaye, M., S. Bell, J. Harte, and D. Simpson. 2018. "Objective Measures for Detecting the Auditory Brainstem Response: Comparisons of Specificity, Sensitivity and Detection Time." *International Journal of Audiology* 57 (6):468–478. https://doi.org/10.1080/14992027.2018.1447697.

Chesnaye, M., S. Bell, J. Harte, and D. Simpson. 2021. "Controlling Test Specificity for Auditory Evoked Response Detection Using a Frequency Domain Bootstrap." *Journal of Neuroscience Methods* 363:109352. https://doi.org/10.1016/j.jneumeth.2021.109352.

Chesnaye, M. A., S. L. Bell, J. M. Harte, and D. M. Simpson. 2020. "The Convolutional Group Sequential Test: Reducing Test Time for Evoked Potentials." *IEEE Transactions on Bio-Medical Engineering* 67 (3):697–705. https://doi.org/10.1109/TBME.2019.2919696.

Dimitrijevic, A., J. Alsamri, M. S. John, D. Purcell, S. George, and F.-G. Zeng. 2016. "Human Envelope Following Responses to Amplitude Modulation: Effects of Aging and Modulation Depth." *Ear and Hearing* 37 (5):e322–e335. https://doi.org/10.1097/AUD.0000000000000324.

Duda-Milloy, V., E. Zorbas, D. L. Benoit, and A. Koravand. 2019. "Using the Auditory Brainstem Response Elicited by Within-Channel Gaps to Measure Temporal Resolution." *Canadian Acoustics* 47 (2):15–22.

Efron, B., and R. LePage. 1992. *Introduction to bootstrap*. New York: Wiley & Sons.

Elberling, C., and M. Don. 1984. "Quality Estimation of Averaged Auditory Brainstem Responses." *Scandinavian Audiology* 13 (3):187–197. https://doi.org/10.3109/01050398409043059.

Elmer, S., I. Kurthen, M. Meyer, and N. Giroud. 2023. "A Multidimensional Characterization of the Neurocognitive Architecture Underlying Age-Related Temporal Speech Processing." *NeuroImage* 278:120285. https://doi.org/10.1016/j.neuroimage.2023.120285.

Gallun, F. J., A. C. Diedesch, L. R. Kubli, T. C. Walden, R. L. Folmer, M. S. Lewis, D. J. McDermott, S. A. Fausti, and M. R. Leek. 2012. "Performance on Tests of Central Auditory Processing by Individuals Exposed to High-Intensity Blasts." *Journal of Rehabilitation Research and Development* 49 (7):1005–1025. https://doi.org/10.1682/jrrd.2012.03.0038.

Garner, W. 1947. "The Effect of Frequency Spectrum on Temporal Integration of Energy in the Ear." *The Journal of the Acoustical Society of America* 19 (5):808–815. https://doi.org/10.1121/1.1916625.

Gelfand, S. A. 2017. *Hearing: An Introduction to Psychological and Physiological Acoustics*. Boca Raton: CRC Press.

Giannela Samelli, A., and E. Schochat. 2008. "The Gaps-In-Noise Test: Gap Detection Thresholds in Normal-Hearing Young Adults." *International Journal of Audiology* 47 (5):238–245. https://doi.org/10.1080/14992020801908244.

Hall, J. 2017. "Update on Auditory Evoked Responses: Evidence-Based ABR Protocol for Infant Hearing Assessment." Audiology, *19040.*

Hoover, E., L. Pasquesi, and P. Souza. 2015. "Comparison of Clinical and Traditional Gap Detection Tests." *Journal of the American Academy of Audiology* 26 (6):540–546. https://doi.org/10.3766/jaaa.14088.

Jafari, Z., M. Esmaili, A. Delbari, M. Mehrpour, and M. H. Mohajerani. 2016. "Auditory Temporal Processing Deficits in Chronic Stroke: A Comparison of Brain Damage Lateralization Effect." *Journal of Stroke and Cerebrovascular Diseases: The Official Journal of National Stroke Association* 25 (6):1403–1410. https://doi.org/10.1016/j.jstrokecerebrovasdis.2016.02.030.

John, A. B., J. W. HallIII, and B. M. Kreisman. 2012. "Effects of Advancing Age and Hearing Loss on Gaps-In-Noise Test Performance."

Lavasani, A. N., G. Mohammadkhani, M. Motamedi, L. J. Karimi, S. Jalaei, F. S. Shojaei, A. Danesh, and H. Azimi. 2016. "Auditory Temporal Processing in Patients with Temporal Lobe Epilepsy." *Epilepsy & Behavior: E&B* 60:81–85. https://doi.org/10.1016/j.yebeh.2016.04.017.

Lee, J.-H., M. Y. Lee, J. E. Choi, and J. Y. Jung. 2020. "Auditory Brainstem Response to Paired Click Stimulation as an Indicator of Peripheral Synaptic Health in Noise-Induced Cochlear Synaptopathy." *Frontiers in Neuroscience* 14:596670. https://doi.org/10.3389/fnins.2020.596670.

Leigh-Paffenroth, E., and C. G. Fowler. 2006. "Amplitude-Modulated Auditory Steady-State Responses in Younger and Older Listeners." *Journal of the American Academy of Audiology* 17 (8):582–597. https://doi.org/10.3766/jaaa.17.8.5.

Lorenzi, C., and B. C. Moore. 2007. "Role of Temporal Envelope and Fine Structure Cues in Speech Perception: A Review." In *Proceedings of the International Symposium on Auditory and Audiological Research*,

Lv, J., D. M. Simpson, and S. L. Bell. 2007. "Objective Detection of Evoked Potentials Using a Bootstrap Technique." *Medical Engineering & Physics* 29 (2):191–198. https://doi.org/10.1016/j.medengphy.2006.03.001.

Marler, J. A., and C. A. Champlin. 2005. "Sensory Processing of Backward-Masking Signals in Children with Language-Learning Impairment as Assessed with the Auditory Brainstem Response." *Journal of Speech, Language, and Hearing Research* 48 (1):189–203.

Moon, I. J., and S. H. Hong. 2014. "What is Temporal Fine Structure and Why Is It Important?" *Korean Journal of Audiology* 18 (1):1–7. https://doi.org/10.7874/kja.2014.18.1.1.

Moon, I. J., J. H. Won, M.-H. Park, D. T. Ives, K. Nie, M. G. Heinz, C. Lorenzi, and J. T. Rubinstein. 2014. "Optimal Combination of Neural Temporal Envelope and Fine Structure Cues to Explain Speech Identification in Background Noise." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 34 (36):12145–12154. https://doi.org/10.1523/JNEUROSCI.1025-14.2014.

Moore, B. C. 2008. "The Role of Temporal Fine Structure Processing in Pitch Perception, Masking, and Speech Perception for Normal-Hearing and Hearing-Impaired People." *Journal of the Association for Research in Otolaryngology: JARO* 9 (4):399–406. https://doi.org/10.1007/s10162-008-0143-x.

Moore, B. C. 2012. *An introduction to the Psychology of Hearing*. Bingley: Emerald Group Publishing.

Moore, D. R., and C. Füllgrabe. 2020. "Cognitive Contributions to Hearing in Older People." *Journal of Hearing Science* 2 (4):58–60.

Musiek, F. E., J. B. Shinn, R. Jirsa, D.-E. Bamiou, J. A. Baran, and E. Zaida. 2005. "GIN (Gaps-In-Noise) Test Performance in Subjects with Confirmed Central Auditory Nervous System Involvement." *Ear and Hearing* 26 (6): 608–618. https://doi.org/10.1097/01.aud.0000188069.80699.41.

Mussoi, B. S., and C. J. Brown. 2019. "Age-Related Changes in Temporal Resolution Revisited: Electrophysiological and Behavioral Findings from Cochlear Implant Users." *Ear and Hearing* 40 (6):1328–1344. https://doi.org/10.1097/AUD.0000000000000732.

Palmer, S. B., and F. E. Musiek. 2014. "Electrophysiological Gap Detection Thresholds: Effects of Age and Comparison with a Behavioral Measure." *Journal of the American Academy of Audiology* 25 (10):999–1007. https://doi.org/10.3766/jaaa.25.10.8.

Phillips, D. P. 1999. "Auditory Gap Detection, Perceptual Channels, and Temporal Resolution in Speech Perception." *Journal of the American Academy of Audiology* 10 (6):343–354. https://doi.org/10.1055/s-0042-1748505.

Poth, E. A., F. A. Boettcher, J. H. Mills, and J. R. Dubno. 2001. "Auditory Brainstem Responses in Younger and Older Adults for Broadband Noises Separated by a Silent Gap." *Hearing Research* 161 (1–2):81–86. https://doi.org/10.1016/s0378-5955(01)00352-5.

Purcell, D. W., S. M. John, B. A. Schneider, and T. W. Picton. 2004. "Human Temporal Auditory Acuity as Assessed by Envelope Following Responses." *The Journal of the Acoustical Society of America* 116 (6):3581–3593. https://doi.org/10.1121/1.1798354.

Rabelo, C. M., J. A. Weihing, and E. Schochat. 2015. "Temporal Resolution in Individuals with Neurological Disorders." *Clinics (Sao Paulo, Brazil)* 70 (9):606–611. https://doi.org/10.6061/clinics/2015(09)02.

Shen, Y., and V. M. Richards. 2013. "Temporal Modulation Transfer Function for Efficient Assessment of Auditory Temporal Resolution." *The Journal of the Acoustical Society of America* 133 (2):1031–1042. https://doi.org/10.1121/1.4773271.

Stürzebecher, E., and M. Cebulla. 2013. "Automated Auditory Response Detection: Improvement of the Statistical Test Strategy." *International Journal of Audiology* 52 (12):861–864. https://doi.org/10.3109/14992027.2013.822995.

Vercammen, C., T. Goossens, J. Undurraga, J. Wouters, and A. van Wieringen. 2018. "Electrophysiological and Behavioral Evidence of Reduced Binaural Temporal Processing in the Aging and Hearing Impaired Human Auditory System." *Trends in Hearing* 22: 2331216518785733. https://doi.org/10.1177/2331216518785733.

Werner, L. A., R. C. Folsom, L. R. Mancl, and C. L. Syapin. 2001. "Human Auditory Brainstem Response to Temporal Gaps in Noise."

Wilcox, R. R. 2010. "The bootstrap." In *Fundamentals of Modern Statistical Methods*, edited by R. R. Wilcox, 87–108. New York: Springer.

Zatorre, R. J., and P. Belin. 2001. "Spectral and Temporal Processing in Human Auditory Cortex." *Cerebral Cortex (New York, N.Y.: 1991)* 11 (10):946–953. https://doi.org/10.1093/cercor/11.10.946.