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Forward Masking of the Speech-Evoked Auditory Brainstem Response

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Abstract

Hypothesis—The hypothesis tested was that forward masking of the speech-evoked auditory brainstem response (sABR) increases peak latency as an inverse function of masker-signal interval (t), and that the overall persistence of forward masking is age dependent.

Background—Older listeners exhibit deficits in forward masking. If forward-masked sABRs provide an objective measure of the susceptibility of speech sounds to prior stimulation, then this provides a novel approach to examining the age dependence of temporal processing.

Methods—A /da/ stimulus forward masked by speech-shaped noise ($t = 4 - 64$ ms) was used to measure sABRs in 10 younger and 9 older participants. Forward masking of sub-segments of the /da/ stimulus ($t = 16$ ms) and click trains ($t = 0 - 64$ ms) was also measured.

Results—Forward-masked sABRs from young participants showed an increase in latency with decreasing t for the initial peak. Latency shifts for later peaks were smaller and more uniform. None of the peak latencies returned to baseline by $t = 64$ ms. Forward-masked /da/ sub-segments showed peak latency shifts that did not depend simply on peak position, while forward-masked click trains showed latency shifts that were dependent on click position. The sABRs from older adults were less robust but confirmed the viability of the approach.

Conclusion—Forward masking of the sABR provides an objective measure of the susceptibility of the auditory system to prior stimulation. Failure of recovery functions to return to baseline suggests an interaction between forward masking by the prior masker and temporal effects within the stimulus itself.

Introduction

Older listeners, even those with relatively normal audiograms, are less able to benefit from the sporadic glimpses of target speech that occur when a fluctuating background noise is in a momentary lull (1–3). This reduced ability to take advantage of the brief low-energy epochs in the masker is due in part to age-related deficits in temporal processing that manifest as increased susceptibility to forward masking. Advanced age is associated with higher

forward-masked thresholds (4,5), as well as a greater persistence of forward masking – i.e., slower recovery from prior stimulation (6,7) – as shown using both simple tonal and speech-shaped noise signals. Fogerty et al. (8) have demonstrated a complex interplay between age-related deficits in forward masking and the differential vulnerability of subclasses of phonemes to such masking. Specifically, vowels are more resilient to forward masking than consonants, and older listeners show more gradual recovery functions from forward masking of these phonemes. Given these findings regarding the susceptibility of speech sounds to forward masking as a function of listener age, it is pertinent to consider whether an objective measure of forward masking can be tailored to focus on the issue of the fidelity of encoded speech sounds under conditions of forward masking.

One candidate objective measure for the assessment of forward masking is the auditory brainstem response (ABR), which is an electrophysiological gauge of synchronous neural response to sound in the peripheral auditory neural pathway. The sounds used to elicit the ABR are typically brief and/or abrupt, such as clicks or tone bursts, since the ABR is primarily an onset response (9). Using tone bursts, Walton et al. (10) demonstrated that the ABR in audiometrically normal older listeners is more susceptible to prior stimulation than it is in younger listeners. This increased susceptibility to forward masking was seen primarily as a more pronounced prolongation of the ABR Wave V latency as a function of the time interval between the offset of the prior masking sound and the onset of the tone burst signal – an interval commonly referred to as t . Specifically, Walton et al. (10) found that the latency of Wave V was more prolonged at the shorter t 's (4 – 16 ms) in older listeners than in young listeners but that the recovery functions converged at the longer t 's (≥ 32 ms). This effect was somewhat frequency specific in that it was evident for the higher frequency tone bursts of 4000 Hz and 8000 Hz but not convincingly so for 1000 Hz. In considering such electrophysiological measures of forward masking, it is important to recognize the caveat that the recovery functions measured with these techniques are unlikely to exactly mirror those measured psychophysically. For example, Turner et al. (11) demonstrated a clear dissociation between psychophysical and neural recovery functions from forward masking in chinchillas. Nevertheless, ABR measures provide a valid assessment of the susceptibility of the auditory system to prior stimulation.

The tone-burst stimuli used in the Walton et al. (10) study were brief – no longer than about 4 ms – and thus were devoid of any of the complexities of speech sounds. In recent years there has been increasing interest in using the ABR to capture the encoding of more complex, naturalistic stimuli such as speech. The ABR elicited by speech sounds is referred to as the speech-evoked ABR (sABR). One of the most common stimuli used to elicit the sABR is a synthetic /da/ phoneme generated by the Kraus laboratory at Northwestern University, and the use of this stimulus has propagated through many investigations (for review, see 12). In the context of age-related effects in sABRs, a number of studies have used this /da/ stimulus (or variations of it) to demonstrate diminished neural synchrony in the senescent auditory system, even in older listeners who retain good audiometric hearing (e.g., 13,14,15). The /da/-evoked sABR therefore appears to be an optimal procedure with which to objectively examine age-related effects in forward masking within a speech-relevant framework. In addition to its naturalistic features, the relatively long duration of the 40-ms /da/ stimulus allows for a gauge of the persistence of forward masking across the time

span of the response window. The purpose of this study, therefore, was to develop a forward-masked sABR protocol with a view to characterizing deficits in temporal processing associated with aging. Successful development of a robust, objective measurement tool might contribute to the clinical assessment of speech-in-noise difficulties experienced by older listeners. The preponderance of this report focuses on reference performance for young, normal-hearing adults. Preliminary results from older adults with relatively normal audiometric hearing are also noted.

Materials & Methods

Subjects

The primary participant pool comprised 16 young adults (13 female) aged 21 – 32 years (median = 24 years). All had audiometric thresholds ≤ 20 dB HL across the octave frequencies 250 – 8000 Hz. All had normal otoscopic exams, and tympanometry indicated normal middle ear function. Ten of these subjects participated in the main experiment; the remaining six participated in combinations of the auxiliary study (reported as Supplemental Digital Content 1) and/or the supplementary experiment (see below). In addition to these young adults, a cohort of nine older listeners (5 female), ranging in age from 60 – 75 years (median = 70 years), participated in the main experiment. They all had audiometric hearing within normal limits across the frequency range 250 – 4000 Hz, with thresholds ≤ 20 dB HL, except for one participant with a threshold of 25 dB HL at 4000 Hz. However, most had some degree of threshold elevation at 8000 Hz. All subjects provided written informed consent and were remunerated for their participation. This study was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Stimuli

The stimulus used to elicit the sABR was the 40-ms synthetic /da/ that originated from the Kraus laboratory at Northwestern University. A detailed description of this stimulus can be found in Skoe et al. (12), and the time waveform is displayed in the upper left section of Figure 4. The level of this stimulus was defined in terms of the dB SPL of a 1000-Hz sine wave to which it was peak-to-peak equivalent (dB ppeSPL). The masker was a speech-shaped noise 100 ms in duration including 10-ms rise/fall ramps. The spectral shape of this noise was based on the long-term average spectrum of multi-lingual speech defined by Byrne et al. (16). Pilot work using the recording procedure outlined below indicated that the optimal presentation levels were 75 dB SPL for the masker and 70 dB ppeSPL for the /da/ stimulus. A /da/ stimulus at this level elicited a relatively robust sABR in quiet yet showed marked susceptibility to the 75-dB SPL masker when the masker offset was abutted to the stimulus onset (i.e., $t = 0$ ms). In the main experiment, four t 's were tested: 4, 16, 32, and 64 ms; responses to the unmasked signal alone were also measured making a total of five stimulus conditions. In the supplementary experiment, the /da/ stimulus was subdivided into four sequential segments, each about 10 ms in duration (see time waveforms in Figure 4). The segmentation occurred at zero-crossings in the time waveform and no further ramping was imposed. The supplementary experiment also employed a click-train stimulus, and is described later. In all conditions, the stimuli were presented monaurally to the right ear in alternating phase using an insert phone. The presentation rate was 3.77 Hz.

Recording set-up

A two-channel recording system was implemented, although only the data from the midline channel were analyzed. The electrode montage consisted of a high-forehead midline electrode that provided the non-inverting input to each channel. The inverting electrode to one channel was placed at midline on the nape of neck, and that of the other channel was placed on the right earlobe. The ground electrode was placed on the low forehead between the eyebrows. Electrode impedances were maintained at $< 3 \text{ k}\Omega$. The electroencephalographic (EEG) recordings were filtered on-line between 50 – 3000 Hz and sampled at 40 kHz, with an artifact rejection level set to 15 μV . For each stimulus condition, two replications with 2048 sweeps per average were recorded. Occasionally, a third recording was obtained if the quality of the initial two traces was unsatisfactory. Off line, all replications for each condition were averaged together for each subject and re-filtered from 50–2000 Hz. The stimulation and recording set-ups were implemented on an Intelligent Hearing Systems SmartEP platform (IHS, Miami, FL).

Procedure

Each subject was tested in a darkened, double-walled sound booth within an electromagnetically shielded room. The subject reclined in a comfortable chair and was encouraged to sleep during the testing. Because each run took approximately 10 minutes to complete, a full data set of at least two replications of each of multiple conditions usually took two or more recording sessions spread across several days.

Results & Discussion

Early in the project, it was observed that the morphology of the sABR elicited with the IHS system consisted of several prominent vertex-positive peaks, which contrasted somewhat with the morphology often reported by other groups (e.g., 17). In those reports, more prominent vertex-negative peaks are described and, indeed, a nomenclature has been developed based on these negative peaks (18). In order to rigorously address this issue of response morphology, an auxiliary study was undertaken in which the /da/ stimulation was consistently provided by the IHS system, and this IHS system was also used to synchronously (externally) trigger two independent recording systems, a Bio-logic Navigator Pro (Pleasanton, CA) and a Compumed Neuroscan (Charlotte, NC). Responses to the same unmasked /da/ stimulus were therefore collected on three different platforms using the same subjects and electrode montage, and using recording parameters that were as similar as possible across platforms. The results of this auxiliary study (reported as Supplemental Digital Content 1) showed similar sABRs across systems, and the morphology of these responses continued to differ somewhat to that often reported by other groups (e.g., 17). The reasons for these differences are not clear but continue to be a topic of active investigation.

Because the auxiliary study strongly supported the use of the vertex-positive peaks in the IHS recordings for measurements of peak latency – the key metric to be used in this investigation – a separate nomenclature was therefore implemented here as a matter of convenience. The peaks of interest were labelled with a prefix ‘P’ to denote vertex positivity,

followed by a second letter. Because the first prominent peak corresponds to the ABR Wave V (as it does in the Kraus lab nomenclature (18)), this peak was labeled 'PV', after transcribing the Roman numeral V to the letter V; the subsequent four prominent vertex-positive peaks were then simply assigned the remaining four letters of the alphabet 'PW', 'PX', 'PY' and 'PZ'.

Main Experiment

The sABRs from 10 young subjects are shown in Figure 1. The sets of traces, from top to bottom, are the recordings for $t = 4, 16, 32$, and 64 ms, as well as the signal alone, respectively. In each set of traces, the light grey lines indicate the individual sABRs, and the black heavy line is the group average response. For reference, vertical dashed lines have been aligned with peaks PV-to-PZ in the signal-alone condition. The mean latency (and standard deviation) in ms for each peak in this signal-alone condition is also provided below the peak label. The vertical lines facilitate the observation that there is an increase in PV latency as t is reduced. This dependency of peak latency on t is less apparent for the later peaks. To quantify the shifts in latency with changing t for each subject, the latencies of the unmasked, signal-alone sABR peaks were used as the reference. Therefore, for each subject, the *shifts* in latency of peaks PV-to-PZ relative to the reference peak latencies in the unmasked sABR were computed. These latency shifts averaged across the 10 subjects are shown in Figure 2. Latency shift is plotted as a function of t with sABR peak as the parameter. The inverse relationship between PV latency shift and t is apparent, as is the relative constancy of latency shift with t for the other response peaks. The latency shift data were submitted to a repeated-measures analysis of variance (RMANOVA) with two within-subjects factors (t and *peak*). The analysis indicated a significant effect of t ($F[3,27] = 12.25$; $p < 0.001$) and *peak* ($F[4,27] = 27.69$, $p < 0.001$) and a significant interaction between these factors ($F[12,108] = 22.55$; $p < 0.001$). To interpret the interaction term, post-hoc pair-wise comparisons were undertaken with Bonferroni correction for multiple comparisons. This analysis indicated that the latency shift of PV exceeded that of the other peaks at each t except $t = 64$ ms. The latency shifts of peaks PW, PX, PY, and PZ did not differ amongst themselves. By way of comparison with published results, the shift in PV latency for $t = 4$ ms was about 1.3 ms which corresponds well to the 1.2-ms Wave V latency shift at $t = 4$ ms found by Walton et al. (10) for ABRs from young adults evoked with 1-kHz tone bursts.

The complementary sABRs from nine older subjects are shown in Figure 3. Again, the light grey lines indicate the individual sABRs, and the heavy black line is the group average response. Vertical dashed lines are referenced to the group mean peaks in the signal-alone condition. There was little evidence of an offset response (PZ) and so no vertical dashed line is provided for this peak. Relative to the younger data in Figure 1, the responses from the older subjects are less robust. A qualitative comparison of the younger and older data in Figures 1 and 3 shows that the absolute peak latencies of older subjects are generally longer than for younger subjects. The qualitative comparison also highlights three trends: (1) PV is largely obliterated by forward masking in the older subjects whereas it continues to be present and shows an orderly dependence on t in the younger subjects; (2) PX continues to show a forward-masking latency shift in older subjects whereas no t -dependent latency

shifts are evident for this peak in the younger subjects; (3) PY appears to be relatively resilient to t -dependent latency shifts in both age groups. (These comparative trends are high-lighted in Supplemental Digital Content 2 which plots the three peaks in juxtaposition on an expanded time base.) If these trends are borne out quantitatively after further data collection, it would support the hypothesis that the sABR of older subjects is more susceptible to forward masking, and that forward masking persists out to later peaks in this age group.

Supplementary Study

One observation that was not initially anticipated in the main experiment was the relatively constant latency shift of about 0.2–0.4 ms across t for peaks PW, PX, PY, and PZ among the young subjects (see Figure 2). By comparison, Walton et al. (10) demonstrated a return to baseline of ABR Wave V latency shift for both younger and older subjects by about $t = 64$ ms. A key difference between studies was the type and duration of the stimulus. The ABRs of Walton et al. (10) were evoked by brief tone bursts, and such stimuli preclude the possibility of both intra-stimulus temporal masking effects (early stimulus segments forward masking later segments) and intra-stimulus adaptation effects (adaptation of the response during the presentation time course of a single stimulus). However, for longer stimuli both such effects are possible as has been demonstrated by Burkard and Hecox (19) in a study of forward-masked click trains. That study found that a click-train stimulus resulted in adaptation effects wherein responses to later clicks in the train were uniformly shifted in latency relative to those evoked by the early clicks, and that this dependency of latency shift on click position was further compounded by the forward masking produced by a preceding masker. One manifestation of this interaction was that the Wave V latency shift associated with the final click in the forward-masked click train response remained elevated by about 0.6 ms. This finding raises the possibility that analogous complexities are present in the sABR paradigm here wherein early segments of the 40-ms stimulus might affect responses evoked by later segments of the stimulus, and that these segment-dependent effects might interact with forward-masking effects associated with the masker itself. To investigate this possibility, a supplementary experiment was undertaken to measure the forward masking of isolated segments of the /da/ stimulus. The goal was to differentiate effects of the forward masker from effects that early stimulus segments might have on later stimulus segments within the full stimulus itself. This exercise allowed the persistence of forward masking on sequential sub-segments of the stimulus to be more clearly observed.

In the supplementary experiment, a series of sABRs were recorded evoked by sequential sub-segments of the /da/ stimulus. For each sub-segment, the sABR was recorded in quiet and in a forward-masked condition with $t = 16$ ms. This t was chosen because the main experiment showed it to be associated with substantial masking but also with robust responses. It is important to note that when the initial segments of the /da/ stimulus were removed, the ‘time zero’ point of the averaging epoch did not change; rather, the silent interval between the offset of the masker and the onset of the sub-segment signal was correspondingly increased by the duration of the excised /da/ waveform. The same masker and signal levels were used as in the main experiment. Six younger subjects were tested.

The group mean results are shown in Figure 4. The stimulus time waveforms comprising the left column of the figure show the full /da/ stimulus (top trace) and the extracted sub-segments sequentially below that. On the right side of the figure are the associated mean responses for the unmasked conditions (solid lines) and the forward-masked conditions (dotted lines). Numbered arrows reference peaks of interest for discussion. The primary focus of the supplementary study was on the pattern of peak latency shifts resulting from the forward masking of the various sub-segments of the stimulus. This was quantified by computing for each subject the shift in latency from baseline for each of the numbered peaks in Figure 4. The mean latency shifts are shown in Figure 5. Three important features of the data pattern can be highlighted. First, the greatest latency shift occurs for peak 1 evoked by the first sub-segment, which is to be expected since the effect of forward masking should be greatest for the stimulus sub-segment closest to the masker offset. Second, for each of the pairs of peaks evoked by sub-segments 2–4, the average latency shift of the second peak appears to be less than that of the first peak (i.e., peak 2 > peak 3; peak 4 > peak 5; peak 6 > peak 7); this would be consistent with a recovery from forward masking function. However, pair-wise comparisons with Bonferroni correction for multiple comparisons shows this difference to be significant only for peaks 4 and 5 ($t(5) = 6.15$; $p = 0.002$) and peaks 6 and 7 ($t(5) = 4.05$; $p = 0.01$), but not for peaks 2 and 3 ($t(5) = 0.77$; $p = 0.475$). The third feature of note is that none of the latency shifts drop below about 0.4 ms. Whereas a complete return to baseline (latency shift of 0 ms) might not be expected for $t = 16$ ms, a linear recovery from forward masking would predict less effect on the responses to the final stimulus segment (e.g., peak numbers 6 and 7) than on earlier stimulus segments (e.g., peak numbers 2 and 3). The absence of a simple monotonicity suggests an interaction between forward masking effects and stimulus complexity, even within the isolated sub-segments.

To confirm the expectation that forward masking effects, per se, should be monotonic even for stimulus components distributed across time, a final set of conditions was run that were conceptually similar to the forward-masked click train paradigm of Burkard and Hecox (19). Here, a click train comprising four clicks with a 15-ms inter-click interval was forward masked by a white noise 100 ms in duration, including 10-ms rise/fall ramps. The level of each individual click was 95 ppeSPL and the masker was 75 dB SPL. The advantage of the click-train stimulus in the present context is that each ‘segment’ of the overall stimulus is identical. Unlike Burkard and Hecox (19), who used a fixed interval between the masker offset and the click-train onset of $t = 12.5$ ms, here the t was varied as in the main experiment with $t = 0, 4, 16, 32$ and 64 ms. Four young subjects were tested, and the recording procedure was otherwise identical to the main experiment.

The individual and group mean ABRs are shown in Supplemental Digital Content 3. Peak latency shifts relative to the unmasked baseline were computed for each individual, and the group mean latency shifts as a function of t are shown in Figure 6. The parameter is peak number – equivalent to click number in the train. The data pattern shows that the response to the first click in the click train is maximally shifted in latency at $t = 0$ ms, and exhibits a monotonic recovery from forward masking with increasing t which does not converge with the other peaks even by $t = 64$ ms. A similar pattern is evident for the response to the second click in the click train except that the initial latency shift is not as large, and the latency shift does converge with that of the later peaks within the range of t ’s tested here.

The responses to the third and fourth clicks show no t -dependent latency shifts. Note that none of the response peaks recover to baseline but, rather, exhibit a uniform latency shift of about 0.4 ms. Based on the work of Burkard and Hecox (19), this fixed offset is likely to reflect the asymptotic latency shift associated with intra-stimulus (click-on-click) adaptation rather than forward masking by the preceding white noise. Although only four subjects participated in these conditions, the monotonic behavior of the data for the click-train series, in contrast to that of the sequence of /da/ sub-segments, suggests that the stimulus complexities of the /da/ introduce additional factors that influence response peak latencies. In summary, the supplementary study supported the contention that the failure of all response peaks to return to baseline in the main experiment is due to an interaction between forward masking effects of the masker and the duration and complexity of the /da/ stimulus which allows for intra-stimulus effects.

Summary and Conclusion

The purpose of this study was to establish a forward-masked sABR protocol with a view to objectively assessing deficits in speech-related temporal processing associated with aging. It sought to test the hypotheses that forward masking of the sABR increases peak latency as an inverse function of t , and that the overall persistence of forward masking is age dependent. The results provided partial support for these hypotheses. First, responses from younger subjects did indicate that latency shifts of the first positive sABR peak (PV) provided a reliable monotonic metric of forward masking. Second, qualitative comparison of responses from younger and older listeners did suggest that forward masking persisted out to later sABR peaks in the older listeners.

However, the overall pattern of forward-masked sABR data revealed a more complex picture. This was likely due to an interaction between forward masking effects associated with the masker and intra-stimulus effects associated with the long-duration, complex stimulus. The pattern of recovery from forward masking was more straightforward for a click-train stimulus than for the speech sound stimulus. The preliminary work on older adults with relatively normal audiometric hearing confirmed the viability of the sABR approach. However, due to the reduced neural synchrony associated with this subject group (e.g., 13,15), the elicited sABRs were less robust, suggesting that additional parametric adjustments are necessary to improve the test outcomes. Such adjustments might include increasing the number of sweeps per average, selecting more streamlined t settings, and manipulating the stimulation levels. In terms of the latter factor, the time course of recovery from forward masking will depend on the relative levels of the masker and signal. For example, both Kramer and Teas (20) and Burkard and Hecox (19) found a continued shift of Wave V latency from baseline even for $t = 100$ ms for their particular level settings. Current work from this laboratory is examining these parametric manipulations.

In conclusion, this study demonstrates that the sABR provides a viable approach to the objective measurement of forward masking of naturalistic stimuli, and holds promise for the assessment of age-related deficits in temporal processing. Understanding the persistence of masking from prior stimulation – particularly in older listeners – will lead to a greater

appreciation of the controls needed over acoustic environments that are challenging for communication.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Fig. 1.

Forward-masked sABRs for the younger subjects grouped, from top to bottom, by increasing Δt with the lowest set of traces being the unmasked sABRs. In each set of traces, the light grey lines indicate individual sABRs and the black heavy line indicates the group average response. Vertical dashed lines mark the peaks in the mean signal-alone sABR that correspond to the peak labels displayed across the top of the plot. The average latencies (and standard deviations) of these unmasked peaks in units of ms are given below each label.

Fig. 2. Group mean shift in peak latency plotted as a function of Δt . The parameter is sABR peak. Error bars are 1 SD. Symbols have been offset slightly for clarity.

Fig. 3.

Forward-masked sABRs for the older subjects grouped, from top to bottom, by increasing Δt with the lowest set of traces being the unmasked sABRs. In each set of traces, the light grey lines indicate individual sABRs and the black heavy line indicates the group average response. Vertical dashed lines mark the peaks in the mean signal-alone sABR that correspond to the peak labels displayed across the top of the plot. PZ was not consistently present and therefore is not marked in these traces.

Fig. 4. Unmasked sABRs for the full /da/ stimulus (top row) and sub-segments of the /da/ (lower rows). Panels in the left column show the time waveforms of the stimuli. The respective mean sABRs are shown on the right side for the signal alone (solid line) and for $t = 16$ ms (dotted line). Numbered arrows refer to measured peaks.

Fig. 5.
Mean latency shifts for the numbered peaks in Figure 4. Error bars are ± 1 SD.

Fig. 6.

Group mean shift in peak latency plotted as a function of Δt . The parameter is the ABR peak associated with each click in the click train. Error bars are 1 SD. Symbols have been offset slightly for clarity.