Research Article

Aided Electrophysiology Using Direct Audio Input: Effects of Amplification and Absolute Signal Level

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Purpose: This study investigated (a) the effect of amplification on cortical auditory evoked potentials (CAEPs) at different signal levels when signal-to-noise ratios (SNRs) were equated between unaided and aided conditions, and (b) the effect of absolute signal level on aided CAEPs when SNR was held constant.

Method: CAEPs were recorded from 13 young adults with normal hearing. A 1000-Hz pure tone was presented in unaided and aided conditions with a linear analog hearing aid. Direct audio input was used, allowing recorded hearing aid noise floor to be added to unaided conditions to equate

SNRs between conditions. An additional stimulus was created through scaling the noise floor to study the effect of signal level.

Results: Amplification resulted in delayed N1 and P2 peak latencies relative to the unaided condition. An effect of absolute signal level (when SNR was constant) was present for aided CAEP area measures, such that larger area measures were found at higher levels.

Conclusion: Results of this study further demonstrate that factors in addition to SNR must also be considered before CAEPs can be used to clinically to measure aided thresholds.

Hearing aid amplification is one type of treatment used for those with impaired auditory systems. The primary goal of hearing aids is to improve audibility, which is achieved through various signal-processing algorithms that affect both temporal and spectral cues within a signal (Souza, 2002). Although modified spectral and temporal cues can improve speech perception, they can also be detrimental; for example, peaks and troughs in the spectrum may be reduced, distorting cues important for speech perception (Souza, Jenstad, & Folino, 2005). In these cases, acoustic changes that result from hearing aid signal processing alter how auditory input is encoded in the peripheral and central auditory system and, in turn, affect auditory perception.

Cortical auditory evoked potentials (CAEPs) are non-invasive electrophysiological measures of central auditory system function that may help to determine how hearing aid signal processing is affecting neural encoding and resulting

perception (Tremblay, Billings, Friesen, & Souza, 2006). To be specific, P1-N1-P2 CAEPs are sometimes used clinically to estimate hearing thresholds and is therefore a potential tool for measuring the neural representation and threshold of amplified sound (for a review see Martin, Tremblay, & Korczak, 2008). For these reasons, there is interest in using aided CAEPs clinically to assist with the hearing aid fitting process in hard-to-test populations such as infants (Golding et al., 2007; Purdy et al., 2005; Van Dun, Carter, & Dillon, 2012; Villaseñor, Dillon, & Martin, 2008) and adults (Carter, Dillon, Seymour, Seeto, & Van Dun, 2013); to evaluate hearing aid technologies such as frequency lowering (Glista, Easwar, Purcell, & Scollie, 2012; Zhang et al., 2014); and to assess the effectiveness of early intervention treatment with amplification (Gravel, Kurtzberg, Stapells, Vaughan, & Wallace, 1989; Rapin & Graziani 1967).

Despite 5 decades of aided CAEP research, several challenges remain for implementing these measures clinically because it can be difficult to disentangle where and when auditory-evoked brain activity is representing extrinsic (e.g., device-driven) versus intrinsic (e.g., neurophysiology capacity) qualities. For example, the amplitudes of N1 and P2 CAEPs are known to reflect the stimulating signal level (e.g., amplitude increases and latency decreases with increased signal intensity level; Rapin, Schimmel, Tourk, Krasnegor, & Pollak, 1966), and this is one reason why

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CAEPs have been used clinically to estimate hearing thresholds in hard-to-test populations. However, when signals are presented in background noise, the neural encoding of signal level is disrupted such that signal-to-noise ratio (SNR), rather than absolute signal presentation level, dominates the CAEP sensitivity (Billings, McMillan, Penman, & Gille, 2013; Billings, Tremblay, Stecker, & Tolin, 2009). Even in quiet conditions, noise is sometimes present in the hearing aid output and can interfere with CAEP intensity/latency patterns (Billings, Tremblay, Souza, & Binns, 2007). Although the source(s) of such extrinsic noise are unknown—possibly reflecting amplified ambient noise or hearing aid circuit noise—the impact this noise has on evoked cortical activity is important to understand (Tremblay & Miller, 2014).

It is important to study extrinsic contributions such as noise to CAEP patterns because they might contribute to inaccurate estimates of an individual's aided threshold and affect neural responses differently than would be expected on the basis of signal level alone (Billings, Papesh, Penman, Baltzell, & Gallun, 2012). The example of SNR is especially important to consider when measuring aided CAEPs to modifications in gain or other hearing aid settings, which may be variably affected by background noise levels (Billings, Tremblay, & Miller, 2011). Although recent aided CAEP studies have begun to measure SNR (Jenstad, Marynewich, & Stapells, 2012; Marynewich, Jenstad, & Stapells, 2012), our understanding of the effects of other important acoustic factors (e.g., modified temporal cues or stimulus onset modification) is still somewhat limited. In order to determine how SNR and other factors are contributing to CAEPs while wearing a hearing aid device, it is necessary to control for SNR across unaided and aided conditions. Therefore, one purpose of this study was to systematically control SNR while investigating other amplification effects.

Some studies have reported CAEP differences in unaided and aided conditions, but they did not equate SNRs (Gravel et al., 1989; Korczak, Kurtzberg, & Stapells, 2005; Miller & Zhang 2014; Rapin & Graziani, 1967). Therefore, reported amplification effects might have resulted from the change in SNR as well as signal modifications from the hearing aid. Only Easwar, Glista, Purcell, and Scollie (2012) have compared unaided and aided CAEPs while fixing SNR across conditions, and still, no amplification effects were found. SNRs were fixed by adding the hearing aid noise floor (taken from the aided condition) to the unaided signal. However, only one signal-level/SNR combination was used. It may be that amplification effects will be present at other signal levels.

The current study compares unaided and aided CAEPs across a range of signal levels while fixing SNR across conditions. Equivalent SNRs across unaided and aided conditions provide a means of investigating the effects of non-SNR-related hearing aid factors. The second purpose of this study was to determine whether an effect of absolute signal level is present for aided CAEPs when SNR is held constant. Although Billings et al. (2009) demonstrated no change in unaided CAEP morphology from an increase in absolute signal level at equated SNRs, hearing-aid-processed

stimuli may modify this result. Therefore, we also examined the effect of absolute signal level on aided CAEPs when presented at a constant SNR.

Two questions were asked: (a) What is the effect of amplification at different signal levels when SNRs are equated between unaided and aided conditions? We hypothesized that no amplification effect would be found at different signal levels. If unaided and aided CAEPs are similar at different signal levels when SNRs are equated, then one might conclude that SNR is the main contributing factor; however, if amplification effects are found when SNRs are equated, then non-SNR-related factors likely resulting from hearing aid modifications will be important to consider and understand when completing aided CAEP measurements clinically. (b) What is the effect of absolute signal level on aided CAEPs when SNR is held constant? We hypothesized that absolute signal level would not influence the morphology of aided CAEPs with a constant SNR.

Methods

Subjects

Thirteen right-handed young adults between 19 and 34 years old (average age = 24 years, $SD = 4.4$ years) participated in this study. Individuals with normal hearing were used in this study to eliminate the effects of hearing impairment on CAEPs. The subjects' right ear pure-tone hearing thresholds were less than or equal to 15 dB HL at 500, 1000, and 2000 Hz (pure tone average = 5 dB HL, $SD = 2.8$ dB HL). Subjects reported that they were in good general health with no significant history of otologic or neurologic disorders. Only right ears were tested in both unaided and aided conditions.

Hearing Aid

A digitally programmable analog behind-the-ear hearing aid was used. It was the same hearing aid programmed to the same frequency response used in our previous study (Billings et al., 2011). The processing strategy of the hearing aid was set to be linear to eliminate effects of compression because compression changes SNR (Naylor & Johannesson, 2009). The hearing aid was programmed to provide 20 dB of gain at 1000 Hz using hearing aid fitting software. All hearing aid settings, including gain setting, were held constant throughout the duration of testing at all conditions. Linear analog amplification is well understood and provided a means to study the most basic effects of amplification on CAEPs without the sophisticated, and often nontransparent, processing of digital hearing aids.

Stimuli

Experimental Design

The stimulus used in this study was a 1000-Hz pure tone with a rise/fall time of 7.5 ms and duration of 756 ms. Table 1 shows the experimental design of this study. As can be seen in the table, eight conditions (four unaided and

Table 1. Experimental design of stimuli and presentation levels measured by the sound level meter.

Condition	Experimental design			Measured presentation level		
	Signal (dB SPL)	Noise (dB SPL)	SNR (dB)	Signal (dB SPL)	Noise (dB SPL)	SNR (dB)
Unaided	80	40	40	81.0	42.2	38.8
	70	40	30	70.8	41.6	29.2
	60	40	20	60.6	40.0	20.6
	50	40	10	50.8	40.0	10.8
Aided	80	40	40	81.0	42.2	38.8
	70	40	30	70.8	41.8	29.0
	60	40	20	60.6	40.7	19.9
	50	40	10	50.7	40.0	10.7
	80	60	20	81.1	61.4	19.7

Note. dB = decibel; SPL = sound pressure level; SNR = signal-to-noise ratio.

four aided) with equated SNRs were used to address the first objective (i.e., determine the effect of amplification at different levels). To address the second objective, an additional aided condition was included to compare aided conditions with two different absolute signal levels but with identical SNRs (see bottom row in Table 1).

Stimulus Construction

All of the stimuli were processed by the hearing aid and recorded by the Brüel & Kjær (Nærum, Denmark) Head and Torso Simulator (HATS). The HATS mannequin allows for hearing aid–output recordings to be made from the ear canal at a point that approximates the location of the tympanic membrane. The PC-based sound generation system of the STIM2 Neuroscan system (Compumedics Neuroscan, Charlotte, NC) delivered the stimuli. In the unaided conditions, the tones were presented via an Etymotic ER2 insert earphone (Etymotic Research, Inc., Elk Grove Village, IL) and recorded using HATS. In the aided conditions, the tones were presented through a direct audio input (DAI) cable connected to the hearing aid, which was coupled to a foam stock earmold. The hearing aid output was recorded using HATS. The main reason for using the HATS system for recording stimuli in aided conditions was to provide better control over the processed signals and to avoid variability that may be introduced through sound-field presentation during electrophysiological measurement. This approach also allowed for the correction of any hearing aid processing delay. With DAI, the background noise level remained constant in the aided condition, so increases in signal level corresponded to increases in SNR, an effect that is not possible using acoustic input to the hearing aid in the sound field (Billings et al., 2007). The hearing aid noise floor, which was a broadband noise, was recorded for 132 s using DAI with a silent input signal. The hearing aid noise floor was then scaled and added to the recorded unaided stimuli in order to equate SNRs between unaided and aided conditions. An additional aided stimulus with an 80 dB sound-pressure level (SPL) tone, and 60 dB SPL noise was created by scaling the recorded hearing aid noise floor up to 60 dB SPL and then adding it to the aided 80 dB SPL tone, providing a stimulus to compare to the aided 60 dB SPL

tone/40 dB SPL noise stimulus. These latter two stimuli were created to investigate the effects of absolute signal level with a constant 20 dB SNR.

After creating stimuli, the output level of the sound presentation system was adjusted so that unaided and aided conditions levels were equivalent. Table 1 shows the sound pressure levels of signal, noise, and resulting SNRs measured with a sound level meter and a 2-cc coupler via ER3A insert earphone (Etymotic Research, Inc., Elk Grove Village, IL) for verification.

Electrophysiology

Evoked potential activity was recorded using an Electro-Cap International, Inc., cap (Eaton, OH), which housed 64 tin electrodes. The ground electrode was located on the forehead and the reference electrode was located at vertex during CAEP acquisition. Data were then rereferenced off-line to an average reference. Eye blink activity was monitored using electrodes located superiorly and inferiorly to both eyes. After electrodes were placed, the subject sat in a sound-treated room and was instructed to ignore the stimuli and watch a silent close-captioned movie of their choice. The stimuli were then presented to the right ear of each subject using an Etymotic ER3A insert earphone. The 1000-Hz stimulus was presented 200 times. Presentation order for the nine conditions (see Table 1 for details) was randomized. An interstimulus interval (offset to onset) of 1,910 ms was used. The subject was asked to minimize head and eye movement during the recording session. Trials containing eye-blink artifact were corrected offline. Neuroscan software was used to calculate the amount of covariation between each channel and vertical eye movement using a spatial singular value decomposition, which enables the removal of vertical eye-blink activity on a point-by-point basis to the degree that evoked activity and blink activity covaried. After blink correction, ocular artifacts exceeding $\pm 70 \mu\text{V}$ were rejected from averaging. The recording window consisted of a 200-ms prestimulus period and a 1100-ms poststimulus time. Evoked responses were analog band-pass filtered online from 0.15 to 100 Hz (12 dB/octave roll off). All channels were amplified with gain $\times 500$, and converted using an analog-to-digital

sampling rate of 1000 Hz. Following ocular artifact rejection, the remaining sweeps were averaged and filtered offline from 1 Hz (high-pass filter, 24 dB/octave) to 30 Hz (low-pass filter, 12 dB/octave).

Data Analysis

To compare results to our previously published studies, growth patterns from electrode Cz were analyzed and reported. Results from electrodes T7 and T8 were also included so as to characterize the effects of level and amplification on the T-complex, whose sources are thought to be distinct from vertex-recorded N1 and P2 waves (McCallum & Curry, 1980; Wolpaw & Penry, 1975). Peak amplitudes were determined relative to the prestimulus baseline. Peak latencies were determined relative to stimulus onset (i.e., 0 ms). Latency and amplitude values of each wave were determined by agreement of two judges using temporal electrode inversion, global field power traces, even and odd bin waveforms, and grand averages to determine peaks for a given condition. One of the judges was blind to stimulus conditions to reduce possible bias. Disagreements between judges occurred for 3% of peaks and were resolved by a third judge. As an unbiased measure of cortical activity, rectified area amplitudes were also calculated, which consisted of measuring the total area under the rectified trace (absolute value of the trace) to baseline within a latency window between 30 and 400 ms. This area measure was used to provide an overall measure of synchrony in the P1-N1-P2 region of the waveform (Billings et al., 2012).

Repeated-measures two-way analyses of variance (ANOVA) were completed on the peak amplitude, peak latency, and rectified area measures of each component of the evoked response (P1, N1, and P2). The 2×4 analysis included the factors of amplification (unaided and aided) and SNR (10, 20, 30, 40 dB). If necessary, additional paired samples *t* tests were completed to compare each measure between the relevant conditions.

Results

The analysis of the current dataset addressed the two primary questions: (a) What is the effect of amplification at different signal levels when SNR is equated between unaided and aided conditions, and (2) what is the effect of absolute signal level when SNR is held constant?

Effect of Amplification

Results from all 64 electrodes are shown in Figure 1, where the effect of SNR is clearly visible in the overall CAEP amplitude changes of the butterfly plots; as SNR increases from 10 to 40 dB, overall amplitude increases as well. This is true for both aided (left) and unaided (right) columns. Figure 2 shows grand mean CAEP waveforms at electrodes Cz (top), T7 (bottom left), and T8 (bottom right) for aided conditions (solid lines) and unaided conditions (dashed lines) in response to changes in SNR with a constant noise

level. The peaks of P1, N1, and P2 are labeled for electrode Cz in response to the 40 dB SNR condition. Waveforms are very similar for unaided and aided conditions except for the 10 dB SNR condition where possible latency differences can be seen. Figure 3 illustrates peak latency and peak amplitude growth functions for P1, N1, and P2 waves and rectified area amplitude of CAEPs as a function of SNR in aided conditions (solid lines) and unaided conditions (dashed lines) at electrode Cz. Similarities between unaided and aided conditions are apparent for all amplitude measures, whereas latency differences are evident especially for the 10 dB SNR conditions. A 2×4 repeated-measures ANOVA was completed with the factors of SNR (10, 20, 30, and 40 dB) and amplification (unaided vs. aided) on latency, amplitude, and area measures (see Table 2). Analyses were completed for electrodes Cz, T7, and T8. Note that in this article, the effect of amplification refers to any changes from hearing aid processing even when signal levels are the same between unaided and aided condition. Although not a main question of this study, it is noteworthy to point out the main effect of SNR for nearly all measures at electrodes Cz, T7, and T8. Significant main effects of SNR were not present for P1 amplitude. These results are similar to Billings et al. (2007), except that in the 2007 study, SNR varied because of hearing aid processing rather than being manipulated with DAI. In either case, SNR appears to be a critical factor affecting morphology of the evoked response.

Table 2 demonstrates that amplification effects were somewhat mixed. All Cz amplitude measures (P1, N1, P2, and rectified area amplitude) as well as P1 latency were not different across unaided and aided conditions. However, N1 and P2 latencies at Cz demonstrated significant differences between unaided and aided CAEPs, such that aided latencies were longer than unaided latencies. A significant SNR $\times$ Amplification interaction was present for N1 latency at electrode Cz (see Table 2). Post hoc paired samples *t* tests at four different SNR conditions for N1 latency demonstrated a significant amplification effect only for the 10 dB SNR condition, $t(12) = -3.7$, $p = .004$, and no amplification effect for 20, 30, and 40 dB SNR: 20 dB, $t(12) = -0.53$, $p = .6$; 30 dB, $t(12) = 0.53$, $p = .6$; 40 dB, $t(12) = -1$, $p = .34$, with a Bonferroni-corrected alpha of 0.05/4. Post hoc paired samples *t* tests demonstrated no significant amplification effect on P2 peak latency in any SNR condition: 10 dB, $t(12) = -1.78$, $p = .1$; 20 dB, $t(12) = -2.16$, $p = .052$; 30 dB, $t(12) = -0.78$, $p = .45$; 40 dB, $t(12) = -1.47$, $p = .17$, $\alpha = 0.05/4$. The growth function of P2 latency in Figure 3 demonstrates a general pattern of delayed latency on aided responses relative to unaided responses, likely contributing to the main effect of amplification on P2 latency.

Figure 4 illustrates the individual Cz data for P1 (top), N1 (middle), and P2 (bottom) latency differences (i.e., aided – unaided latency) with the parameter of SNR condition. Latency differences are sorted from largest to smallest values. A positive number means aided latency is longer than unaided latency. No significant effects of amplification were found for P1. There were several subjects with large latency differences in the 10 dB condition, but this effect

Figure 1. Butterfly plots (64 electrodes) of grand averaged waveforms ($N = 13$). Overlaid waveforms are shown in blue. Aided (left) and unaided (right) are shown along with the higher signal level condition (bottom left).

did not reach statistical significance. Individual N1 data demonstrated that aided N1 latency is longer than unaided N1 latency for 11 out of 13 subjects for the 10 dB SNR condition; however, no distinct pattern of longer aided N1 latencies was observed for 20, 30, or 40 dB SNR. For P2 latency, it appears that the main effect of longer aided latency relative to unaided latency may be driven by individual data rather than a particular SNR condition—that is, Subjects 1–5 had considerable positive values, whereas the majority of the other subjects showed differences close to 0, with the exception of Subject 13 who displayed negative values.

Peak amplitude and latency measures at electrodes T7 and T8 (representing the T-complex) were analyzed and resulted in effects very similar to those found at electrode

Cz. Main effects ($p < .05$) of SNR were found for all but P1 amplitude (and P1 latency in the case of T8) measures. Main effects of amplification were only found for P2 latency at electrode T7. Significant SNR $\times$ Amplification interactions were present for P2 latency at electrode T8, and P2 amplitude at electrode T7. Similar to results at electrode Cz, significant T7/T8 interactions appear to be driven by amplification effects that were isolated to the 10 dB SNR condition, as seen in Figure 2.

Effect of Absolute Signal Level

In the second part of this study, the effect of absolute signal level on aided CAEPs was investigated using two conditions: (a) a 60 dB SPL signal with 40 dB SPL noise,

Figure 2. Grand averaged ($N = 13$) waveforms for aided (black solid lines) and unaided conditions (gray dashed lines) at electrode Cz (top), T7 (bottom left), and T8 (bottom right) are shown in response to changes in SNR. Peak amplitudes increase and peak latencies decrease as SNRs increase.

and (b) an 80 dB SPL signal with 60 dB SPL noise. These conditions were designed such that both would have a 20 dB SNR. Figure 5 shows grand mean waveforms for both conditions at electrode Cz (60 dB signal = black solid line, and 80 dB signal = gray dashed line). Bar graphs demonstrate the peak latency and peak amplitude values for P1, N1, and P2 waves, as well as rectified area. Figure 5 shows larger amplitudes for the higher absolute signal level. However, a statistical analysis using paired samples t tests demonstrates that only the rectified area amplitude shows a significant effect of absolute signal level, P1 latency: $t(12) = 1.3, p = .22$; N1 latency: $t(12) = 1, p = .34$; P2 latency:

$t(12) = 0.2, p = .85$; P1 amplitude: $t(12) = -0.68, p = .51$; N1 amplitude: $t(12) = -2.15, p = .053$; P2 amplitude: $t(12) = -1.34, p = .21$; Rectified area amplitude: $t(12) = -2.5, p = .028$. To more directly compare previous results to the current study, a paired-samples t test was completed on the data in Billings et al. (2013) to confirm this signal level effect. The SNR conditions closest to those used in the current study were chosen: 60 dB SPL signal with 45 dB SPL noise, and 80 dB SPL signal with 65 dB SPL noise. The paired t test resulted in a trend toward significance for the rectified area amplitude, $t(14) = -1.9, p = .077$, lending general support to the current finding.

Figure 3. SNR ratio growth functions at electrode Cz for P1, N1, and P2 components and rectified area amplitude in aided conditions (black solid line) and unaided conditions (gray dashed lines). Error bars represent 1 SEM.

Discussion

The purpose of this study was to examine the effects of hearing aid amplification on auditory cortical evoked activity while controlling for the known SNR contributions previously described in the literature. What is original about this experiment is the investigation of amplification effects when actively controlling the noise floor through the use of DAI. By fixing the noise floor, it was possible to equate SNR across unaided and aided conditions (through adding hearing aid noise to the unaided stimuli), thereby eliminating SNR as an explanation for amplification effects

(or lack of amplification effects) that might be present as a result of hearing aid processing. Although this approach limits the direct clinical usefulness of these data, the results clearly illustrate the need to examine hearing-aid-related factors other than SNR (e.g., changes to the temporal characteristics of the acoustic waveform resulting from hearing aid signal processing).

Does Amplification Alter CAEPs?

An amplification effect for the N1 and P2 peak latencies was observed. The interaction between signal level and

Table 2. Two-way repeated-measures analyses of variance (ANOVA) results for data collected at electrode Cz.

Measure	Effect of SNR		Effect of amplification		SNR × Amplification	
	<i>F</i> (df)	<i>p</i>	<i>F</i> (df)	<i>p</i>	<i>F</i> (df)	<i>p</i>
Latency						
P1	11.74 (3.0, 36.0)	<.001	2.106 (1,12)	.172	1.683 (1.4, 17.3)	.216
N1	20.039 (1.6, 19.6)	<.001	11.035 (1, 12)	.006	5.686 (3, 36)	.003
P2	14.139 (1.7, 20.9)	<.001	7.674 (1, 12)	.017	0.567 (3, 36)	.64
Amplitude						
P1	0.381 (1.4, 16.7)	.614	0.165 (1, 12)	.692	0.777 (3, 36)	.514
N1	20.89 (3.0, 36.0)	<.001	0.774 (1, 12)	.396	1.252 (3, 36)	.305
P2	19.566 (1.8, 21.3)	<.001	0.19 (1, 12)	.893	1.41 (3, 36)	.256
Rectified Area Amplitude	30.972 (1.5, 18.2)	<.001	0.333 (1, 12)	.575	0.403 (3, 36)	.752

Note. SNR = signal-to-noise ratio.

amplification effects builds on the study by Easwar et al. (2012) in which no amplification effect was found when SNRs were equated at one signal level/noise level combination (i.e., signal level = 60 dB SPL and SNR = 45 dB). In the current study, the amplification effect at electrodes Cz, T7, and T8 is isolated to N1 and P2 latencies and appears to be driven primarily by the 10 dB SNR condition. At the largest SNRs (i.e., 30 and 40 dB), the effect of amplification is small or absent, which may explain the results of Easwar et al. (2012), who used an SNR of 45 dB. This implies the effect of amplification may exist only at relatively poor SNRs. Figure 3 demonstrates that the latency increase associated with amplification is about 20 ms. Unaided and aided stimuli were recorded signals from the HATS mannequin, which eliminated any potential for overall signal delay resulting from hearing aid processing. Whatever the hearing-aid-related cause, neural coding of the aided stimulus demonstrates a subtle delay in neural processing. This is true even for a relatively simple analog hearing aid with linear processing. More complex digital hearing aids are likely to acoustically modify signals even more dramatically and unpredictably, including significant modifications to stimulus onset characteristics. Further study is needed using digital hearing aids with more complex algorithms to determine the specific acoustic modifications that are made to the stimulus and how those changes may effect clinical aided CAEP measurements.

What Is The Effect of Absolute Signal Level?

Another interesting finding is that amplitudes of CAEPs increased when absolute signal levels increased in the aided condition with a fixed SNR of 20 dB. This effect was found for the overall area measure and trended toward significance for N1 peak amplitude. Such an effect of absolute signal level in the presence of background noise has not been shown in unaided conditions (Billings et al., 2009). Higher absolute signal level previously tended to generate larger amplitudes only when presented in quiet or when the background noise was not audible (Billings et al., 2012). However, the current results support the idea that in an aided condition, absolute signal level is coded, but perhaps

dominated by SNR in most cases. It should be noted that signal level effects shown here might be due to increases in the signal level (i.e., the level of the tone) or the overall level (i.e., the level of the tone plus noise). However, given existing unaided speech-evoked CAEP data (Billings et al., 2013), it is unlikely that overall level is the cause.

There are some hints of absolute signal-level effects in the literature; for example, Whiting, Martin, and Stapells (1998) demonstrated the possible presence of such an effect although not the focus of the study. Korczak et al. (2005) also showed that aided CAEPs were influenced by stimulus intensity and degree of sensorineural hearing loss. Moreover, Sharma, Purdy, Munro, Sawaya, and Peter (2014) studied unaided /da/-evoked CAEPs in continuous white noise in 12 young adults at a fixed SNR of 3 dB and three different subjective loudness levels (on average 41, 59, and 78 dB SPL). They found an effect of loudness on N1 peak amplitude, N1 dipole amplitude, and P2 peak latency. Therefore, there is converging evidence to support the idea that stimulus level is coded despite the SNR effects. However, it is important to remember that the impact SNR has on aided CAEPs will depend on the characteristics of the noise level present in the amplified signal relative to the sensitivity thresholds of the individuals.

Other Signal-Processing Considerations

In the current study, an analog hearing aid was used instead of a conventional digital hearing aid. It remains unclear how digital signal processing would influence aided CAEPs, although a few researchers have started investigating this issue. Marynewich et al. (2012) found that amplitudes of aided CAEPs were smaller for the digital hearing aids compared with an analog hearing aid, and none of the hearing aids resulted in a reliable increase in response amplitude relative to the unaided across conditions. Latencies of aided CAEPs from an analog hearing aid were not significantly different from latencies in the unaided conditions; however, digital hearing aids resulted in significantly delayed CAEP latencies. In their subsequent study, Jenstad et al. (2012) found that digital hearing aids with linear amplification altered the rise time of the stimuli such that

Figure 4. Individual data of Cz peak latency differences (aided – unaided) for P1 (top), N1 (middle), and P2 (bottom) in various SNRs sorted from largest to smallest latency differences. Positive difference values represent longer latencies in the aided condition compared to the unaided condition.

maximum gain was reached well past 30 ms after stimulus onset, which could result in altered aided CAEPs; in addition, rise times differed between the digital aids. Easwar et al. (2012) studied the effects of digital hearing aid processing on the CAEP elicited with tone bursts and found shortened rise times and overshoots at the onset of the tone burst were evident in the hearing-aid-processed stimuli with fast compression (attack/release time: 10/60 ms). These studies imply that various factors introduced from digital signal-processing algorithms can also influence the

Figure 5. Grand averaged ($N = 13$) Cz waveforms for the signal level of 60 dB SPL (black solid lines) and 80 dB SPL (gray dashed lines) with the same 20 dB SNR. Bar graphs show the peak latency and peak amplitude values for P1, N1, and P2 waves as well as rectified area amplitude values with error bars representing 1 SEM. Higher absolute signal level tends to generate larger amplitudes.

morphology of aided CAEPs. Those factors would influence aided CAEPs differently in different hearing aid models because every hearing aid model may have different onset responses. Moreover, in real life situations, individuals with hearing impairments use various digital signal-processing algorithms such as a directional microphone, noise reduction, frequency lowering, and so forth. It is not clear how each digital signal-processing algorithms would influence aided CAEPs. It is clear that additional research is needed to illustrate the effects of these more complex signal-processing factors.

Study Limitations

Analog hearing aids were selected in the current study so as to establish the contribution of signal-processing factors other than SNR in the most controlled condition (an analog linear hearing aid). Digital hearing aids are difficult to control in research studies because turning off hearing aid features in fitting software does not necessarily mean all digital signal-processing algorithms are inactive. Moreover, different hearing aid manufacturers allow different levels of control. Different manufacturers and hearing aid characteristics likely contribute to the variability of results seen in the aided CAEP literature. It is important that even with a simple linear analog circuit, somewhat complex amplification and absolute signal level effects were present in the current study, highlighting some of the difficulties that may be present when using current digital hearing aids and trying to make individual treatment decisions on the basis of aided CAEP morphology.

Last, the generalizability of these findings to wearable hearing aids and clinical populations is limited in two ways. First, hearing aids are designed to process speech, not tones, in everyday environments. A tone was used in this study because of the need to tightly control SNR effects that would have confounded the comparison with existing aided CAEP literature (Billings, 2013). Second, people tested in this study had normal hearing and therefore SNR is more likely to be a contributing factor than if people had had decreased audibility associated with hearing loss, which would result in portions of the background being inaudible.

Conclusion

There has been increasing interest among audiologists to use aided CAEPs clinically in the hearing aid fitting process with hard-to-test populations. Previous research has demonstrated that SNR and audibility of background noise must be considered when using aided CAEPs. The results of this study further demonstrate that factors in addition to SNR must also be considered before CAEPs can be used to clinically measure aided thresholds for speech understanding. These results confirm that the combined use of CAEPs and hearing aids should be completed with care given the introduction of variables that complicate the fitting and verification of hearing aids using CAEPs.

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