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الجهود السمعية المُحرّضة
كمؤشرات على أدَاء سماعات الأذن في إدراك الكلام

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الخـلاصـة

يمثل الجهد السمعي المحرّض مجموع النشاط العصبي في المسارات السمعية استجاباً للأصوات. توفر هذه الجهود المحرّضة مقياس موضوعي لمدى استجابة الدماغ للصوت. لذلك تعد أداة فعالة للعلماء ومختصي السمع للتحقق من الوظيفة السمعية في الناس الطبيعيون ومن لديه فقدان في السمع. الهدف الرئيسي من هذه الدراسة هو تحديد اي من مكونات الجهد السمعي، بين N2 ، P2، N1، P1 وP3، هي الأكثر فائدة في تقييم قدرات كشف وتمييز الكلام عند البالغين من فاقدي السمع الحسي العصبي. تعتزم هذه الدراسة أيضا إلى التحقيق فيما إذا كانت التغييرات في سعة وزمن المكون لهذه المكونات التي تحدث مع فقدان السمع الحسي العصبي ومع استخدام سماعات الأذن تختلف في الردود لتعكس مراحل مختلفة من المعالجة السمعية. تم تسجيل الجهود السمعية عن طريق أَلْقَى المحفزين / دا / و / با / لمجموعتين من البالغين الماليزيين. مجموعة الأشخاص الطبيعيين والأصحاء واشتملت على 12 شخص بالغ وذو يد يمنى ومجموعة المرضى اللذين يعانون من فقدان السمع الحسي العصبي واشتملت على 10 اشخاص بالغين وذو أيدي يمنى. النتائج أظهرت أن المكون P2 والمكون P3 كانا الأكثر استفادة من استخدام سماعات الأذن عند فاقدي السمع، وبالتالي يمكن استخدامها في التطبيقات السريرية والبحوث كمؤشرات لأداء سماعات الأذن في إدراك الكلام. وأظهرت الدراسة أيضا أن المخ يعالج المحفزين بطريقة مختلفة عند الأشخاص الاصحاء وعند المرضى. هذه الدراسة يمكن أن توفر المزيد من المعلومات التشخيصية للأطباء ويمكن أيضا أن تقدم أفضل فوائد إدراك الكلام لفاقدي السمع التي يحصلون عليها من سماعات الأذن. وتشير النتائج ايضا ان مستخدمي سماعات الأذن من فاقدي السمع، على الرغم من الفوائد التي يحصلون عليها من سماعاتهم، يجدون صعوبة في اكتشاف وتمييز الفروق الصوتية بين محفزات الكلام.

Cortical auditory evoked potentials as indicators of hearing aids performance in speech perception

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ABSTRACT

Cortical auditory evoked potentials represent summation of neural activity in the auditory pathways in response to sounds. They provide an objective measure of the brain's response to sound. For this reason, they are an effective tool for scientists and audiologists for investigating auditory function in normal people and those with hearing loss. The main objective of this study is to determine what components among the P1, N1, P2, N2, or P3 are most beneficial in assessing the speech detection and discrimination abilities of adult sensorineural hearing loss population. This study also intends to investigate whether changes in the amplitudes and latencies of these components occurring with sensorineural hearing loss and hearing aids differ in responses reflecting different stages of auditory processing. Auditory Potentials were recorded to /ba/ and /da/ stimuli from two Malay adult groups. A control group of 12 right-handed having normal hearing and a group of 10 right-handed with sensorineural hearing loss. The results showed that P2 and P3 components had the most benefits from the use of hearing aids in the hearing loss subjects and therefore could be used in both clinical and research applications as a predictor and objective indicator of hearing aids performance in speech perception. The study also showed that the brain processes both stimuli in a different pattern for both the normal and the aided hearing loss subjects. The present study could provide more diagnostic information for clinicians and could also offer better speech perception benefits for hearing-impaired individuals from their personal hearing aids. The findings also suggest that the aided hearing loss subjects, despite the benefits they get from the hearing aids, find it difficult to detect and discriminate the acoustic differences between the two speech stimuli.

Keywords: Cortical auditory evoked potentials; consonant vowels; hearing loss; sensorineural hearing loss; speech stimuli.

INTRODUCTION

People with sensorineural hearing loss (SNHL) require hearing aids to improve their hearing and listening abilities. However, hearing aids do not restore hearing to normal and there are still difficulties to optimal speech perception. Hearing aids' fitting and evaluation have long proved difficult for audiologists. It is even more difficult when dealing with difficult-to-test patients. It actually requires thorough hearing tests to measure the softest sound one can hear at different levels of frequencies. These tests are normally conducted using Auditory Brainstem Response (ABR), Pure Tone Audiometry (PTA), and Behavioural Observation Audiometry, which require responses from candidates. However, with some patients (e.g., infants, children, and difficult-to-test patients) Cortical Auditory Evoked Potential (CAEP) recording proved to be better applicable to hearing aid evaluation and has several advantages over ABR recordings. Difficult-to-test hearing aids candidates are those who find it troublesome (or impossible) to accurately carry out routine audiological assessments (e.g, ABR or PTA) (Ray, 2002). CAEPs basically represent summation of the activity of neuron cells in the auditory pathways in response to sounds. They are an effective tool for measuring brain responses to auditory stimuli where they provide information about auditory function underlying speech processing (S. C. Purdy, 2005). For this reason, CAEPs have been successfully used to assess the cognitive processes involved in the detection and discrimination of complex stimuli, including speech sounds, in people with normal hearing and impaired auditory systems.

CAEPs are usually classified based on the latency of the brain wave into early, middle, and late latency responses. Early responses are always elicited between 1 and 10 ms after the onset of the stimuli followed by 10 – 50 ms of middle responses and later latency responses as > 50 ms (Alain et al., 2013). A typical curve of these responses is shown below in Figure 1. While early and middle latency responses involve no cognitive processes by the participants, late responses involve neural processes such as discrimination of pure tones that vary in frequency or complex signals such as speech (Alain et al., 2013). In adults, late latency responses are dominated by a well-defined positive peak, P1, that is typically located between 50 and 80 ms after the onset of the stimulus (Julia Louise Wunderlich & Cone-Wesson, 2006). This is followed by a negative peak, N1, which occurs between 90 and 150 ms post-stimulus onset. N1 is also followed by a positive peak, P2, which has latency between 175 and 200 ms. The P1-N1-P2 complex is followed by the negative peak, N2, at 200 to 250 ms from the stimulus onset. The N2 peak is not always found in adults CAEP (Purdy et al., 2001). N2 component is then followed by a positive deflection at midline parietal site called P3 or P3b. P3 is a large positive component that usually occurs between 220 and 380 ms and is the most common elicited by oddball paradigm. P3 is generated in different areas in the brain including the auditory cortex. N2 and P3 waves are called later cognitive CAEP. They could be used by audiologists to provide information concerning the ability of the brain to discriminate or differentiate between the acoustic differences between speech stimuli as they provide information on higher-order processing of sensory stimuli needed for sound discrimination (Donchin et al., 1978; Stapells, 2002).

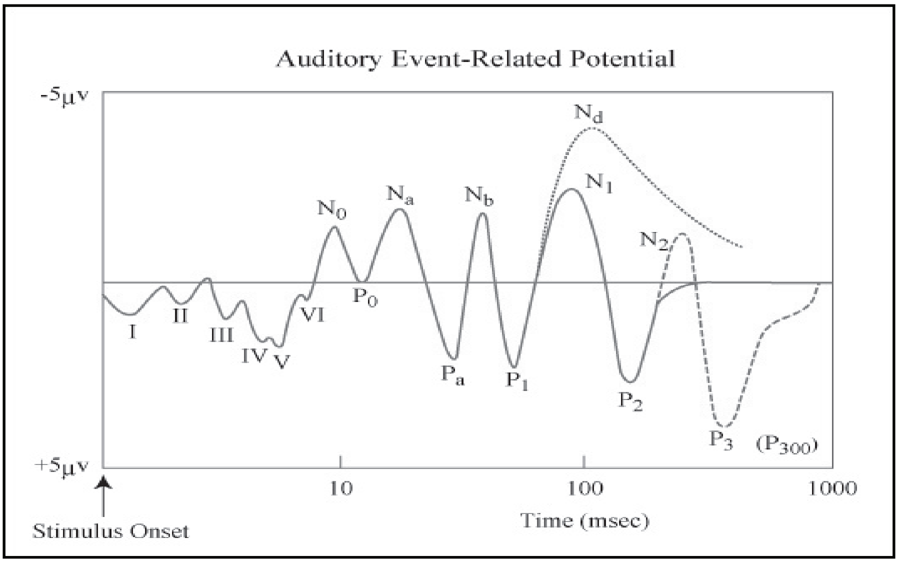

Figure 1. A typical CAEP curve (Bertrand Delgutte, 2005).

Several studies have established that the components of CAEP can be used to examine neural activities of the brain involved in discriminating speech and can be useful in the study of auditory processing not only in people with normal hearing but also with those who suffer hearing difficulties (Csepe & Molnar, 1997; Näätänen, 1995). A number of studies have also demonstrated that CAEPs can be elicited by a variety of speech including vowels and naturally produced consonant-vowel syllables (Agung et al., 2006; Obleser et al., 2003; Obleser et al., 2004; A. Sharma & Dorman, 1999). For example, the naturally produced /da/ and /ta/ produced two negative peaks (N1 and N1') instead of a single negative peak (A. Sharma & Dorman, 1999). Similarly, the results of Tremblay et al. (2003) showed unique CAEP patterns elicited by syllables that differed in their initial phoneme /bi pi si ʃi/. Moreover, the impact of speech characteristics on CAEPs comes from the findings of which the used consonant vowels (CVs) monosyllables produced overlapping P1-N1-P2 complexes.

In CAEP recording, stimuli type and duration have an impact on the outcome of the recording. However, the type and the duration of the stimuli in the previous studies varied widely and not all stimuli are suitable for recording CAEPs. For example, CAEPs can be recorded to different auditory stimuli including simple tones, CVs, words, and even full sentences. Additionally, several studies have indicated that the recording of CAEPs to speech stimuli provides better insights into late cognitive processes in the brain, while tones provide better insights to early CAEPs and are optimal for ABR recording (P. A. Korczak et al., 2005; Stelmachowicz et al., 1990). The work of Picton et al. (2000) recommended that naturally produced speech stimuli should be used for CAEPs research, since the goal is to apply results to speech perception in everyday life. Different durations of speech stimuli were used in many literatures, ranging from 90 to 600 ms (Obleser et al., 2001; Anu Sharma et al., 1997). The duration for naturally produced speech stimuli can vary widely, from 300 ms (Ostroff et al., 1998) to 756ms (Tremblay et al., 2003). However, there seems to be no consensus in the literature regarding optimal stimulus durations for speech-evoked CAEP recordings.

The effects of SNHL and hearing aids on the CAEPs have been the interest of many researches. In a very early study, Rapin & Graziani (1967) showed that the majority (58/) of their 5-to-24 month-old infants with severe-to-profound SNHL had aided CAEP thresholds to clicks and tones that were at least 20 dB lower compared to their unaided thresholds. It was also demonstrated by Oates et al. (2002) that as the degree of hearing loss increases, the amplitudes of CAEPs are reduced and the latencies are prolonged. It was also shown that SNHL has a less detrimental impact on the earlier stages of auditory processing compared with the later stages. In a recent study, CAEPs were used to evaluate the speech detection in hearing aids users; the results demonstrated the increased presence of cortical response with hearing aids (Durante et al., 2014). In another study that tested the effects of hearing aids on CAEPs using tone bursts, the results showed shortening of rise time and overshoot at the onset of the tone burst was evident in the hearing aid–processed stimuli (Easwar et al., 2012). The effects of SNHL and hearing aids on the CAEPs were also investigated by P. A. Korczak et al. (2005) using two different intensities of two speech stimuli. Results showed that the use of hearing aids substantially improved the detectability of all CAEPs especially for individuals with severe-to-profound SNHL.

Hence, the main purpose of this study was to investigate what CAEP components (P1, N1, P2, N2, or P3) are most beneficial in assessing the speech detection and discrimination abilities of hearing-impaired population. Knowing this could provide diagnostic information for clinicians and could also provide clinicians and audiologist with the speech perception benefits that hearing loss people get from their personal hearing aids. This study also intends to investigate whether changes in the amplitudes and latencies of these CAEP components occurring with SNHL and hearing aids differ in responses reflecting different stages of auditory processing.

METHODOLOGY

Participants/subjects

CAEPs were recorded from two groups of participants. An adult control group is comprising of 12 right-handed Malay male volunteers aged between 20 and 30 years (mean age = 23.5) having tested normal hearing and confirmed by PTA measurement. Subjects showed normal audiological presentation in both ears (air conduction thresholds 20 dB hearing level from 125–4000 Hz bilaterally, 40 dB HL at 6000 and 8000 Hz, and pure tone averages (PTA; average from 500–4000 Hz) 15 dB HL) (Brant & Fozard, 1990). The participants recruited were undergraduate students from Faculty of Engineering, University of Malaya. The second group consists of 10 right-handed Malay male adults with SNHL aged between 15 to 49 years (mean age = 39.1) who were recruited from the local community through Department of Otorhinolaryngology (ENT), University of Malaya Medical Centre, Kuala Lumpur. Those adults had bilateral hearing loss, with moderately severe-to-severe hearing loss (between 56 - 90 dB), and wearing bilateral hearing aids of more than 1 year. All participants signed a consent form prior to participation in experiment. A Mini Mental State Examination (MMSE) test was also conducted prior to the experiment to evaluate the subject’s mental abilities, memory capabilities, attention, and language deficiency (Folstein et al., 1975). All participants showed no cognitive impairments as the score of the MMSE was always higher than 2430/ for each participant. The study was approved by the Ethical Committee of the University of Malaya.

Stimuli

Naturally produced speech CVs (/ba/ and /da/) were used in this study. Although there are many auditory stimuli that can evoke CAEPs responses (e.g., tones, clicks, and noise bands), naturally produced speech stimuli were chosen for this study due to the fact that they represent high complex signals that are poorly approximated by non-speech stimuli. This feature makes speech stimuli able to elicit a more robust waveform and enjoy a special and distinct mode of perception (Dorman, 1974; Tremblay et al., 2003) . These specific CV syllables were selected due to a number of reasons. First, the high contrast between the consonant and the following vowel makes them stronger stimuli. Furthermore, these stimuli differ in place of articulation, an articulatory feature of speech that is particularly susceptible to the effects of peripheral hearing impairment. The speech confusion, in hearing-impaired people, happens mainly between stop consonants that differ in place of articulation. This means that acoustic cues that signal place of articulation appear to be particularly vulnerable when auditory processing breaks down (Kraus et al., 1995; Oates et al., 2002; Raz & Noffsinger, 1985). Finally, the CVs were also chosen so that comparisons can be made with other studies that used these same stimuli (P. A. Korczak et al., 2005). The stimuli were presented at 80 dB sound pressure level (Association, 2005; Dehaene-Lambertz & Baillet, 1998; Peggy A Korczak & Stapells, 2010; Ladefoged & Maddieson, 1998; Julia L Wunderlich & Cone-Wesson, 2001) using Sennheiser HD 428 headphones. It was confirmed with each subject that this was at a loud but comfortable listening level. The /ba/ and /da/ tokens were characterized by their contrasting voiced/voiceless articulatory features of speech. The speech stimuli were recorded at 44100 Hz sampling rate from the natural speech produced by a female Malay speaker using Sony IC recorder (ICD-UX513F). The CVs were 300 ms in duration each. The stimuli presented were calibrated at ear level using Brüel & Kjær 2218 sound level meter to obtain the desired SPL level (Anderson et al., 2013; Billings et al., 2007).

The stimuli were presented with a pseudo-randomized oddball sequence of 80% standard and 20% deviant presentations with inter-stimulus interval (ISI) of 800500± ms and delivered monaurally via headphones to both ears. The CV stimuli were tested for two runs. Each run consisted of 350 stimuli, that is, 70 deviant stimuli and 280 standard stimuli. Thus, there were 140 deviant stimuli and 560 standard stimuli presented over the two runs. The order in which the stimuli were presented ensured that there were 3-5 standard stimuli between deviant stimuli. There was no counterbalance for this study; that is, the (/da/) stimulus was always the standard and the (/ba/) stimulus was always the deviant. The normal hearing participants were tested only in the unaided condition and the hearing-impaired participants were tested in two conditions, unaided and aided conditions (while wearing their prescribed personal hearing aids), one session each. The headphones were placed over the hearing aids in the aided condition.

CAEP recording

Subjects were seated in a comfortable armchair in a sound-proof chamber. They were instructed to ignore the stimulus and minimize their eye blinks and muscle movements. Recording was done twice with approximately 35 minutes duration each. To ensure continuation of passive listening condition, written short stories were presented throughout the experiment. Recording was done at 500 Hz sampling rate using an Enobio wireless Electroencephalogram [EEG] device system (EnoBio, Neuroelectrics, Spain) (Ruffini et al., 2007; Ruffini et al., 2006). Data were recorded using 8 Ag/AgCl electrodes mounted on Neoprene EEG cap located over the scalp sites Fz, Cz, Pz, FPZ, F7, C3, P7, and F7 (according to the modified International 10–20 System) (Lee et al., 2007). EEG activity from each electrode was measured with one active electrode called Common Mode Sense (CMS) and one passive electrode Driven Right Leg (DRL) linked to the right mastoid.

CAEP waveform and component analysis

After the collection of the data, the responses evoked by the standard and deviant stimuli were processed offline (e.g., correction of the baseline drift, removing the power line frequency, and digital filtering). These were done using notch filter at 50 Hz and Butterworth band-pass filter in the frequency domain of 1 – 49 Hz. The evoked responses were then averaged separately for each stimulus. All standard and deviant evoked responses were initially denoised by the Empirical Mode Decomposition (EMD) technique (Kopsinis & McLaughlin, 2009; Wang et al., 2013) and inspected visually.

The criteria used to determine CAEP response presence or absence were (1) using visual inspection where the CAEP is present if individual CAEP peak was larger than the level of the pre-stimulus baseline, and then (2) using statistical methods where correlation coefficient test and t-test were used to compare a typical standard CAEP waveform, used by previous studies, with individual subjects' responses and those responses that had maximum correlation coefficient (r) between 0.75 and 1 and $p < 0.05$ were considered present (this criterion was done only for the control subjects data). CAEP analysis included baseline-to-peak amplitude and latency comparison with a typical standard CAEP waveform described by (Näätänen, 1992) where N1 and N2 were defined as the most negative peaks occurring 80 - 150 ms and 180 - 250 ms after stimulus onset, respectively. P1, P2, and P3 were also defined as the most positive peaks between 55 - 80 ms, 145 – 180 ms, and 220 - 380 ms, respectively. In some trails P1 and P2 were below the baseline, that is, a negative value, in which case the latency of the peak was measured and the amplitude recorded as missing. All measurements reported here are from responses recorded at the Cz electrode, and since it was at this electrode, the CAEP was largest.

The correlation coefficient test and t-test were done on two stages. Firstly, it was done between individual subjects' CAEP responses and the typical standard CAEP. The waveform with the maximum correlation coefficient (r) among the 12 subject data to the standard waveform was then selected as the standard waveform. Secondly, the selected waveform was then used for comparison purposes between the rest of the individual subjects' responses. Waveforms with the correlation coefficient (r) in the range of 0.75 to 1 having $p < 0.05$ were accepted and those with low correlation coefficient (r) were neglected. It should be noted that 2 subjects' data out of 12 had low correlation value and were neglected. Therefore, only 10 control subjects were used in the analysis of the control subjects.

After each subject's data was processed individually, the mean and standard deviation of the peak-to-peak amplitudes and latencies of the P1, N1, P2, N2, and P3 components for all subjects of the three groups (Control, unaided SNHL, and aided SNHL) were calculated separately for each stimulus for the purpose of easing the statistical analysis. The mean latency and amplitude measures for the CAEPs of the three groups were then analyzed separately using one way ANOVA test. The test was done on the electrode that showed the maximum responses (Cz). The differences were only considered significant at a level of $p < 0.05$. The mean latency and amplitude measures for the CAEP's components of the unaided and aided conditions for SNHL participants for both stimuli were also analyzed separately using t-test. This was done to show if there are any differences between stimuli. The differences were only considered significant at a level of $p < 0.05$.

The mean latency and amplitude measures for the CAEP's components of the unaided and aided conditions for SNHL subjects were subtracted from each other to find the gain of the mean amplitude and latency the subjects acquired from their hearing aids. This was done separately for each individual.

RESULTS

Subjects' results

As mentioned in the methodology, the averaged responses were initially denoised by EMD technique. A sample of the cleaned responses is shown in Figure 2.

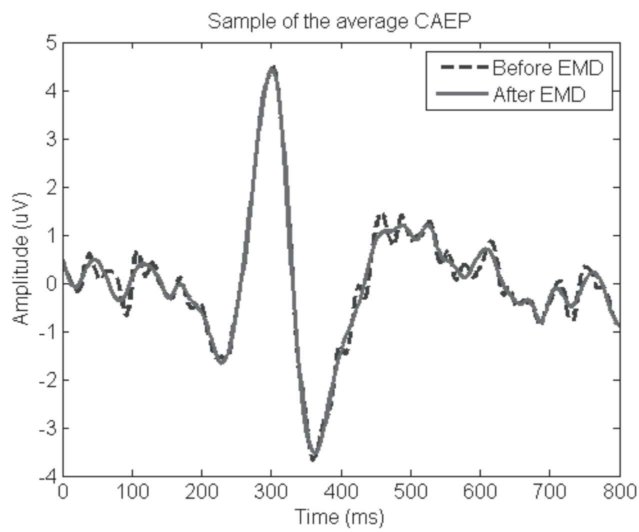

Figure 2. CAEP waveform recorded before and after EMD denoising process. The blue waveform (before EMD denoising) showed the stimulus onset position presented at 200ms throughout the recording session. The red waveform is the cleaned CAEP waveform.

A sample of the average CAEP waveforms for the control and SNHL subjects for both stimuli is shown in Figure 3.

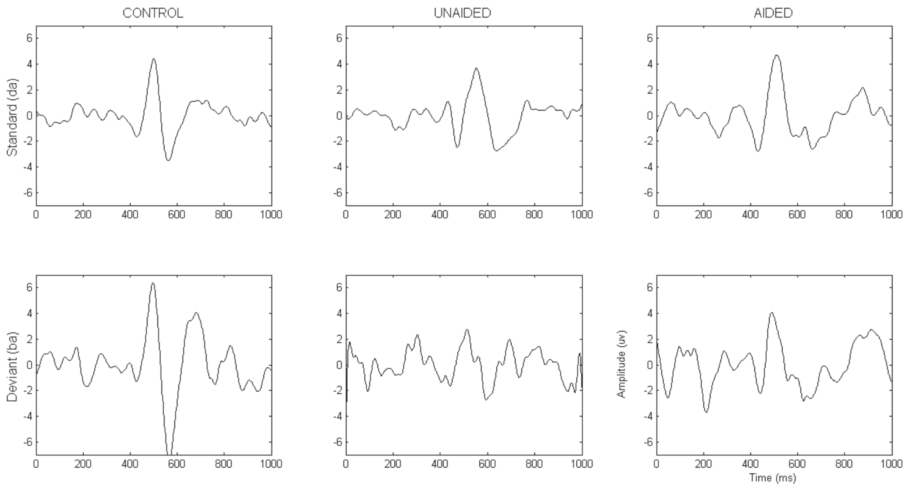

Figure 3. A sample CAEP from both standard and deviant stimuli for control subject and SNHL subject (Aided and Unaided) from Cz electrode; the marker is at 200 ms.

The correlation coefficient test and t-test were applied to the control subjects' data where the mean and the standard deviation for both amplitude and latencies for all subjects are shown in Table 1. The correlation coefficient test showed high resemblance between this study results and CAEP waveforms that were outlined in previous studies. In addition, the p-value of the t-test also confirmed that there is only a small difference.

Table 1. Mean amplitudes in (µV) and latencies in (ms) with standard deviations for the recorded CAEP components of the 10 control subjects.

	Amplitude (μV)									
	P1	**N1**	**P2**	**N2**	**P3**					
	Da	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**
Mean	1.27	0.62	1.02	0.75	2.49	0.43	2.90	1.35	3.01	2.64
SD	0.42	0.34	0.38	0.45	0.95	0.22	0.61	0.35	0.76	0.67

	Latency (ms)									
	P1	**N1**	**P2**	**N2**	**P3**					
	Da	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**
Mean	83	68	152	117	192	194	271	272	358	362
SD	39	30	41	29	32	36	25	26	16	24

The mean and standard deviation of the peak-to-peak amplitudes and latencies of the P1, N1, P2, N2, and P3 components for SNHL group are shown in Table 2. The table shows the results for both unaided and aided cases.

Table 2. Mean amplitudes in (μV) and latencies in (ms) with standard deviations for the recorded CAEP components of the 10 SNHL subjects.

	Amplitude (μV)										
	P1	**N1**	**P2**	**N2**	**P3**						
	Da	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	
Unaided	**Mean**	0.54	1.11	0.99	2.27	0.30	1.25	0.83	1.42	2.63	5.18
	SD	0.88	0.84	0.96	3.01	0.16	1.06	1.02	1.49	1.72	3.9
Aided	**Mean**	1.66	3.07	1.98	4.13	1.59	2.21	1.24	3.14	3.94	7.79
	SD	2.92	4.25	3.88	5.66	2.20	2.16	0.8	3.60	5.5	6.54
	Latency (ms)										
	P1	**N1**	**P2**	**N2**	**P3**						
	Da	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	**Da**	**Ba**	
Unaided	**Mean**	71	66	102	100	164	169	214	214	330	335
	SD	10	8	16	20	18	19	22	48	40	34
Aided	**Mean**	74	72	98	108	158	162	212	218	321	324
	SD	10	13	24	29	12	17	22	25	16	35

The gained amplitude and latency between the unaided and aided conditions for both stimuli were calculated to show how the hearing aids contributed to the CAEP components. The changes in amplitude and latency are shown in Figures 4 and 5, respectively.

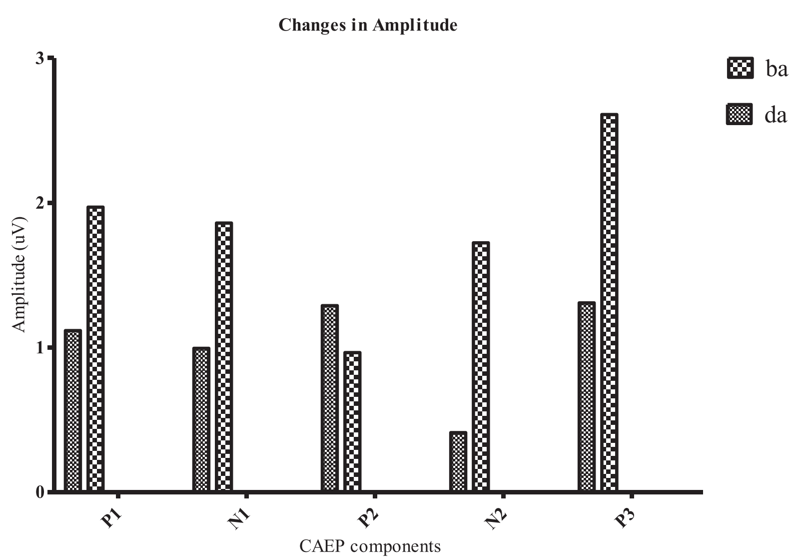

Figure 4. Changes in amplitude between the unaided and aided conditions for both stimuli.

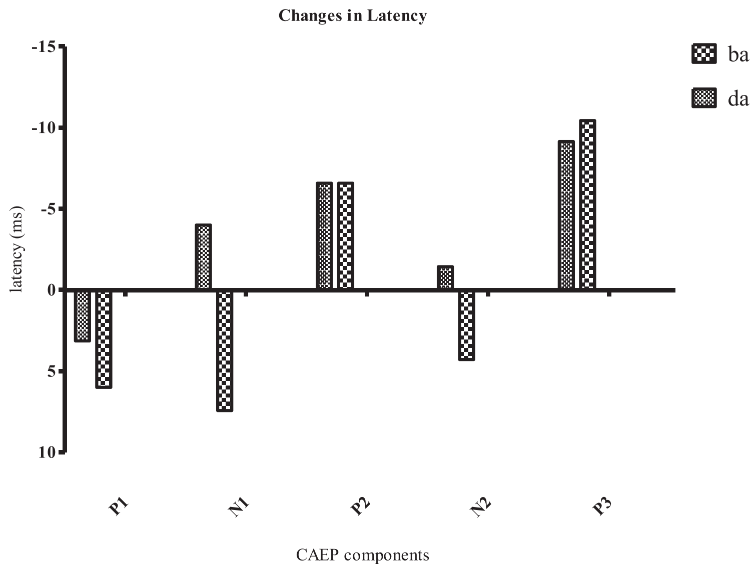

Figure 5. Changes in latency between the unaided and aided conditions for both stimuli.

Statistical analysis

No significant differences were observed when one way ANOVA was performed between averaged amplitudes and latencies of control, unaided and aided data in response to the standard stimulus (da) where F =1.988, p =0.1796 for the mean amplitude and F =0.005, p =0.9942 for the mean latencies . The differences were only considered significant at a level of $p < 0.05$. The right side of Figure 6 shows a graph of the obtained results for the mean amplitude for da stimulus and the right side of Figure 7 shows a graph of the obtained results for the mean latencies for da stimulus.

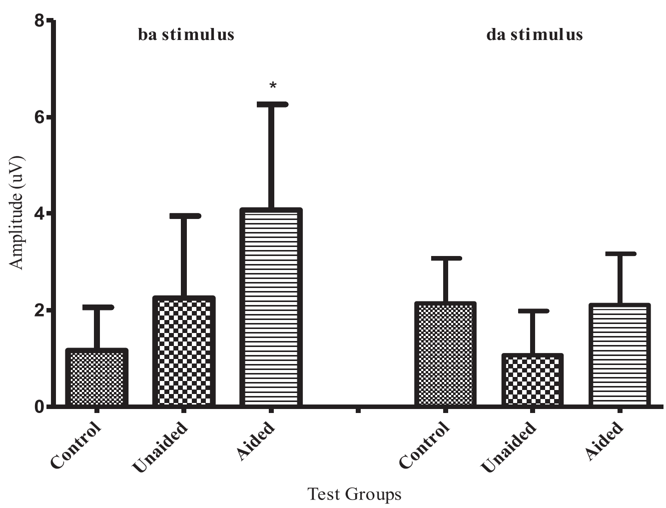

Figure 6. ANOVA test results for the mean amplitude between control, unaided and aided data in response to both stimuli.

One way ANOVA test also showed no significant differences when it was performed between averaged amplitudes and latencies of control, unaided and aided data in response to the deviant stimulus (ba) where F = 3.837, p = 0.0515 for the mean amplitudes and F = 0.079, p = 0.923 for the mean latencies. The differences were only considered significant at a level of $p < 0.05$. The left side of Figure 6 shows a graph of the obtained results for the mean amplitude for ba stimulus and the left side of Figure 7 shows a graph of the obtained results for the mean latencies for ba stimulus. However, with a small difference between the test p-value and significant level p-value (0.0515 and 0.05, respectively), Tukey's multiple comparison test was done to see if there are any significant differences between each pair of columns. The results showed only significant difference between the control and the aided group where the p-value was less than 0.05. This is indicated by a star over the aided column in Figure 6.

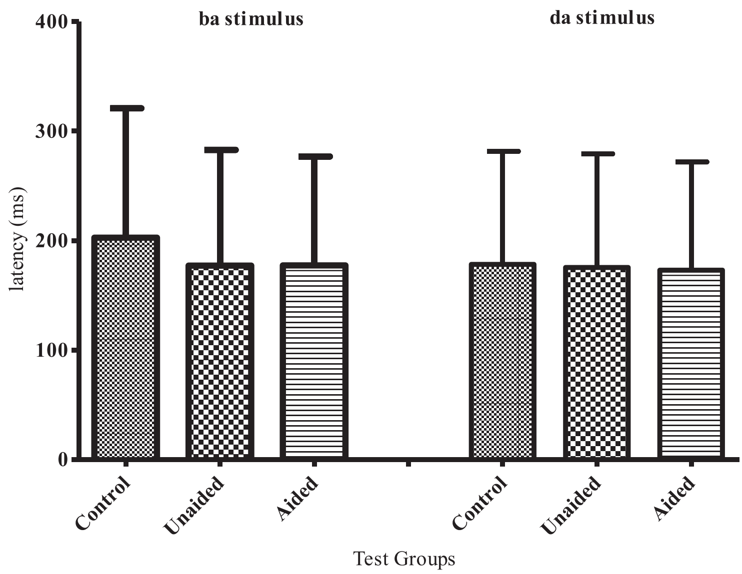

Figure 7. ANOVA test results for the mean latency between of control, unaided and aided data in response to both stimuli.

After comparing the means of the three groups to test if there are any significant differences between them, t-test was then performed between the mean amplitude of the responses to the standard and deviant stimuli during unaided and aided cases. The results indicated that the responses to ba and da differ significantly where the p-value was 0.0006 < 0.05. The results are depicted in Figure 8. The test was repeated on the mean latency of the responses to the standard and deviant stimuli during unaided and aided cases. The results indicated that the responses to da and ba do not differ significantly where the p-value was 0.48 < 0.05. The results are depicted in Figure 9.

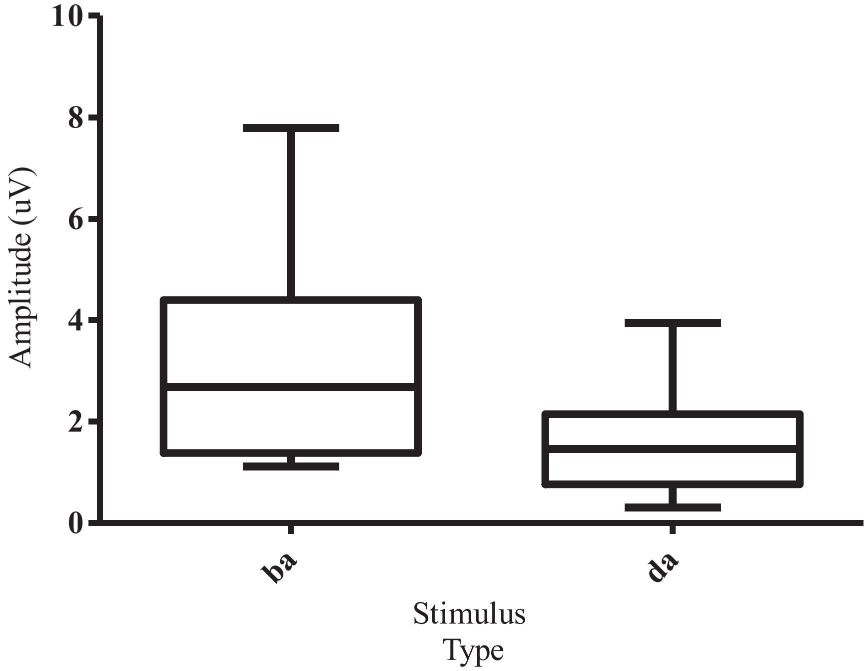

Figure 8. T-test results for the mean amplitude of the standard and deviant responses for unaided and aided conditions.

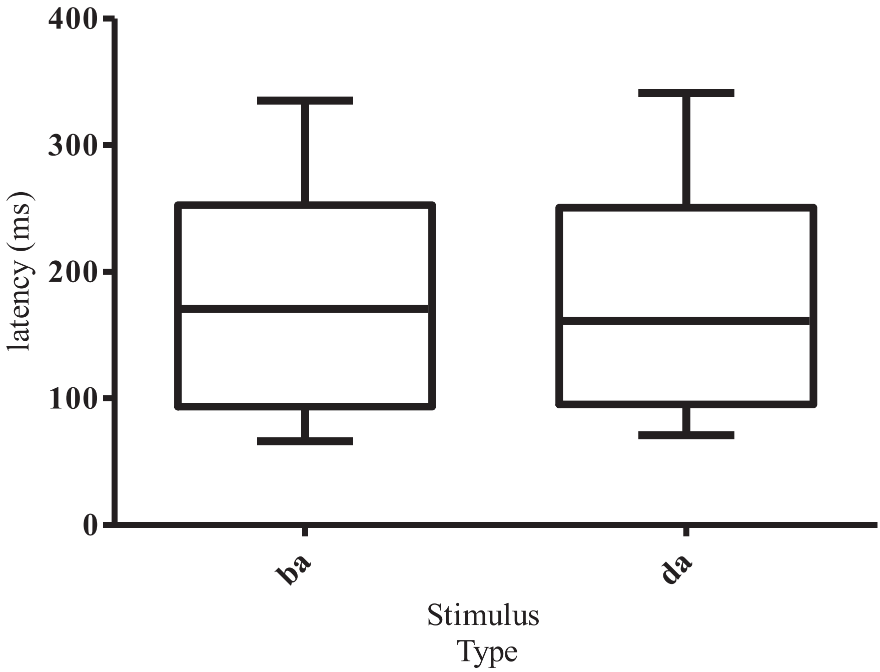

Figure 9. T-test results for the mean latency of the standard and deviant responses for unaided and aided conditions.

DISCUSSION

Summary of main findings

The present study examined the effects of CAEPs and hearing aids on speech perception on SNHL individuals. CAEPs recordings were processed from the data of 20 participants; 10 of them had normal hearing threshold and 10 suffered SNHL. The latencies and amplitudes were measured in response to the speech stimuli and then analyzed. Overall, the results for the control subjects showed that the components P1, N1, P1, P2, N2, and P3 of CAEP were clearly visible in response to both stimuli. The correlation coefficient test showed high resemblance between present study results and previous similar studies using English CV by native English speakers (Näätänen, 1992; Julia L Wunderlich & Cone-Wesson, 2001). On the other hand, the results from SNHL subjects showed clear CAEP components in the aided condition where the hearing aids improved the responses compared to the unaided condition. As can be seen from Figures 4 and 5, the results showed that the use of a personal hearing aid increased the amplitude and decreased the latency of most of this subject's CAEP components. These response changes are at both standard and deviant stimuli, where, for example, the latencies are approximately 30 ms shorter for P3 and the amplitudes of P3 are approximately 30% larger in the aided versus unaided condition. These results are in agreement with the previous studies where it is expected that hearing aids improve the CAEP responses (P. A. Korczak et al., 2005; Oates et al., 2002). This was confirmed by ANOVA results between the three groups (see Figures 6 and 7) where there were a gain in amplitude and a decrease in latency in the aided conditions compared to the unaided condition despite the insignificant differences.

In light of the aforementioned findings, the main goal of this study was to find what components of CAEP gained the most benefit from the use of hearing aids in assessing the speech detection and discrimination in SNHL individuals. Figure 4 revealed that P3 gained the highest amplitude in both standard and deviant stimuli compared to the other CAEP components. The mean latency also showed that P3 had the largest decrease among the other components as evident from Table 2 and Figure 5. The higher amplitudes and lesser latencies of P3 indicated that P3 had a better performance and had the most obvious effect by both stimuli in the aided condition. P3 results suggest that physiological evidences of the CV stimuli reached the auditory cortex and the individual heard the stimuli. According to a review by Stapells, the absence or presence of later CAEP components (e.g., N2 or P3) can provide clinicians with valuable information concerning the ability of the brain to detect and discriminate speech stimuli (Stapells, 2002). Figures 4 and 5 also demonstrated that P2 component followed the general pattern that the hearing aids individuals acquire, where it gained higher amplitudes and lesser latencies between the aided and unaided conditions in both stimuli compared to the remaining components. The improvements or changes that occurred to the P3 and P2 waves, in the aided versus unaided conditions, respectively, provided evidences that the speech sounds or signals have reached the auditory cortex in a faster and more effective way and are therefore audible to the person wearing the hearing aids (Martin et al., 1997; Näätänen & Picton, 1987). Due to these results, P3 and P2 could be used in both clinical and research applications as a predictor and objective indicator of hearing aids performance in speech perception. The other components (P1, N1, and N2) showed a somewhat different pattern in their latencies responses where there was no reduction at all in P1 wave in both stimuli, and there was only very small reduction of both N1 and N2 waves in the standard stimulus (see Figure 5 for the gain in latency between aided and unaided conditions for SNHL subjects).

Differences in amplitudes and latencies with stimulus type

CAEP could provide information regarding the ability of the brain to differentiate between speech sounds or stimuli (e.g., /da/ vs /ba/) and whether or not these differences reflect various levels of auditory processing. The current results showed that SNHL has different effects on various levels of auditory processing. This is evident in Figure 8 where t-test was performed between the two stimuli for the amplitude of all components and showed significant differences between the two stimuli as the p-value was $0.0006 < 0.05$. However, t-test showed no significant differences between the latencies of both stimuli as evident in Figure 8. Furthermore, Table 2 shows that the differences between /ba/ and /da/ stimuli in the later CAEP (e.g., P3) are higher than those in the early cognitive components (e.g., P2) where, for example, the mean amplitude increased nearly two times for P3 (i.e., from 3.94 μV to 7.79 μV) vs P2 (i.e., from 1.59 μV to 2.21 μV) in the aided condition. The difference was also evident in the latencies of both stimuli, however, with only a small one. These findings imply that as cognitive processes of the brain move from detection to discrimination of the speech signals, the difference between the two speech stimuli increases. Thus, these findings suggest that changes in the amplitude and latencies of CAEP due to SNHL and hearing aids usage reflect various levels of auditory processing.

Comparison between control and aided SNHL results

The capability of the brain to process the speech stimuli in normal hearing individuals versus SNHL individuals wearing hearing aids showed inconsistent results. One way ANOVA test among the three groups (control, unaided, and aided) for the standard stimulus (da) showed no significant results where the p-value was $0.1792 > 0.05$ (see the right side of Figure 6). This suggests that the brain processes the standard stimulus in a similar pattern for both the normal subjects and the aided SNHL subjects. The results of ANOVA for mean latencies of the standard stimulus support this claim where there was only a small difference between the normal subjects and the aided SNHL subjects' results (see the right side of Figure 7). However, ANOVA results for the deviant stimulus, interestingly, show a very small difference between p-value (0.0515) which urged us to do Tukey's post hoc test to determine if there is any significant difference between each pair of columns. The results showed that the control group and the aided group differ significantly where the p-value was less than 0.05 (see the left side of Figure 6). This result suggests that the brain processes the deviant stimulus in a different pattern for both normal subjects and the aided SNHL subjects despite the fact that there was no significant difference between the mean latencies. These findings suggest that the aided SNHL subjects, despite the benefits they get from the hearing aids, find it difficult to detect and discriminate the acoustic differences between the two speech stimuli.

CONCLUSION

The present study attempted to investigate what CAEP components among P1, N1, P2, N2, or P3 are most beneficial in assessing the speech detection and discrimination abilities of the adult SNHL population. CAEPs were processed from 10 adults having normal hearing and 10 adults with SNHL while listening to Malaya consonant-vowel speech stimuli of /ba/ and /da/. The results showed that the P3 and P2 components followed the general pattern that the hearing aids individuals acquire, where they gained higher amplitudes and lesser latencies between the aided and unaided conditions in both stimuli compared to the remaining components. This indicates that P2 and P3 components had better performance and had the most obvious effect by both stimuli in the aided condition compared to the unaided condition. Therefore, this study suggests that P2 was the most beneficial component in assessing the speech detection ability and P3 was the most beneficial component in assessing the speech discrimination abilities of the adult SNHL population in Malaya subjects.

The study also attempted to find whether the changes in the amplitudes and latencies of these CAEP components occurring with SNHL and hearing aids differ in responses reflecting different stages of auditory processing. The results showed that SNHL has different effects on various levels of auditory processing.

The sample size was a concern while conducting our experiments. The issue was due to genuine reasons related to the region and the prevailing culture. The numbers of people affected with the problems under investigation were plenty, but getting them ready for experiment was very challenging. Since the study needs to be conducted and was time bound, the authors had to be satisfied with this reasonable size with a scientific spirit that got us moving forward to report the findings.

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REFERENCES

Agung, K., Purdy, S. C., McMahon, C. M. & Newall, P. 2006. The use of cortical auditory evoked potentials to evaluate neural encoding of speech sounds in adults. J Am Acad Audiol, **17**(8), 559- 572.

Alain, C., Roye, A. & Arnott, S. R. 2013. Middle-and long-latency auditory evoked potentials: What are they telling us on central auditory disorders. Handbook of Clinical Neurophysiology: Disorders of Peripheral and Central Auditory Processing, **10**, 177- 199.

Anderson, S., Parbery-Clark, A., White-Schwoch, T., Drehobl, S. & Kraus, N. 2013. Effects of hearing loss on the subcortical representation of speech cues. The Journal of the Acoustical Society of America, **133**(5), 3030- 3038.

Association, A. S.-L.-H. 2005. Guidelines for manual pure-tone threshold audiometry.

Bertrand Delgutte, D. C., Frank Guenther, Jennifer Melcher, Joe Adams, Joseph Perkell, Kenneth Hancock & M. Brown. 2005. Brain Mechanism for Hearing and Speech. MIT OpenCourseWare.

Billings, C. J., Tremblay, K. L., Souza, P. E. & Binns, M. A. 2007. Effects of hearing aid amplification and stimulus intensity on cortical auditory evoked potentials. Audiology and Neurotology, **12**(4), 234-246.

Brant, L. J. & Fozard, J. L. 1990. Age changes in pure-tone hearing thresholds in a longitudinal study of normal human aging. The Journal of the Acoustical Society of America, **88**(2), 813 -820.

Csepe, V. & Molnar, M. 1997. Towards the possible clinical application of the mismatch negativity component of event-related potentials. Audiology and Neurotology, **2**(5), 354-369.

Dehaene-Lambertz, G. & Baillet, S. 1998. A phonological representation in the infant brain. Neuroreport, **9**(8), 1885-1888.

Donchin, E., Ritter, W. & McCallum, W. C. 1978. Cognitive psychophysiology: The endogenous components of the ERP. Event-related brain potentials in man, 349-411.

Dorman, M. F. 1974. Auditory evoked potential correlates of speech sound discrimination. Perception & Psychophysics, **15**(2), 215-220.

Durante, A. S., Wieselberg, M. B., Carvalho, S., Costa, N., Pucci, B., Gudayol, N. & Almeida, K. d. 2014, Cortical Auditory Evoked Potential: evaluation of speech detection in adult hearing aid users. Paper presented at the CoDAS.

Easwar, V., Glista, D., Purcell, D. W. & Scollie, S. D. 2012. Hearing aid processing changes tone burst onset: effect on cortical auditory evoked potentials in individuals with normal audiometric thresholds. American Journal of Audiology, **21**(1), 82-90.

Folstein, M. F., Folstein, S. E. & McHugh, P. R. 1975. "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. Journal of Psychiatric Research, **12**(3), 189-198.

Kopsinis, Y. & McLaughlin, S. 2009. Development of EMD-based denoising methods inspired by wavelet thresholding. Signal Processing, IEEE Transactions on, **57**(4), 1351-1362.

Korczak, P. A., Kurtzberg, D. & Stapells, D. R. 2005. Effects of sensorineural hearing loss and personal hearing AIDS on cortical event-related potential and behavioral measures of speech-sound processing. Ear Hear, **26**(2), 165-185.

Korczak, P. A. & Stapells, D. R. 2010. Effects of various articulatory features of speech on cortical event-related potentials and behavioral measures of speech-sound processing. Ear and hearing, **31**(4), 491-504.

Kraus, N., McGee, T., Carrell, T. D. & Sharma, A. 1995. Neurophysiologic bases of speech discrimination. Ear and Hearing, **16**(1), 19-37.

Ladefoged, P. & Maddieson, I. 1998. The sounds of the world's languages. Language, **74**(2), 374-376.

Lee, C.-Y., Jaw, F.-S., Pan, S.-L., Lin, M.-Y. & Young, Y.-H. 2007. Auditory cortical evoked potentials in tinnitus patients with normal audiological presentation. Journal of the Formosan Medical Association, **106**(12), 979-985.

Martin, B. A., Sigal, A., Kurtzberg, D. & Stapells, D. R. 1997. The effects of decreased audibility produced by high-pass noise masking on cortical event-related potentials to speech sounds/ba/ and/da. The Journal of the Acoustical Society of America, **101**(3), 1585-1599.

Näätänen, R. 1992. Attention and brain function: Psychology Press.

Näätänen, R. 1995. The mismatch negativity: a powerful tool for cognitive neuroscience. Ear and Hearing, **16**(1), 6-18.

Näätänen, R. & Picton, T. 1987. The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. Psychophysiology, **24**(4), 375-425.

Oates, P. A., Kurtzberg, D. & Stapells, D. R. 2002. Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. Ear Hear, **23**(5), 399-415. doi: 10.109701/.aud.0000034777.12562.31

Obleser, J., Elbert, T., Lahiri, A. & Eulitz, C. 2003. Cortical representation of vowels reflects acoustic dissimilarity determined by formant frequencies. Cognitive Brain Research, **15**(3), 207-213. doi: http://dx.doi.org/10.1016/S0926-64 10(02)00193-3

Obleser, J., Eulitz, C., Lahiri, A. & Elbert, T. 2001. Gender differences in functional hemispheric asymmetry during processing of vowels as reflected by the human brain magnetic response. Neuroscience Letters, **314**(3), 131-134.

Obleser, J., Lahiri, A. & Eulitz, C. 2004. Magnetic brain response mirrors extraction of phonological features from spoken vowels. Journal of Cognitive Neuroscience, 16(1), 31-39.

Ostroff, J. M., Martin, B. A. & Boothroyd, A. 1998. Cortical evoked response to acoustic change within a syllable. Ear and Hearing, **19**(4), 290-297.

Picton, T. W., Alain, C., Otten, L., Ritter, W. & Achim, A. 2000. Mismatch negativity: different water in the same river. Audiol Neurootol, 5(3-4), 111139-. doi: 13875

Purdy, S. C., Kelly, A. S. & Thorne, P. R. 2001. Auditory evoked potentials as measures of plasticity in humans. Audiology and Neurotology, **6**(4), 211-215.

Rapin, I. & Graziani, L. J. 1967. Auditory-evoked responses in normal, brain-damaged, and deaf infants. Neurology, **17**(9), 881-894.

Ray, C. 2002. Mental retardation and/or developmental disabilities. Handbook of clinical audiology (5th ed.). NewYork: Lippincott W| lliams & W| filkins.

Raz, I. & Noffsinger, D. 1985. Identification of synthetic, voiced stop-consonants by hearing-impaired listeners. International journal of audiology, **24**(6), 437-448.

Ruffini, G., Dunne, S., Farrés, E., Cester, I., Watts, P. C., Ravi, S., . . . Marco-Pallares, J. 2007, ENOBIO dry electrophysiology electrode; first human trial plus wireless electrode system. Paper presented at the Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE.

Ruffini, G., Dunne, S., Farrés, E., Marco-Pallarés, J., Ray, C., Mendoza, E., . . . Grau, C. 2006. A dry electrophysiology electrode using CNT arrays. Sensors and Actuators A: Physical, **132**(1), 34-41.

S. C. Purdy, R. K., H. Dillon, L. Storey, M. Sharma & K. Agung. 2005. Aided cortical auditory evoked potentials for hearing instrument evaluation in infants. in Proceedings of the 3nd International Conference of A Sound Foundation through Early Ampliciation, pp. 115–128, Phonak, Stafa., Switzerland.

Sharma, A. & Dorman, M. F. 1999. Cortical auditory evoked potential correlates of categorical perception of voice-onset time. J Acoust Soc Am, **106**(2), 1078- 1083.

Sharma, A., Kraus, N., J. McGee, T. & Nicol, T. G. 1997. Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables. Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 104(6), 540 -545. doi: http://dx.doi.org/10.1016/S01686-00050(97)5597-

Stapells, D. R. 2002. Cortical event-related potentials to auditory stimuli. In I. J. Katz (Ed.), Handbook of Clinical Audiology (pp. 378–406). Baltimore: Lippincott, Williams and Wilkins.

Stelmachowicz, P. G., Lewis, D. E., Seewald, R. C. & Hawkins, D. B. 1990. Complex and pure-tone signals in the evaluation of hearing-aid characteristics. J Speech Hear Res, **33**(2), 380- 385.

Tremblay, K., Friesen, L., Martin, B. & Wright, R. 2003. Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. Ear and Hearing, **24**(3), 225 -232.

Wang, T., Lin, L., Zhang, A., Peng, X. & Zhan, C. a. A. 2013. EMD-based EEG signal enhancement for auditory evoked potential recovery under high stimulus-rate paradigm. Biomedical Signal Processing and Control, 8(6), 858868-. doi: http://dx.doi.org/10.1016/j.bspc.2013.08.004

Wunderlich, J. L. & Cone-Wesson, B. K. 2001. Effects of stimulus frequency and complexity on the mismatch negativity and other components of the cortical auditory-evoked potential. The Journal of the Acoustical Society of America, **109**(4), 1526- 1537.

Wunderlich, J. L. & Cone-Wesson, B. K. 2006. Maturation of CAEP in infants and children: A review. Hearing Research, **212**(1–2), 212- 223. doi: http://dx.doi.org/10.1016/j.heares.2005.11.008

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