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Neurophysiological Correlates of the Critical Bandwidth in the Human Auditory System

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ABSTRACT

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The critical bandwidth (CBW) is an auditory phenomenon that has been used to study various aspects of auditory processing, including auditory masking, complex tone processing, and loudness perception. Although the psychoacoustic aspects of the CBW have been well studied, the underlying neurophysiology of the CBW has not been as thoroughly examined. The current study examined the neurophysiology of the CBW in young adults, as well as loudness perception in response to the CBW. Auditory stimuli consisting of complex tones of varying bandwidths were presented to 12 individuals (6 male and 6 female, ages 18-26 years). Complex tones were presented around center frequencies (CFs) of 250, 500, 1000, and 3000 Hz at bandwidths of 2, 5, 8, 10, 20, 50, 100, 200, 500, 1000, and 2000 Hz. Participants made loudness perception judgments while electroencephalography measured and recorded components of the event related potentials (ERPs) in response to the acoustic stimuli. Reaction time (RT) was recorded for each behavioral response, and the latencies of the N1, P2, C3, and C4 components of the ERPs were obtained. The results showed that RT increased with increasing bandwidth followed by a decrease in RT corresponding approximately with the CBW. This indicated that participants perceived a change in loudness at bandwidths greater than the CBW. Significant differences, $p \leq .05$, in RT were observed in bandwidths of 5 Hz and greater, although there was not complete consistency in this observation across all CFs and bandwidths. No significant critical band-like behavior amongst ERP latencies was observed. The results indicated that responses to acoustic stimuli originating in the superior temporal gyrus progressed to areas of higher neural function in the mid-temporal lobe. It was observed that each response must be processed temporally and independently to determine if a frequency difference is present for each stimulus. This observation is significant because this type of processing had not been identified prior to the current study.

Keywords: auditory cortex, auditory processing, brain mapping, critical bandwidth, dipole localization, electroencephalography, event related potentials

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DESCRIPTION OF STRUCTURE AND CONTENT

The body of this thesis was written as a manuscript suitable for submission to a peer-reviewed journal in speech-language pathology. This thesis is part of a larger collaborative project, portions of which may be submitted for publication, with the thesis author being one of multiple co-authors. Appendix A includes an annotated bibliography. Appendix B includes the consent form for research subjects. Level of evidence in the annotated bibliography was determined by the following guidelines; Level I: Evidence obtained from a systematic review of the majority (more than one) of relevant randomized control trials (meta-analysis). Level II: Evidence obtained from at least one well-designed randomized control trial. Level III (a): Evidence obtained from well-designed controlled trials without randomization. Level III (b): Evidenced from well-designed cohort or case-controlled analytic studies, preferably from multiple clinical programs or research centers. Level III (c): Evidence from multiple time series, with or without intervention, showing dramatic results from uncontrolled research. Level IV: Opinions of respected authorities, based on clinical experience, descriptive studies or reports of expert committees.

Introduction

The Critical Bandwidth

The critical bandwidth (CBW) is an auditory phenomenon first explained by Fletcher in 1953. Fletcher discussed how the cochlea processes sounds based on frequency bandwidths. Certain portions of the basilar membrane are activated by specific frequency bands. Fletcher supported this with evidence showing that the only portion of a noise that is effective in masking a given center frequency (CF) is that portion of the spectrum which lies near the CF (Fletcher, 1953). In other words, only the energy within a certain band of frequencies around the CF will contribute to masking, indicating the presence of a CBW.

Numerous studies have provided evidence that the cochlea processes sounds in critical band-like ways and those specific portions of the inner ear are activated by the same frequencies. The frequencies of incoming auditory stimuli trigger specific outer hair cells, which in turn activate the frequency specificity of the inner ear (Okamoto, Stracke, & Pantev, 2008). The distance along the basilar membrane corresponding with each CBW has been estimated to be approximately .5 mm to 1.3 mm (Durrant & Lovrinic, 1977; Fletcher, 1940; Zwicker & Fastl, 1990). These characteristics give insight into how specifically the cochlea processes frequency differences and how the ear processes sounds in general.

The concept of the CBW is relevant on a general level because it gives insight into how the cochlea processes both simple and complex sounds. Since Fletcher's (1953) initial studies, researchers have used the CBW to understand properties of auditory masking, neurological and physiological aspects of sound, loudness summation, pitch perception, and timbre resolution (Emanuel & Letowski, 2009; Moore & Glasberg, 1983).

It has also been observed that there is not one singular CBW for all frequencies; rather, the CBW is a function of the CF (Durrant & Lovrinic, 1977; Emanuel & Letowski, 2009; Scharf, 1961; Zwicker & Fastl, 1990). It is only in low frequencies, estimated to be around 200 Hz to 500 Hz, that the CBW maintains essentially a constant bandwidth (Durrant & Lovrinic, 1977; Fletcher, 1940; Zwicker, Flottorp, & Stevens, 1957). For frequencies above 500 Hz, the CBW increases with increasing frequency (Scharf, 1961). Various studies have produced differing results as to the actual CBWs of given CFs. Zwicker and Fastl (1990) developed a compilation of the CBWs for a number of CFs, which has been used in many experiments since its development and is the basis of the current study.

A primary use of the CBW is in auditory masking. Fletcher (1940) introduced this concept and investigated the effect of varying bandwidths on tonal thresholds by presenting a pure tone masked by a wideband noise. While adjusting the intensity of the stimuli to maintain a constant total intensity level, Fletcher measured auditory thresholds of a pure tone masked by various frequency bandwidths of noise. As the bandwidth of the noise increased, a higher intensity noise was required to mask the given tone, but only up to a certain frequency bandwidth: outside of that frequency bandwidth, any increase in the masking noise bandwidth no longer affected the hearing threshold of the tone. Fletcher termed this frequency range as the CBW.

The CBW also significantly influences loudness summation. Fletcher (1940) worked on the development of a loudness scale using CBWs. Durrant and Lovrinic (1977) also discussed this concept in detail. They explained that when two tones are separated in frequency by more than the CBW, the loudness of each tone will add linearly. Yet, if the two tones are within the CBW, the total loudness depends more on the increase in intensity that occurs from adding each tone together, which results in a non-linear increase in intensity. Durrant and Lovrinic concluded that the total loudness of tones occurring within the CBW is a function of the total loudness level, but for tones lying outside the CBW, the total loudness of the noise is more closely equivalent to the actual sum of the levels of each individual tone.

Although the CBW is a well-known topic of discourse, it is not fully understood or standardized. There are various methods for determining the CBW of a given frequency. Zwicker and Fastl (1990) described five methods for determining the ranges of critical bands that are typically used in current research. The first method involves using threshold measurements to determine CBWs. The second method is relatively similar and uses masking in frequency gaps. Third, Zwicker and Fastl used phase changes to determine when a listener can detect amplitude and frequency modulations. The fourth method is likely the most relevant to the current study and utilizes the measurement of loudness as a function of bandwidth for a constant sound pressure level. Finally, the last method measures the localization of short impulses that differ slightly in frequency and utilizes the binaural hearing phenomena that are present in typical listeners. Scharf (1961) also described similar methods in which critical bands have been measured. These methods involved using the absolute threshold of complex sounds, masking of a band of noise by two tones, sensitivity to phase differences, and the loudness of complex sounds. These methods produced similar results and were actually a foundation for the list compiled by Zwicker and Fastl that is commonly used today. This compilation is used in the current study (Figure 1).

The psychoacoustic aspects of the CBW have been well studied for pure tone and complex tone masking as well as loudness perception; however, the neurophysiology of the

CBW at the level of the central auditory system has not been thoroughly studied. The current study investigates central neurophysiological activity in the brain in response to the CBW.

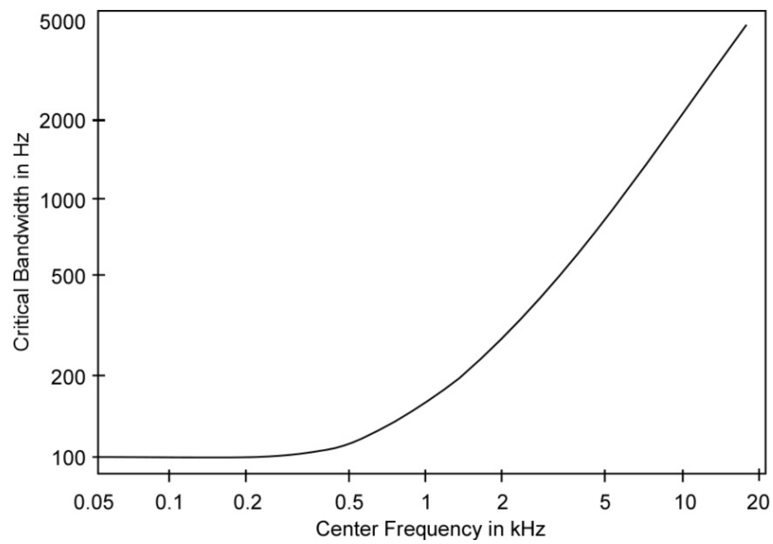

Figure 1. Graph of the CBWs as a function of frequency. Adapted from *Psychoacoustics: Facts and Models* (p. 158), by E. Zwicker and H. Fastl, 1990, Germany: Springer-Verlag Berlin Heidelberg.

Imaging Techniques

Functional magnetic resonance imaging. Functional magnetic resonance imaging (fMRI) is a noninvasive means of assessing brain activity and cortical organization (Seghier et al., 2001). This method of brain imaging is based on the observation that increased brain activity will result in increased blood flow. Functional MRI uses the magnetic properties of oxygenated and deoxygenated hemoglobin in the bloodstream. The MRI applies a strong magnet to the target area, which collects information regarding the ratio of each type of hemoglobin, relative to the surrounding tissues (Lee, Kannan, & Hillis, 2006). The MRI then produces images of anatomical structures in the target area. The technique of fMRI uses changes in local blood flow following a behavioral event to localize various brain functions. Functional MRI is a useful procedure that has increased brain imaging abilities in recent years.

Functional MRI also provides insight into language activity and related functions in the brain. The technique provides information about structural changes by enabling users to visualize changes in blood flow (Lee et al., 2006). It is a relatively accessible method of localizing areas of the brain involved in various language components in both healthy and impaired structures (Seghier et al., 2001;Voets et al., 2006), and it is a quicker, less invasive, and safer method for determining language dominance or lateralization than the Wada test (Lee et al., 2006).

Despite its promising nature and recent use in research, fMRI presents several issues that need to be resolved before it can fully be effectively utilized in a clinical setting (Crosson et al., 2007). Lee et al. (2006) point out that the basis of fMRI relies on a few assumptions, namely a normal hemodynamic response to brain activity and the absence of additional confounding factors. However, a normal hemodynamic response to activation is not always functional in cerebrovascular disease. Lee et al. also describe some of the additional factors that can alter an fMRI result. Neurovascular coupling in the brain can vary based on time of day as well as external factors such as caffeine and non-steroidal anti-inflammatory agents. Researchers must also account for changes in cerebral tissue signals due to head motion during imaging (Crosson et al., 2007; Lee et al., 2006). Lee et al. also recognized that it is difficult to test specific target cognitive functions without activating the brain in the resting state. Another limitation is that although fMRI is very good at spatial reconstruction, it gives poor temporal resolution (Friederici, 2004; Kim, Richter, & Ugurbil, 1997; Lee et al., 2013).

Electroencephalography. Electroencephalography (EEG) is a brain imaging technique that uses electrodes placed on the scalp to measure the electrical activity of the cortex. This process measures the flow of electrical currents through the tissues of the brain between the site of generation and the recording electrode (Fisch, 1999). These impulses are relatively small in respect to the complexities of brain activity, but rhythmic activity is yet present and can be identified using measures such as EEG. Fisch described EEG as "the difference in voltage between two different recording locations plotted over time" (p. 4). This technique measures inhibitory and excitatory potentials of pyramidal cells in the cortex and gives insight into the activation of the brain in response to various stimuli.

A significant strength of EEG is its increased temporal resolution as compared to fMRI (Kim et al., 1997; Lee et al., 2013). The use of EEG allows researchers to view the activity of the cortex at a millisecond by millisecond level (Friederici, 2004). This is an advantage in examining brain activation patterns in motor control and learning activities. Electroencephalography measures event related potentials (ERPs) of the brain, including resting potentials, postsynaptic potentials, and action potentials (Fisch, 1999).

Another strength of EEG as an imaging technique is its versatility. It is a noninvasive procedure and does not utilize radioactive imaging as in positron emission tomography. Likewise, it has a high temporal resolution unlike other imaging techniques. These benefits increase the ease of use and make EEG a good candidate for use with children and at risk individuals. It has also been used in studying auditory responses in other populations. Zhang, Anderson, Samy, and Houston (2010) used EEG to examine the adaptive patterns of the late auditory evoked potentials in cochlear implant users, demonstrating the versatility of this method. Congedo, John, Ridder, Prichep, and Isenhart (2010) used EEG to map brain activity in the resting state in two different participant samples. Electroencephalography has been increasingly used as of late as a reliable and noninvasive method for examining cortical activity.

Although a valuable imaging method, EEG is not without limitations. An increased temporal resolution typically implies a reduced spectral resolution, as is the case with EEG in comparison to fMRI. Fisch (1999) also described other limitations of EEG. As images are measured based on electrodes placed on the scalp, the data gathered tend to be rather superficial, and it is more difficult to measure deep brain activity. This can be compensated for by reducing the space between electrodes and altering the combination of electrodes, but it is still a surface level measurement. Additionally, increased electrical impedance between the source and the electrode may occur for a number of reasons, and this can reduce the amplitude of recordings. Finally, Fisch explained that abnormalities in the brain may not localize to the site of pathology, which may make it difficult to identify the location of a signal generation. These considerations must be taken into account in order to fully and effectively utilize EEG in brain imaging studies.

Despite the limitations of EEG, it is still a significantly useful imaging technique. Its increased temporal resolution over fMRI, ease of use, and noninvasive nature make it a prudent choice for examining electrical activations in the brain. The ability of EEG to measure ERPs related to the auditory system is critical. It is for these strengths and capabilities that EEG was selected for use in the current study.

Event related potentials. Event related potentials are activations in the cortex of the brain based on increased activity in response to stimulation. These potentials can be very telling in the examination of audiological responses in the brain (Sosa, Martinez, Gomez, & Jauregui-Renaud, 2009). There are four aspects of ERPs that can be measured, including latency in milliseconds, amplitude in millivolts, polarity in degrees, and topographic location as spatial distribution of latency, amplitude and phase. The current study focused specifically on auditory evoked potentials (AEPs), particularly in response to the CBW. These AEPs correspond with the transfer of electrical activity from the cochlea to the cortex (Sosa et al., 2009).

The study of AEPs has been applied to various aspects of audiology, and EEG has often been a key aspect of these studies. Sosa et al. (2009) used EEG to study AEPs in aphasic patients recovering from stroke and compared the results with the patients' performance on the Boston Diagnostic Aphasia Examination. Zerlin (1986) used EEG to show changes in brainstem AEPs, namely waveform V, in response to critical bands, finding similar results to other studies on this subject. Auditory evoked potentials have been used in essentially all aspects of auditory function.

Many studies have examined AEPs in the human auditory system, particularly in response to the CBW. Soeta, Nakagawa, and Matsuoka (2005) used magnetoencephalography (MEG), an imaging method similar to EEG that uses magnetic sensors targeted at specific areas of the brain, to measure the N1m component in response to changes in the CBW. They presented pure tone and bandpass filtered noises to 12 normal-hearing adults. Stimuli were centered around a frequency of 1000 Hz and included bandwidths set at 40, 80, 160, 320, and 640 Hz. Soeta et al. observed clear N1m responses from all stimuli types in both left and right temporal regions. They did not observe a significant effect of bandwidth on N1m latency. However, there was a notable difference in N1m latencies between hemispheres, with significantly shorter responses in the left hemisphere than in the right hemisphere. The researchers also observed that the N1m magnitudes decreased with increasing bandwidth when the bandwidth was within the CBW, yet increased with increasing bandwidth when the bandwidth moved outside the CBW. The study concluded that N1m magnitude was significantly affected by CBW, but the latency and source location of the N1m response in the cortex were not. The N1m component is a response that occurs at approximately 50 to 150 ms post stimulus and occurs primarily over the fronto-central region of the scalp (Picton, 2011).

In a similar study, Soeta and Nakagawa (2006) examined physiological correlates of the CBW, also using MEG. Ten adults with normal hearing participated in this two-part experiment. In the first part, the researchers presented two-tone stimuli to participants centered around 1000 Hz with frequency separations of 20, 50, 100, 200, 500, and 1000 Hz. In the second part, they presented three-tone complexes, with bandwidths of 8, 50, 100, 200, 500, and 1000 Hz. Soeta and Nakagawa found clear N1m responses in the temporal region of both hemispheres. They observed significant effects of stimuli bandwidth on N1m amplitude. When the bandwidth of the two- or three-tone complex was less than the CBW, the N1m magnitude was approximately constant. However, when the bandwidth became greater than the CBW, the magnitude of the N1m response increased with increasing separation. The researchers also observed a greater N1m amplitude in the right hemisphere than in the left hemisphere for both types of stimuli. They concluded that there is strong evidence to support the notion that the auditory cortex does exhibit critical band-like behavior. The current study sought to investigate aspects related to this conclusion, and similar procedures were employed.

Although various studies have examined the type and extent of the presence of the CBW beyond the cochlea, there is still a degree of uncertainty due to differing results across studies on the CBW (Burrows & Barry, 1990; Okamoto et al., 2008; Soeta & Nakagawa, 2006; Soeta et al., 2005). Variations in procedure and contradictions among results indicate a need for further research in the area of focus. The present study aimed to investigate further the role the CBW plays in AEPs in the brain, specifically in young adults. This study utilized EEG measures (auditory ERPs) to assess the neurological response to various auditory stimuli, particularly as a function of the CBW.

Method

The purpose of the present study was to examine the extent to which the CBW is represented in the cortex of the brain by measuring ERPs in response to auditory stimuli. This study aimed to identify these responses specifically in young adults.

Participants

Participants in this study included 12 right-handed individuals (6 males and 6 females) between the ages of 18-26 years. All participants demonstrated normal hearing bilaterally and presented no history of neurological problems. Normal hearing thresholds for pure tones were defined as ≤ 15 dB HL for octave intervals between 250-8000 Hz with symmetrical thresholds for 250, 500, 1000 and 3000 Hz, the CFs used in the present study. All participants signed an informed consent document approved by the Institutional Review Board at Brigham Young University prior to participating in testing.

Instrumentation

Stimulus preparation. Adobe Audition 3.0 was used to produce stimuli and to prepare stimuli for interface with the Compumedics (Charlotte, NC) Neurostim 2 software.

Instrumentation for initial hearing screening. Instrumentation used for hearing screenings and test stimuli during data collection included a Grason-Stadler model GSI-1761 audiometer with Etymotic EA-3 insert phones for auditory testing (Etymotic Research, Elk Grove Village, IL). Actual hearing tests were conducted in a double-walled, sound-treated test booth. Noise levels were within the limits as specified by ANSI S3.1-1999 R2008 Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms.

EEG data collection. Participants were fitted with an electrode cap (ElectroCap International, Inc., Eaton, OH, 2003) consisting of 64 silver-silver chloride electrodes placed on the scalp, distributed according to the 10-20 International System (Jurcak, Tsuzuki, & Dan, 2007). In addition to the scalp electrodes, six electrodes were placed on the right and left mastoid processes (linked-mastoid references), the outer cantha of the right and left eyes, and one above and one below the supraorbital foramen of the left eye. These six electrodes were used to monitor movement and activity of the eye and facial muscles. Electrode impedances of the cap did not exceed 3000 ohms.

Specific software programs were used to record electroencephalographic data and present stimuli. Compumedics Curry 7 software was used for EEG data collection and initial analysis. Additionally, Compumedics Neurostim 2 software was used for stimulus presentation, and Compumedics Curry 7 software was used for cortical localization of the electrophysiological responses, post hoc.

Stimuli

The CBW for 250, 500, 1000, and 3000 Hz were taken from Zwicker and Fastl (1990), and the limits adjusted such that the CF is the geometric mean of the CBW (Table 1).

Stimuli were comprised of tones presented in pairs, as indicated by the bandwidths and CFs in Table 1. Each tone in the pair consisted of two pure tones overlaid. The overlaid stimuli consisted of tones centered around each CF. One tone was at the lower frequency, and the other tone was at the upper frequency, according to the values indicated by Zwicker and Fastl (1990). The tones were presented at a duration of 500 ms, a 10 ms rise and fall time, and 100 ms separating each tone in the two-tone pair (Soeta & Nakagawa, 2006). Time between the presentations of each pair of tones depended on the reaction time (RT) of the participant. During

Table 1

Central Frequencies and Critical Bandwidths, in Hz, as Defined by Zwicker and Fastl (1990)

			Geometric Mean	
CBW	CF	BW	Lower Frequency	Upper Frequency
100 Hz	250	2	249	251
	250	5	248	253
	250	8	246	254
	250	10	245	255
	250	20	240	260
	250	50	226	276
	250	100	205	305
	250	200	169	369
110 Hz	500	2	499	501
	500	5	498	503
	500	8	496	504
	500	10	495	505
	500	20	490	510
	500	50	476	526
	500	100	452	552
	500	200	410	610
	500	500	309	809
	500	1000	207	1207
160 Hz	1000	2	999	1001
	1000	5	998	1003

	1000	8	996	1004
	1000	10	995	1005
	1000	20	990	1010
	1000	50	975	1025
	1000	100	951	1051
	1000	200	905	1105
	1000	500	781	1281
	1000	1000	618	1618
	1000	2000	414	2414
450 Hz	3000	2	2999	3001
	3000	5	2998	3003
	3000	8	2996	3004
	3000	10	2995	3005
	3000	20	2990	3010
	3000	50	2975	3025
	3000	100	2950	3050
	3000	200	2902	3102
	3000	500	2760	3260
	3000	1000	2541	3541
	3000	2000	2162	4162

Note. CBW = critical bandwidth (Zwicker and Fastl, 1990); CF = center frequency; BW = bandwidth probe for the current study each session, the tone pairs were presented in a randomized order. All stimuli were presented bilaterally at 55 dB SPL.

Each participant selected one of two buttons on a push-button response pad based on the perceived loudness of the tones. The participant was asked to determine if the perceived loudness of the tones was the same or different and push a corresponding button based on his or her selection (i.e., two-interval forced choice).

The first stimulus in each stimuli pair was always the tone with the 2 Hz bandwidth for each block of CFs being presented. The 2 Hz bandwidth was used as the standard comparison stimuli in order to maintain somewhat of a perceptual task similarity in the comparisons. The second stimulus in the pair was either the tone with the 2 Hz bandwidth again or another of the bandwidths within the block. The decision to be made was based on the perceived loudness comparison between these two stimuli.

Stimuli were presented in four segments or blocks. Each block consisted of the frequency bands indicated for each CF. Stimuli were randomized within blocks, and the order of presentation among blocks was randomized as well.

Procedures

Behavioral data acquisition. Prior to data collection, each participant was read the following instructions:

> This test takes about 1 hour and 45 minutes. You will be given rest breaks throughout the test. Please be sure your mobile phone or other alerting devices are de-activated. You are going to hear a series of tones in pairs. Each pair of tones may have a different pitch or may have the same pitch. You are to ignore the pitch but pay attention only to the loudness of the tones. If the loudness of the two tones is the same, push button 1. If the

loudness of the two tones is different, push button 4. Remember, ignore the pitch and only evaluate the loudness of the two sounds. You must make a decision before the next stimuli will be presented. Are there any questions?

Participants responded manually to all stimuli complexes with a button push. The participants were presented with 2,000 randomized stimuli combinations made up of tones representing different CFs and bandwidths, as previously described. Behavioral RTs were collected alongside functional data in the Compumedics Curry 7 software.

Due to the amount of time required during this experiment, participant fatigue was reduced by periodic breaks during data collection, without removing the electrode cap. Also, the ongoing EEG was monitored for increased alpha wave and sleep spindle (sigma waves) activity. Furthermore, the order of stimuli presentation was randomized to reduce the effect of participant fatigue on the data. During testing, a dark computer screen with an illuminated "X" in the center was placed in front of the participant at a distance of 1 m to aid in keeping the participant's focus and to reduce contamination from eye movements. The participant was instructed not to "stare."

Event related potential acquisition. During data collection, participants sat in an audiometric test room with rests allowed between each stimulus block. However, participants were not permitted to remove the electrode cap throughout the duration of data collection. Electroencephalography data was streamed to a computer using the Compumedics NeuroScan 4.5 software for post hoc averaging and processing. Participants' responses, RTs, and EEG data were recorded and stored on a secure computer.

Data Analysis

Statistical analysis was completed using IBM SPSS Statistics for Windows, Version 22. All neurophysiological recordings were analyzed using Compumedics Curry 7 software.

Behavioral data. The behavioral data were streamed raw to the computer while stimuli were presented to participants. The data were then analyzed for RTs. Descriptive statistics were used to show these results. An ANOVA for repeated measures was completed for RT for each stimulus type. An Honest Significant Difference post hoc comparison was completed for RT for each stimulus type as well.

Event related potential data. Functional EEG data were also streamed during stimulus presentation to be analyzed by the Compumedics Curry 7 software. A raw data file was created for each participant with recorded stimulus presentations with functional EEG data. Using this information, epochs were created for each stimulus type. Individual epochs were then filtered using a bandpass filter from 1-10 Hz and baseline corrected to remove artifacts caused by eye and jaw movement. Epochs were averaged for each participant within each block of stimuli. The ERP average for each stimulus type was completed across all participants to create a total of 12 grand averages. The ERP latencies that were identified and recorded include N1 and P2, as well as two additional components labeled C3 and C4.

Results

Behavioral Data

Twelve participants were selected for inclusion in this study; however, participant 12 was excluded during data analysis due to greatly prolonged RTs suggesting that this participant's data were extreme outliers.

Descriptive statistics were computed for the RTs for each stimulus type (Table 2). A general trend among the mean RTs appeared showing increased latency with increasing bandwidth subsequently followed by decreased latency for all CFs. The highest mean latencies occurred at the 10 Hz bandwidth for the 250 Hz CF, the 50 Hz bandwidth for CFs of 500 and

Table 2

Behavioral Descriptive Statistics for Reaction Time for Each of the 40 Stimuli Comparisons (in ms)

Stimulus Type					
CF	BW	*M*	*SD*	Minimum	Maximum
250	2	859.56	127.86	142	2477
250	5	946.37	340.64	381	2427
250	8	969.68	387.42	482	2500
250	10	1000.77	402.24	398	2470
250	20	909.57	353.41	382	2492
250	50	869.54	375.47	323	2487
250	100	952.01	382.91	375	2319
250	200	807.16	337.91	179	2496
500	2	858.42	110.93	102	2470
500	5	916.98	321.49	289	2493
500	8	927.13	357.07	226	2462
500	10	947.73	376.46	417	2450
500	20	948.37	346.46	441	2455
500	50	972.36	385.81	362	2447
500	100	913.81	404.26	230	2385
500	200	864.75	357.62	363	2495
500	500	822.46	320.90	343	2271
500	1000	828.21	339.00	370	2453
1000	2	850.96	100.46	108	2475

1000	5	878.10	322.07	454	2320
1000	8	858.57	329.91	204	2309
1000	10	863.22	330.70	352	2439
1000	20	859.86	313.10	400	2389
1000	50	924.17	374.78	211	2456
1000	100	869.14	341.93	349	2418
1000	200	858.95	354.65	400	2464
1000	500	786.41	310.13	345	2261
1000	1000	752.89	293.01	362	2294
1000	2000	778.93	318.32	268	2475
3000	2	851.74	100.94	105	2481
3000	5	915.11	370.02	412	2489
3000	8	891.72	370.34	263	2385
3000	10	886.31	354.09	372	2420
3000	20	893.66	366.86	377	2469
3000	50	921.69	386.08	252	2497
3000	100	926.87	385.97	362	2493
3000	200	917.23	384.62	344	2497
3000	500	829.84	328.87	379	2486
3000	1000	791.78	311.99	301	2459
3000	2000	796.13	332.95	368	2467

Note. CF = center frequency in Hz; BW = bandwidth in Hz

1000 Hz, and the 100 Hz bandwidth for the 3000 Hz CF. The lowest mean latencies occurred at the 200 Hz bandwidth for the 250 Hz CF, the 500 Hz bandwidth for the 500 Hz CF, and the 1000 Hz bandwidth for the 1000 and 3000 Hz CFs. It was noted that the lowest standard deviation for latency was at the 2 Hz bandwidth for all four CFs. The highest standard deviation for latency was the 10 Hz bandwidth for the 250 Hz CF, the 100 Hz bandwidth for the 500 Hz CF, and the 50 Hz bandwidth for the 1000 and 3000 Hz CFs.

An ANOVA for repeated measures was computed for RT for each stimulus type. Significant differences, $F(39, 43{,}473) = 32.70$, $p \leq .05$, were found in latencies between measures for all CFs. An HSD post hoc comparison was completed for RT for each stimulus type. Significant differences for each stimulus type comparison are indicated in Table 3. No significant differences were seen at the 2 Hz bandwidth. In general, significant differences in RT were observed once the bandwidth reached 5 Hz or greater, although there was not complete consistency for all CFs across all bandwidths, as noted in Table 3.

Table 3

ANOVA Table of Repeated Measures for Differences in RTs for each CF as a Function of Bandwidth

	Bandwidth in Hz										
CF	2	5	8	10	20	50	100	200	500	1000	2000
250	NA	*	*	*	*		*	*	NA	NA	NA
500	NA	*	*	*	*	*	*		*	*	NA
1000	NA	*				*			*	*	*
3000	NA	*	*	*	*	*	*	*		*	*

Note. Blank spaces denote failure to reach significance at $p \leq .05$, and NA denotes comparisons not appropriate for this design. CF = center frequency in Hz; * = significance at $p \leq .05$.

Event Related Potential Data

Tables 4 through 7 show the descriptive statistics for the physiological data collected for components N1, P2, C3, and C4. The N1 component (Table 4) produced relatively consistent mean latencies across CFs. The highest mean latencies were at the 20 Hz bandwidth for the 250 Hz CF, 100 Hz bandwidth for the 500 Hz CF, 50 Hz bandwidth for the 1000 Hz CF, and 8 Hz bandwidth for the 3000 Hz CF. The highest standard deviations for latency were in similar bandwidths, and there was not a great deal of variability among the mean latencies. The CFs of 250 and 500 Hz showed general trends of increasing standard deviations for latency with increasing bandwidth.

The P2 component (Table 5) did not present any strong general trends amongst the mean latencies, with the highest mean latencies at the 8 Hz bandwidth for the 250 Hz CF, 10 Hz bandwidth for the 500 Hz CF, 50 Hz bandwidth for the 1000 Hz CF, and 5 Hz bandwidth for the 3000 Hz CF. There appeared to be generally lower standard deviations for latency at the smaller bandwidths for all CFs, although the highest standard deviations for latency were inconsistent across CFs.

The C3 component (Table 6) showed similarly varied results. The highest mean latencies were observed at the 50 Hz bandwidth for the 250 Hz CF, 1000 Hz bandwidth for the 500 Hz CF, 10 Hz bandwidth for the 1000 Hz CF, and 100 Hz bandwidth for the 3000 Hz CF. The lowest mean latencies were at the 2 Hz bandwidth for both the 1000 and 3000 Hz CFs. Standard deviations for latency varied across CFs, although the highest standard deviation for latency was observed at the 2 Hz bandwidth for the 500, 1000, and 3000 Hz CFs.

The C4 component (Table 7) also showed similar results with no strong general trends amongst the mean latencies. The highest mean latencies were observed at the 50 Hz bandwidth

Table 4

Descriptive Statistics for Latencies of Component N1 (in ms)

Stimulus Type					
CF	BW	*M*	*SD*	Minimum	Maximum
250	2	77.64	19.35	55	109
250	5	61.13	13.94	42	84
250	8	97.82	27.45	64	142
250	10	86.36	36.92	49	149
250	20	98.78	34.08	57	142
250	50	91.44	32.81	56	132
250	100	88.50	37.56	51	142
250	200	90.70	31.97	51	142
500	2	74.90	18.76	48	105
500	5	73.70	18.89	51	119
500	8	74.00	19.57	51	103
500	10	78.40	23.82	57	127
500	20	79.70	26.29	54	131
500	50	75.10	29.62	47	145
500	100	90.63	34.50	55	136
500	200	78.67	33.44	51	145
500	500	87.25	35.87	50	129
500	1000	93.67	37.56	46	143
1000	2	75.50	13.78	58	93
1000	5	65.70	8.82	53	79

1000	8	85.29	30.34	53	140
1000	10	72.80	16.84	59	108
1000	20	68.13	10.56	52	81
1000	50	97.90	37.28	60	146
1000	100	92.00	34.58	56	142
1000	200	86.50	34.01	50	139
1000	500	89.73	33.99	51	133
1000	1000	92.73	29.35	55	138
1000	2000	94.60	29.71	47	126
3000	2	84.80	23.97	55	128
3000	5	99.82	36.64	53	184
3000	8	109.86	30.85	57	149
3000	10	107.57	37.08	63	143
3000	20	94.43	26.06	63	140
3000	50	85.00	29.82	60	134
3000	100	97.38	32.61	59	145
3000	200	100.30	34.73	62	142
3000	500	89.00	30.34	56	137
3000	1000	90.11	29.01	51	123
3000	2000	88.36	31.49	51	130

Note. CF = center frequency in Hz; BW = bandwidth in Hz

Table 5

Descriptive Statistics for Latencies of Component P2 (in ms)

Stimulus Type					
CF	BW	*M*	*SD*	Minimum	Maximum
250	2	153.00	28.40	118	187
250	5	161.09	28.93	135	210
250	8	198.70	33.90	136	230
250	10	177.60	40.47	138	243
250	20	181.00	40.70	131	235
250	50	165.60	38.20	122	227
250	100	149.57	22.63	128	194
250	200	172.70	48.69	111	244
500	2	167.00	11.48	142	186
500	5	161.67	34.39	121	227
500	8	166.40	32.70	126	233
500	10	166.45	29.93	131	229
500	20	158.40	30.06	126	205
500	50	157.30	19.97	138	188
500	100	174.45	37.91	131	234
500	200	173.91	43.67	126	240
500	500	169.91	39.23	123	223
500	1000	150.00	34.18	121	212
1000	2	164.30	12.96	141	188
1000	5	157.60	16.78	134	191

1000	8	180.36	37.47	138	233
1000	10	178.45	55.17	108	251
1000	20	166.91	21.17	139	203
1000	50	189.10	38.68	138	249
1000	100	166.22	39.73	134	236
1000	200	166.55	37.04	127	231
1000	500	171.10	39.10	123	215
1000	1000	182.64	45.16	121	246
1000	2000	174.20	39.20	115	222
3000	2	175.50	29.69	135	237
3000	5	197.00	35.83	152	244
3000	8	181.18	38.65	109	225
3000	10	183.11	43.61	121	236
3000	20	182.55	19.22	152	216
3000	50	163.55	31.75	129	242
3000	100	181.30	40.26	139	259
3000	200	177.70	42.27	138	235
3000	500	173.27	36.84	128	226
3000	1000	158.44	36.33	122	223
3000	2000	168.64	36.98	127	216

Note. CF = center frequency in Hz; BW = bandwidth in Hz

Table 6

Descriptive Statistics for Latencies of Component C3 (in ms)

Stimulus Type					
CF	BW	*M*	*SD*	Minimum	Maximum
250	2	440.00	35.18	385	494
250	5	431.00	49.72	354	485
250	8	423.38	27.93	385	464
250	10	440.63	35.03	399	493
250	20	435.80	29.62	414	495
250	50	442.82	32.92	390	490
250	100	419.25	29.62	390	481
250	200	438.00	37.14	389	491
500	2	429.67	51.90	308	484
500	5	440.67	21.79	414	491
500	8	438.88	36.90	385	494
500	10	418.09	12.46	399	441
500	20	422.30	36.27	380	484
500	50	438.33	28.16	398	479
500	100	426.56	20.94	395	462
500	200	435.18	30.15	393	487
500	500	429.22	35.79	367	479
500	1000	446.00	36.23	377	484
1000	2	406.00	50.66	315	474
1000	5	433.63	31.29	408	488

1000	8	420.73	31.58	374	480
1000	10	443.11	30.12	377	471
1000	20	419.33	13.97	398	441
1000	50	435.78	37.68	392	492
1000	100	419.10	27.74	382	469
1000	200	421.55	27.26	369	463
1000	500	426.18	32.45	380	493
1000	1000	423.64	27.47	384	471
1000	2000	427.50	40.93	364	484
3000	2	415.17	46.46	323	453
3000	5	432.64	27.58	380	465
3000	8	435.64	31.74	369	478
3000	10	436.20	27.91	395	496
3000	20	441.00	30.76	399	494
3000	50	433.60	32.96	390	489
3000	100	445.78	30.98	407	489
3000	200	422.00	23.51	403	472
3000	500	445.18	30.96	398	484
3000	1000	443.44	25.98	412	480
3000	2000	442.00	32.64	402	484

Note. CF = center frequency in Hz; BW = bandwidth in Hz

Table 7

Descriptive Statistics for Latencies of Component C4 (in ms)

Stimulus Type					
CF	BW	*M*	*SD*	Minimum	Maximum
250	2	532.78	24.76	499	570
250	5	533.91	21.36	513	578
250	8	543.00	25.39	499	572
250	10	540.67	36.11	478	584
250	20	519.43	18.17	493	545
250	50	544.88	34.80	479	584
250	100	531.80	37.01	489	596
250	200	528.70	40.03	477	585
500	2	512.71	32.72	482	582
500	5	542.10	19.73	516	586
500	8	536.36	30.48	497	593
500	10	521.82	24.87	488	564
500	20	523.20	26.67	489	579
500	50	529.50	14.43	506	555
500	100	513.30	20.42	491	552
500	200	538.25	26.91	506	579
500	500	526.89	27.11	500	573
500	1000	531.43	34.32	483	576
1000	2	531.00	22.49	499	564
1000	5	515.43	14.58	490	529

1000	8	527.80	26.62	476	577
1000	10	545.70	21.56	521	583
1000	20	526.60	33.70	482	573
1000	50	529.70	27.49	494	569
1000	100	522.00	24.43	496	589
1000	200	538.78	29.17	498	594
1000	500	558.40	36.45	499	618
1000	1000	530.89	19.51	511	569
1000	2000	548.67	30.71	508	588
3000	2	544.00	23.49	508	583
3000	5	538.57	21.55	505	575
3000	8	534.29	39.89	471	594
3000	10	536.80	31.96	491	597
3000	20	543.82	34.91	485	599
3000	50	537.50	34.72	491	581
3000	100	536.11	25.36	504	578
3000	200	529.91	38.05	485	593
3000	500	543.55	30.67	501	584
3000	1000	527.38	25.44	492	574
3000	2000	536.56	44.46	480	594

Note. CF = center frequency in Hz; BW = bandwidth in Hz

for the 250 Hz CF, 5 Hz bandwidth for the 500 Hz CF, 500 Hz bandwidth for the 1000 Hz CF, and 2 Hz bandwidth for the 3000 Hz CF. The lowest mean latencies were at similarly inconsistent bandwidths. The standard deviations for latency for the C4 component were more consistent across CFs, although no general trend was noted. The highest standard deviations for latency were at the greatest bandwidth at the 200, 500, and 3000 Hz CFs and at one of the higher bandwidths, 500 Hz, at the 1000 Hz CF. The lowest standard deviations for latency were observed at smaller bandwidths, namely the 20 Hz bandwidth for the 250 Hz CF, 50 Hz bandwidth for the 500 Hz CF, and 5 Hz bandwidth for the 1000 and 3000 Hz CFs.

The grand averaged epochs for each component are given in Table 8. The N1 component presented average latencies in a similar range (47-71 ms) across all bandwidths and CFs, with a few noted exceptions. The 8 Hz bandwidth at 500 Hz presented an average latency of 124 ms. The 8 and 10 Hz bandwidths at 1000 Hz presented no clear average N1 responses within the typical range. Clear responses were observed for all bandwidths for P2. The P2 component resulted in average latencies that, although within a wider range than the N1 latencies, were similar across bandwidths and CFs as well. The highest average latencies were at the 5-10 Hz bandwidths for all CFs, and a general decrease in average latency followed for each CF.

The C3 component resulted in average latencies that were higher at the smaller bandwidths. The highest average latencies were at the 10 Hz bandwidth for the 250 and 1000 Hz CFs, 8 Hz bandwidth for the 500 Hz CF, and 2 Hz bandwidth for the 3000 Hz CF. All CFs showed a general decrease in average latency in the subsequent bandwidths. The C3 component was the least consistent component in terms of presenting clear average latencies at all bandwidths. Ten bandwidths did not result in clear responses, including 2, 5, and 8 Hz at the 250 Hz CF, 100 Hz at the 500 Hz CF, 2 and 500 Hz at the 1000 Hz CF, and 5, 10, 200, and 2000 Hz

Table 8

Grand Averaged Epochs for Latencies of the Four Components, N1, P2, C3, and C4 (in ms)

Stimulus Type					
CF	BW	N1	P2	C3	C4
250	2	58	168	-	525
250	5	71	172	-	507
250	8	55	232	-	520
250	10	63	238	479	-
250	20	65	161	424	513
250	50	57	150	400	515
250	100	60	148	424	512
250	200	59	137	425	535
500	2	54	134	435	563
500	5	54	128	438	504
500	8	124	207	473	545
500	10	60	121	370	518
500	20	58	146	390	526
500	50	61	132	421	542
500	100	63	148	-	505
500	200	52	139	430	507
500	500	56	134	424	515
500	1000	56	139	407	509
1000	2	67	139	-	507
1000	5	59	165	443	534

1000	8	-	243	448	527
1000	10	-	204	459	-
1000	20	61	197	433	539
1000	50	66	169	440	524
1000	100	61	156	438	535
1000	200	53	147	425	508
1000	500	52	142	-	501
1000	1000	52	129	413	511
1000	2000	47	128	421	509
3000	2	52	126	473	-
3000	5	66	174	-	497
3000	8	71	172	435	535
3000	10	55	154	-	514
3000	20	61	152	425	522
3000	50	58	137	402	511
3000	100	58	145	429	524
3000	200	61	137	-	506
3000	500	57	140	413	516
3000	1000	53	129	414	516
3000	2000	52	133	-	498

Note. Dashes indicate values where no clear response was recorded. CF = center frequency in Hz; BW = bandwidth in Hz at the 3000 Hz CF. The C4 component resulted in relatively inconsistent highest average latencies, including averages at the 200 Hz bandwidth for the 250 Hz CF, 2 Hz bandwidth for the 500 Hz CF, 20 Hz bandwidth for the 1000 Hz CF, and 8 Hz bandwidth for the 3000 Hz CF. However, the lowest average latency for each CF was less variable, with lowest average latencies being observed at the 5 Hz bandwidth for the 250, 500, and 3000 Hz CFs and the 500 Hz bandwidth for the 1000 Hz CF. No other general trends were noted among the average latencies of the C4 component. Furthermore, an ANOVA for repeated measures failed to show any significant differences in latencies for all components as a function of bandwidth.

Figure 2 shows the dipole distribution for each of the bandwidths for the CFs of the N1 response. The dipoles are primarily located in the left, center, and frontal lobes near the superior to medial temporal gyri. The dipoles show a tendency to shift from the right hemisphere to the center and then to the left hemisphere as the bandwidth increases except at the widest bandwidths. The origin of the N1 response has been shown to be located in the superior temporal gyrus; however, this observation has been for static, that is nondecision making, studies (Picton, 2011). It has been shown that the middle temporal gyri are associated with perceptual integration (Orrison, 1995). The superior temporal gyri have been shown to have various functions. The lateral surface on the dominant hemisphere is associated with Wernicke's area and receptive language (Picton, 2011), and the superior portions include the gyri of Heschel, which make up the primary auditory cortex (Orrison, 1995; Picton, 2011). Anterolateral regions of the auditory cortex may be an important area in pitch perception (Warren & Griffiths, 2003).

The P2 component (Figure 3) shows dipoles primarily located in the frontal superior gyri on both sides of the temporal lobes. Unlike the N1, there is little to no consistency in the

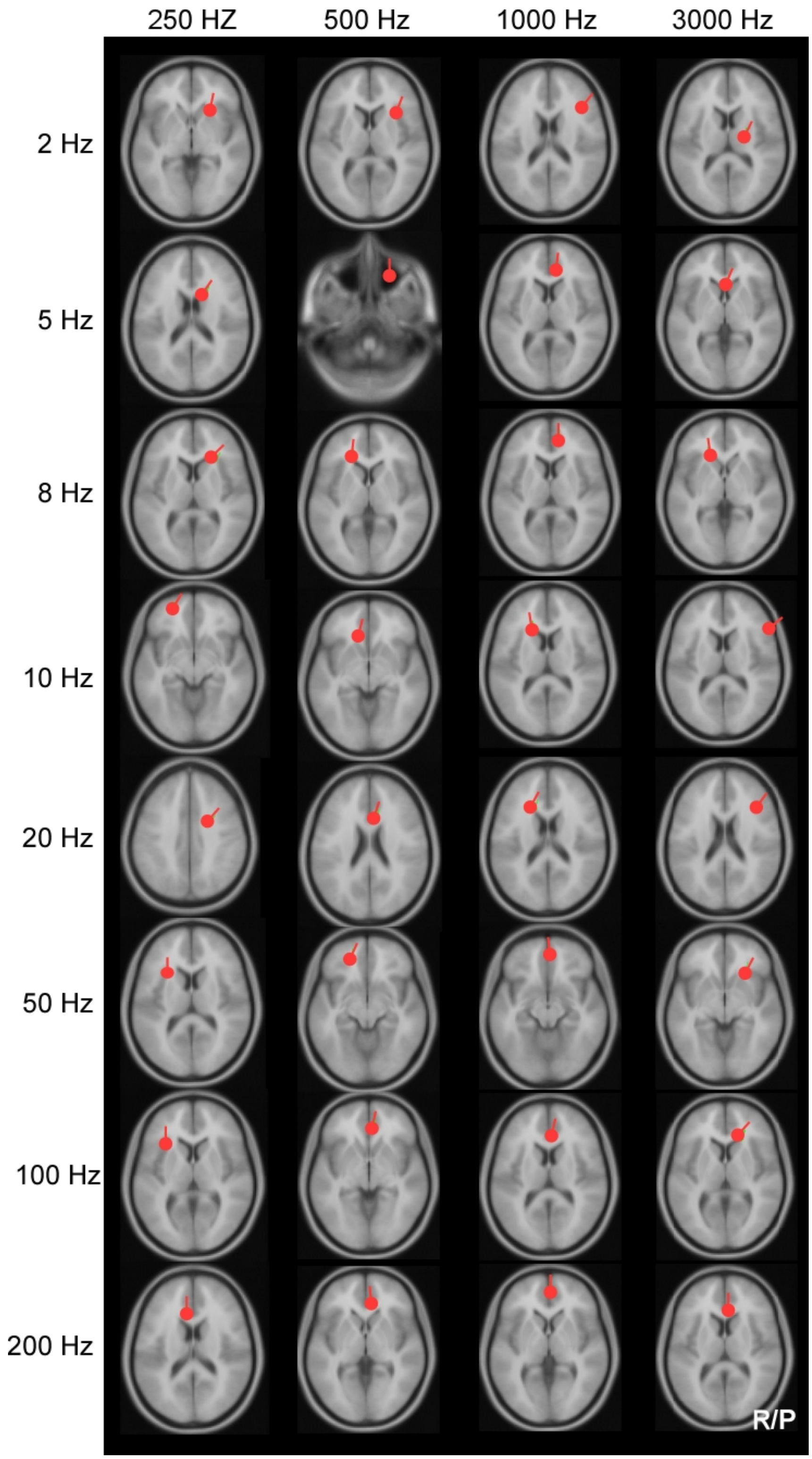

Figure 2. Axial view of the dipole distribution for all CFs and bandwidths for the N1 component. CFs are listed on the horizontal axis and bandwidths are listed on the vertical axis. The red marks indicate the dipole location and its direction for each N1 response.

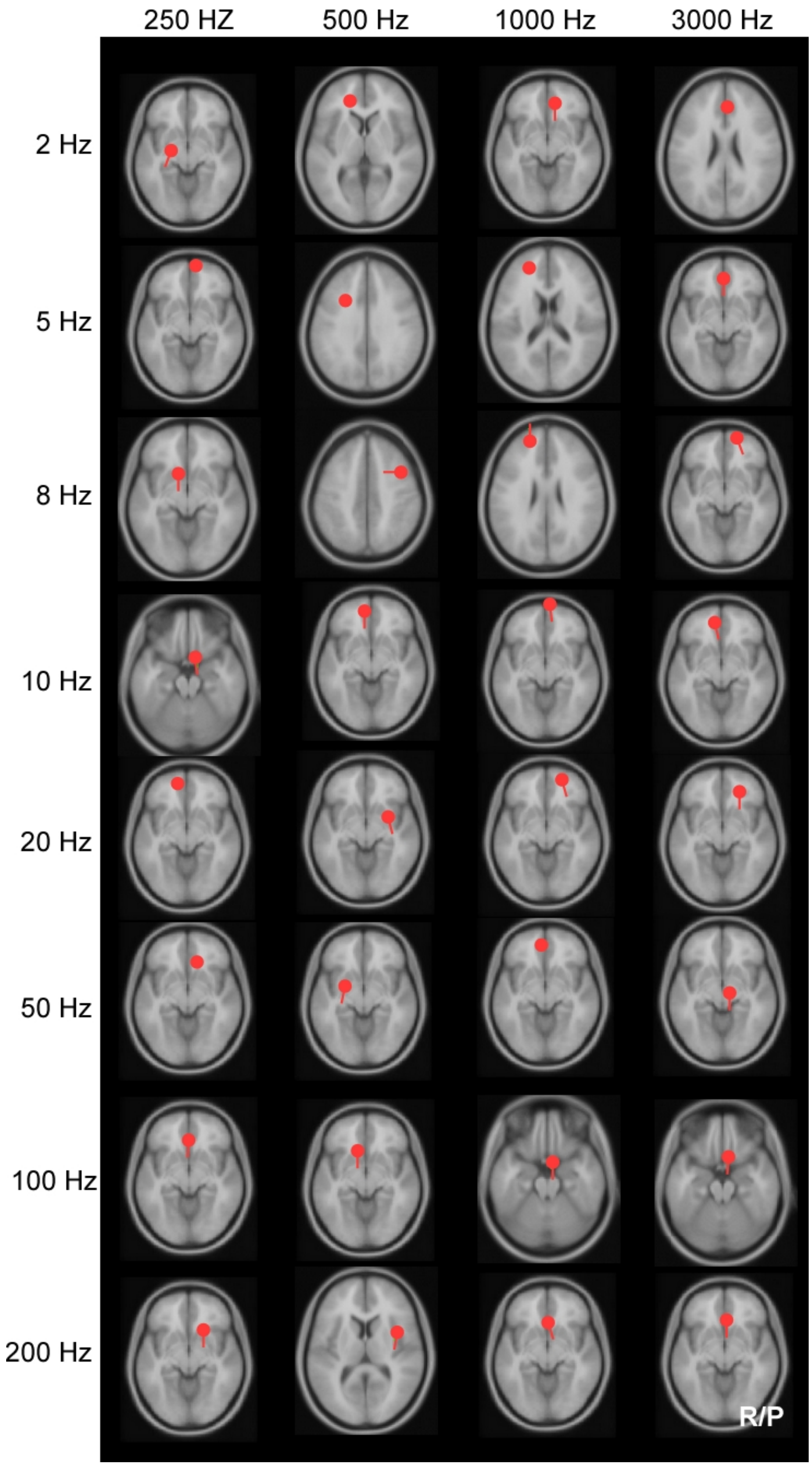

Figure 3. Axial view of the dipole distribution for all CFs and bandwidths for the P2 component. CFs are listed on the horizontal axis and bandwidths are listed on the vertical axis. The red marks indicate the dipole location and its direction for each P2 response.

distribution of the dipoles. This may be due, in part, to the observation that the N1-P2 components are oftentimes seen as a composite single component (Picton, 2011).

The C3 component (Figure 4) differs considerably in that there is little shift from the center of the frontal lobe across all conditions. There is some anterior-posterior movement, but little lateralization is seen.

Figure 5, which shows the dipole distribution for the C4 component, is similar to the C3 component (Figure 4) in that the activity is seen primarily in the central-frontal areas, with essentially no shift in the dipoles from center.

Discussion

The purpose of the current study was to determine the extent to which auditory stimuli are processed differently in the brain according to frequency differences, specifically in response to the CBW. The author also assessed the loudness perception of these frequency differences amongst listeners. The study examined the loudness perception and EEG responses of young adults with typical hearing. The results of the current study add to the current research base regarding the processing of complex sounds in the auditory cortex.

Summary and Evaluation of Results

Behavioral data. Reaction times were recorded for all participants and all stimuli, giving insight into the decision making process involved in determining the perceived loudness of each stimulus pair. A trend was observed amongst the mean RTs showing increased latency with increasing bandwidth followed by decreased latency for all CFs. There was a general decrease in RTs for bandwidths greater than the CBW in comparison to the RTs for bandwidths leading up to the CBW. This suggests a perceived difference in the loudness level at bandwidths greater than the CBW.

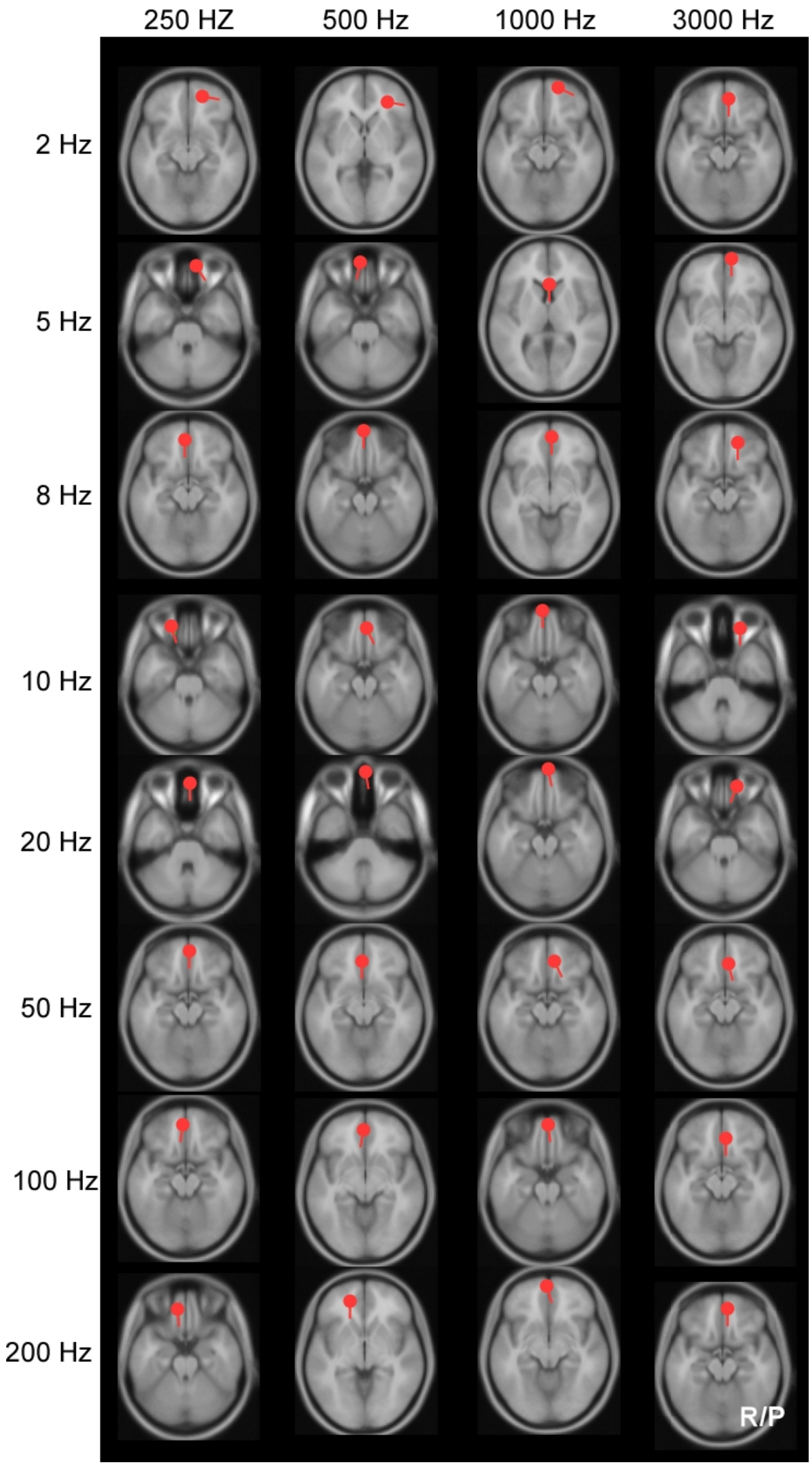

Figure 4. Axial view of the dipole distribution for all CFs and bandwidths for the C3 component. CFs are listed on the horizontal axis and bandwidths are listed on the vertical axis. The red marks indicate the dipole location and its direction for each C3 response.

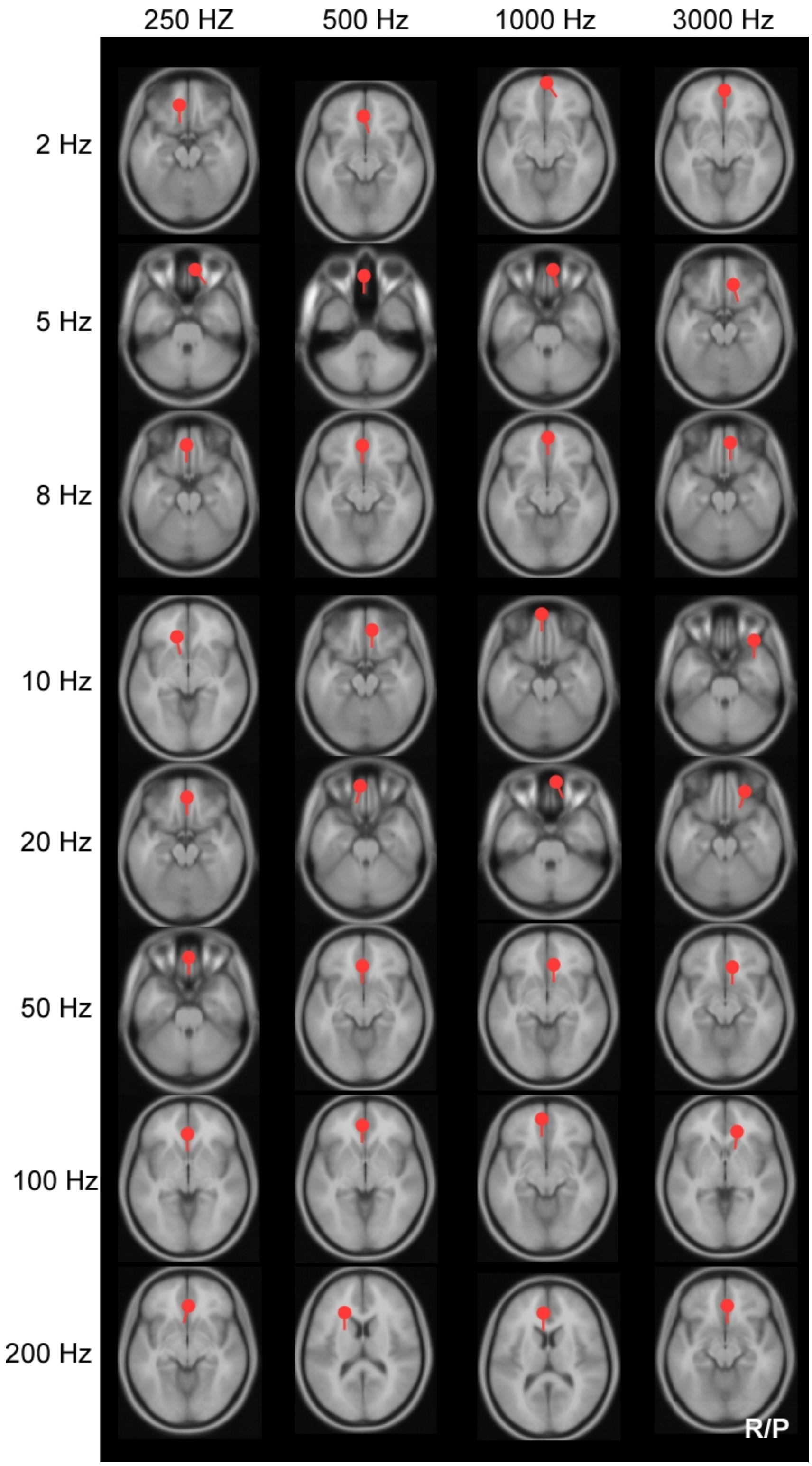

Figure 5. Axial view of the dipole distribution for all CFs and bandwidths for the C4 component. CFs are listed on the horizontal axis and bandwidths are listed on the vertical axis. The red marks indicate the dipole location and its direction for each C4 response.

An increase in RT is usually indicative of increased uncertainty. Greater standard deviations in RT, and thus variability, also suggest uncertainty in decision making. Participants tended to exhibit more uncertainty when determining the differences at higher bandwidths, to an extent. Once the bandwidth surpassed the CBW, however, there was typically a decrease in mean RT, as well as standard deviation, for all CFs.

The smallest standard deviations for RT were consistently at the 2 Hz bandwidth across CFs. This correlates with some of the shorter RTs as well and suggests essentially a nonambiguous decision as to the observation that the comparisons were the same, or that there was no perceived difference in loudness.

There generally were significant differences in RT at bandwidths of 5 Hz and greater for all CFs. The inconsistency in RTs at and above the 5 Hz bandwidth was likely due in part to difficulties in decision making. Participants had more trouble determining if there was or was not a difference in perceived loudness at these bandwidths. The lack of significant differences in RTs at the 2 Hz bandwidth is not surprising, for research has shown that a 2 Hz gap from the CF is not sufficient for identification of frequency differences.

Event related potential data. The current study examined the ERP components N1, P2, C3, and C4. The N1 response has been observed to occur at approximately 50 to 150 ms post stimulus, primarily over the fronto-central region of the scalp (Picton, 2011). The P2 component is generally the next peak or major response occurring before 250 ms post stimulus (Picton 2011). The C3 and C4 components are subsequent responses that were selected. The C3 component was typically observed between 400 and 500 ms post stimulus, and the C4 component was typically the next major response following the C3 component.

No significant differences were found in latency as a function of bandwidth for all components. Similar results have been found in other studies on the CBW in the human auditory system. Soeta and Nakagawa (2006) looked primarily at the amplitudes of AEPs, although they also examined latency as well. They found that the N1m component exhibited critical band-like behavior in amplitude, but they did not find significant results in latency. Soeta et al. (2005) also found that the N1m latencies were not significantly affected by stimulus bandwidth, although there were significant differences in N1m latency between each hemisphere. These researchers also observed changes in the N1m amplitude corresponding with the CBW, indicating critical band-like behavior in N1m amplitude. These and the results of the current study suggest that it is likely that the latency component of AEPs does not exhibit critical band-like behaviors, although other components of AEPs may.

Further observations from EEG data collection revealed interesting results regarding the origins and processing of the N1, P2, C3, and C4 components. The origins of these components were observed primarily in the superior temporal gyrus. This is not surprising, as this is the location of the auditory cortex (Orrison, 1995; Picton, 2011), yet the dipoles were not shifting into the temporal lobes in the time frame that would be expected. Because of the latency of the response, however, it would appear that the stimuli were being processed in the proper sequence, but that they were also being processed at the same time in the temporal lobes, which are responsible for auditory decision making. This points to a shift in processing from the primary areas for the response to the temporal areas to makes decisions about that response.

This shift in processing indicates that the N1 component has to process information temporally and independently to determine whether or not there is a difference acoustically. The same is true for each of the other components, in that they too process information temporally and independently to determine if an acoustic difference is present.

The various components showed no significant differences in latency across bandwidths. None of the acoustic differences presented by the various bandwidths resulted in a varied latency, yet there were clearly still differences among components. This suggests that it is the decision process itself that requires processing time, rather than the acoustic differences among the stimuli.

These results indicate that as the responses to acoustic stimuli proceed into areas of higher neural function, each must make its own independent decision as to whether or not an acoustic or frequency difference is present. This finding is significant because this type of processing has not typically been identified prior to these results. The results of this study state that these neural responses process sounds independently for each frequency in each incoming auditory stimuli. This notion offers valuable insight into how the brain processes the complex auditory stimuli it receives on a daily basis.

Recommendations for Future Research

The results of the current study contribute to the research base regarding the processing of complex sounds in the human auditory cortex. However, future studies are needed to continue the investigation of this area of focus. Discrepancies among results of various studies examining the CBW in the human auditory system call for continued investigation on the matter. It would be beneficial to the audiology and neuroscience communities to replicate similar studies in order to solidify and expand on previously reported results.

Future studies may be done in similar manners with a focus on different aspects of AEPs, namely latency, amplitude, polarity, and topographic location. These would contribute to a more holistic understanding of AEPs and greater knowledge regarding other aspects of sound processing. Soeta and Nakagawa (2006) and Soeta et al. (2005) studied both amplitude and latency in N1m responses. Both studies observed critical band-like results in N1m amplitude, but found no significant differences in latency as a function of bandwidth. However, Okamoto et al. (2008) found significant critical band-like results in both latency and source strength across frequencies. The current study contributed additional insights into the effects of the CBW on auditory processing, although further knowledge is still needed.

Less focus has been placed on the loudness perception of tones in response to the CBW, although it is still an important area of study. Various authors have, however, discussed loudness perception in relation to the CBW to various degrees (Durrant & Lovrinic, 1977; Emanuel & Letowski, 2009). Okamoto et al. (2008) found no significant differences in perceived loudness at various bandwidths above and below the CBW, for all test stimuli. Zwicker et al. (1957) found different results. These researchers presented complex tones around various CFs at different bandwidths and assessed loudness perception among the frequencies. They observed that within a critical band, the loudness was independent of tonal separation, or frequency bandwidth, but outside the CBW, the loudness of the tones began to increase. This concept has serious implications with respect to areas of audiology relevant to loudness perception, namely hearing aids, audiological testing, hearing loss, and more. As such, continued research on loudness perception of complex sounds in general and specifically in relation to the CBW is crucial.

Finally, further research into the origin and processing shift in the N1, P2, C3, and C4 components that was observed in the current study would be beneficial. Future studies on the shift from the STG to more temporal regions for frequency processing and decision making would help to expand and solidify knowledge in this area. Studies may focus on how each component processes incoming stimuli temporally and independently to investigate how these temporal regions determine whether or not an acoustic difference is present. Further research would benefit both the audiology and neuroscience communities in better understanding how the brain processes complex auditory stimuli, with many relevant applications.

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Appendix A

Annotated Bibliography

Bonelli, S. B., Thompson, P. J., Yogarajah, M., Vollmar, C., Powell, R. H. W., Symms, M. R., . . . Duncun, J. S. (2012). Imaging language networks before and after anterior temporal lobe resection: Results of a longitudinal fMRI study. *Epilepsia, 53,* 639-650. doi: 10.1111/j.1528-1167.2012.03433.x

Objective: In this study, Bonelli et al. sought to further understand the effects on language function of anterior temporal lobe resection (ATLR) in patients with temporal lobe epilepsy (TLE). Using functional magnetic resonance imaging (fMRI), the authors analyzed language reorganization in patients with both left and right TLE, assessed language activation and proficiency preoperatively, and predicted postoperative language deficits following left ATLR. *Method:* Forty-four patients participated in this study. Twenty-four of the patients had left TLE and 20 patients had right TLE. All patients were native English speakers, left-language dominant on fMRI, and underwent ATLR for hippocampal sclerosis. Patients were administered the McKenna Graded Naming Test and a phonemic verbal fluency (VF) test both pre- and postoperatively. Patients also each performed a VF fMRI task, both pre- and postoperatively. The tasks were administered in a blocked experimental design with 30 second activation blocks alternating with 30 seconds of crosshair fixation. The first portion of the task involved the patients generating different words beginning with a visually presented letter, with a given rest condition. The second portion of the task involved verb-generation; concrete nouns were presented every 3 seconds in blocks of 10 with 30 seconds of crosshair fixation as rest. The patients were to either generate verbs associated with the nouns, or silently repeat the nouns presented. *Results:* The left TLE group demonstrated significantly lower naming scores both pre- and postoperatively, as compared to the right TLE group, and there was a significant reduction in naming scores in the left TLE group preoperatively to postoperatively. There were no significant differences in VF scores between the two groups or preoperatively to postoperatively in either group. Via fMRI, the researchers observed preoperative activation for VF in the left inferior frontal gyrus and middle frontal gyrus in both the left and right TLE groups. Postoperatively, the researchers observed fMRI activation for VF bilaterally in the inferior frontal gyrus and middle frontal gyrus for the left TLE group and fMRI activation for VF in the left middle and inferior frontal gyrus for the right TLE group. They also found a significant correlation between preoperative fMRI activation in the left middle frontal gyrus for VF and change in VF scores outside of the scanner. This indicated a greater fMRI activation being associated with a greater decline in VF. Furthermore, the authors found no significant correlation between preoperative naming scores or left hippocampal volume and postoperative naming change in the left TLE group. *Conclusions:* The authors observed that within four months following left ATLR, patients demonstrated reorganization to the contralateral hemisphere. This was not observed following right ATLR, which led the authors to conclude that there are multiple systems supporting language. These systems may come into action when the primary system in the speech dominant hemisphere is disrupted. It is likely, however, that according to the results of this study, reorganization to the contralateral hemisphere is less effective than reorganization involving the ipsilateral posterior hippocampus, particularly in naming functions. There is no specific cause that is known to determine which process will take place, but possible factors include genetic factors, age of onset, and extent of hippocampal resection. The authors went on to discuss how these results can help predict possible postoperative changes in language function. Clinically, predicting possible changes in naming and VF following ATLR is important because it allows physicians, therapists, and other team members to better prepare the patient and family members for what they might expect following the procedure. It also helps the team members to be more prepared in recovery and therapy approaches. *Relevance to current work:* The authors used fMRI intensively to observe activation throughout the brain during various language tasks, including VF and naming tasks, before and after ATLR. Functional MRI allowed the researchers to view changes in the language functioning in the brain pre- and postoperatively. Although fMRI was not used in the current study, it is important in gaining a complete understanding of the brain imaging techniques that may be applicable to this type of experiment. *Level of evidence:* Level IIIb.

Burrows, D. L., & Barry, S. J. (1990). Electrophysiological evidence for the critical band in humans: Middle-latency responses. *The Journal of the Acoustical Society of America, 88,* 180-184. doi: 10.1121/1.399938

Objective: The purpose of this experiment was to examine the components Na and Pa of the middle-latency response and wave V of the auditory brainstem response as a function of the critical bandwidth (CBW) in order to better understand the concept of critical bands. *Method:* Ten females (ages 20-30) with normal hearing participated in this study. Two-tone complexes were presented at 85 dB SPL for a duration of 20 ms, with 5 ms rise and fall times, at a repetition rate of 11.7 per second. The complexes were centered around 2000 Hz, with frequency separations, or bandwidths, of 76, 150, 268, 330, 592, 868, and 1012 Hz. Na, Pa, and wave V responses were collected, via electrodes on the scalp, and recorded. *Results:* Two components, both of which were types of measurements of component Na, resulted in an increase in amplitude with a bandwidth beyond the CBW. Measures on components Pa and wave V showed no increase with CBW. *Conclusions:* Na amplitude demonstrated the existence of critical band-like behavior, while Pa and wave V did not show similar effects. *Relevance to current work:* This study directly examined event related potential components, as they relate to the CBW, as was done in the current study. This study also produced differing results than various other studies on CBW in the auditory cortex, indicating a need for further research in this area of study. *Level of evidence:* Level IIIa.

Congedo, M., John, R. E., Ridder, D. D., Prichep, L., & Isenhart, R. (2010). On the ‘‘dependence’’ of ‘‘independent’’ group EEG sources; an EEG study on two large databases. *Brain Topography, 23,* 134-138. doi: 10.1007/s10548-009-0113-6

Objective: This study aimed to explore the coherence profile, or dependence, of eyes-closed resting electroencephalography (EEG) sources. The authors used two large sample normative databases and a test-retest strategy to draw conclusions. *Method:* Two samples of individuals were selected prior to the study (N = 84, age range 18-30; and N = 57, age range 17-30). All participants were healthy, without history of drug or alcohol abuse, head injury, or psychiatric illness. During data collection, participants sat on a comfortable chair in a dimly lit room with their eyes closed. In all cases, 3-5 minutes of EEG was continuously recorded. The authors used a group blind source separation (gBSS) method in order to extract scalp spatial maps and associated EEG time-courses. *Results:* The profiles for both databases appeared non-random, with concentrated results in discrete frequency regions. The coherence profile showed peaks at nearly identical frequencies for each database, although with inconsistent amplitude of the peaks. Almost all peaks found in each database could be found in the other as well. The components were organized in two independent (both in-phase and out-of-phase) networks, whereas significant out-of-phase cross-talk existed in each network. *Conclusions:* The authors concluded that a gBSS method allows for the study of residual (out-of-lag) cross-talk between relevant brain sources. With EEG, gBSS can be used to replicate a set of seven components with nearly identical spatial and spectral content. They also concluded that the organization of these components in networks communicating by specific frequency and time-lag protocols was replicable as well. *Relevance to current work:* This study used EEG to study brain activity in a resting state and map out activity in the brain. Similar procedures were used in the current work. *Level of evidence:* Level IIIb.

Crosson, B., McGregor, K., Gopinath, K. S., Conway, T. W., Benjamin, M., Chang, Y., . . . White, K. D. (2007). Functional MRI of language in aphasia: A review of the literature and the methodological challenges. *Neuropsychology Review, 17*, 157-177. doi: 10.1007/s11065-007-9024-z

Objective: The authors of this review of literature discussed and analyzed the benefits of and, more extensively, the challenges facing the use of functional magnetic resonance imaging (fMRI) as a useful clinical tool for imaging language production of individuals with aphasia. The authors first addressed neuroplasticity in the brain, related to which hemisphere is responsible for language recovery and production in aphasia. They cited many studies on the topic and concluded that it is most likely that reorganization of language activity to either the right hemisphere (RH) or to perilesional regions of the left hemisphere (LH) may be possible, under the right circumstances. Functional MRI has allowed significant advances in brain-behavior research, but there are still facets that must be addressed to improve clinical usage. The authors discussed six topics of concern: selection of a baseline task, the structure of language production trials, various techniques available for mitigation of motion-related artifacts, the importance of stimulus onset versus response onset in analysis, the use of trials with correct responses and errors in analyses, and reliability and stability of images across fMRI sessions. According to these researchers, there are questions of consistency and reliability among each of these areas of focus, which are preventing the full use of fMRI as an effective clinical tool. This article also included a case study involving a patient who showed a shift in frontal activity toward the RH following aphasia treatment. This case study utilized fMRI to effectively show this shift. However, the researchers declared that a much larger sample size would be needed to draw valid conclusions regarding that specific aphasia therapy. *Conclusions:* The authors concluded that they cannot adequately answer the question of which hemisphere is responsible for language recovery in aphasia. Rather, they posited that the more important question is in what circumstances each hemisphere plays a greater role. Functional MRI shows great promise in developing answers to this question, but only following thorough and appropriate attention to the current above stated issues. *Relevance to current work:* Functional MRI is a promising modality for the analysis of language in the brain, yet there are several key issues that must be addressed regarding its future clinical use. This article is significant in its thorough review of the literature regarding these issues and concepts. *Level of evidence:* Level IIIc.

Durrant, J. D., & Lovrinic, J. H. (1977). *Bases of hearing science*. Baltimore, MD: The Williams and Wilkins Company.

Objective: This book discussed various fundamental aspects of hearing science. The chapter on psychoacoustics discussed various aspects of psychoacoustic measures, including threshold, the auditory response area, considerations in the measurement of hearing, loudness, the power law, perception of complex sounds, the frequency-resolving power of the auditory system, and masking, as well as other areas of focus. *Conclusions:* The authors gave a good explanation, although at an introductory level, of these concepts. In the section on the perception of complex sounds, the authors touched on the topic of the critical bandwidth (CBW) as it relates to loudness summation. If two tones are separated by more than the CBW, the loudness levels will summate completely, and the total loudness will approach the sum of the individual loudness levels. However, if the two tones presented are within in the CBW, the loudness of the complex sound will depend on the increase in intensity resulting from adding the individual tones together and the power-law relation of loudness to this change in intensity. Furthermore, the authors pointed out that there is not one single CBW, but rather that the CBW depends on the center frequency. The CBW is only constant at low frequencies, around 200 Hz. The CBW is an important concept in masking and studying auditory perception in the human auditory system. *Relevance to current work:* This chapter, among other topics, described the CBW as it relates to loudness summation, which is a relevant and significant concept in the current work. *Level of evidence:* Level IIIc.

Emanuel, D. C., & Letowski, T. (2009). *Hearing science.* Philadelphia, PA: Lippincott Williams & Wilkins.

Objective: This book was a foundational text on the basics of hearing science. The chapter of focus, chapter 12, addressed psychoacoustics as they relate to hearing and perception. *Conclusions:* The authors discussed hearing thresholds, various auditory scales, loudness, pitch, masking, critical bands, timbre and sound quality, binaural hearing, and spatial hearing. They touched on the background and history of the concept of critical bands, including reviewing some of Harvey Fletcher's early work. The authors briefly discussed the importance of critical bands, particularly as they relate to masking noises. Critical bands are key to understanding pitch perception and timbre resolution. The authors discussed the critical band scale and how that is used clinically and in research. *Relevance to current work:* This chapter explained the concepts of critical bandwidths at a foundational level and gave some good supplementary information that was beneficial in the current study. *Level of evidence:* Level IIIc.

Fisch, B. J. (1999). *EEG primer.* Amsterdam, Netherlands: Elsevier Science, B. V.

Objective: This book went into detail on many aspects of electroencephalography (EEG). The purpose of the first chapter was to explain the processes behind EEG, as well as some strengths and limitations. *Conclusions:* An EEG recording is essentially a measure of voltage over time, and is shown as a graph of voltage on the y-axis and time on the x-axis. The operational definition of EEG is the difference in voltage between two different recording locations plotted over time. This can be interpreted as inhibitory and excitatory postsynaptic potentials generated in the cortex of the brain. Currents flow through tissues between the electrical generator and the recording electrode, which provides EEG measurements. The author described some limitations to EEG interpretation, including that abnormalities may not localize to the area of pathology in the brain, and that it can be difficult to determine the location of a signal generator. If limitations such as this are accounted for, EEG recordings can be very functional. The author went on to describe how EEG works. This imaging technique measures the event related potentials in the brain, including resting potentials, postsynaptic potentials, and action potentials. It has been observed that human EEG recordings typically contain rhythmical activity, despite the complexity of the neuronal activities of the brain. This is consistent during wakefulness and sleep. These rhythmic patterns are believed to be driven by thalamic pacemaker cells. Theories concerning the mechanism behind these pacing activities in the thalamus have been proposed, but the reality of these cellular mechanisms remains unknown. These rhythmical patterns allow researchers to measure EEG activities and draw conclusions about the brain based on the results. EEG recordings take place via electrodes on the scalp. These electrodes primarily record summated electrical changes of the underlying cortex. This process has limitations, such that the amplitude of the scalp EEG may be decreased as a result of either an increased electrical impedance between the source and the recording electrodes or a decrease in the impedance at various places across the path of these currents. Furthermore, the author stated that because these signals are transmitted at almost the speed of light, similar waveforms occurring in different or non-adjacent scalp locations likely arise from the same cortical generator. However, the strengths and abilities of this process make it yet a beneficial imaging method in many cases. *Relevance to current work:* This book, and the first chapter in specific, gave a basic review of the functions and associated aspects of EEG. This is the method of brain imaging used in the current study. *Level of evidence:* Level IIIc.

Fletcher, H. (1940). Auditory patterns. *Reviews of Modern Physics, 12,* 47-66. doi: 10.1103/RevModPhys.12.47

Objective: The purpose of this document was to address what the author referred to as the "problem" of understanding the hearing processes taking place when we sense a sound. Fletcher stated that to address this problem we must know how to describe and measure sound reaching the ears, how to describe and measure the sensations of hearing produced by a sound upon the listener, and the degree and kind of hearing ability possessed by the listener. These aspects were addressed to some degree in the article. *Conclusions:* Fletcher discussed intensity in sound and variation in the air wave relative to that intensity. Fletcher stated that it is possible to represent a pure tone by a point on a chart by giving the frequency in cycles per second, or Hz, and the intensity in dB. Fletcher then gave a brief overview of the hearing mechanism, including elements of the outer ear, middle ear, inner ear, hair cells, and auditory nerve. Fletcher included that the nerve endings are spread out along a relatively long yet narrow membrane, making it possible to designate the position of a small group of nerves by a single point. Fletcher set up a chart with ascending numbers assigned to portions of the cochlea, starting at the inside of the spiral portion and moving outwards. Low pitch tones seem to stimulate areas corresponding with low numbers, and as the frequency increases, so does the number of corresponding area. Fletcher then addressed masking and just perceptible differences in hearing, and here introduced critical bands. Fundamentally, the concept of critical bands stemmed from the valid expectation that when the width or frequency range of a masked noise becomes smaller than a particular value, then all of the acoustical intensity could be considered to be acting upon the same nerve endings as those being stimulated by the tone being masked. This value corresponds with the critical bandwidth (CBW). In examining this concept, I_f represents the intensity per cycle of a noise at frequency f, and I_m represents the sound intensity a tone of frequency f which is just perceptible in the presence of noise. The ratio of I_m to I_f is critical. For bandwidths smaller this critical value, that referred to previously, the ratio of the intensity decreases as the bandwidth decreases. For all bandwidths larger than this critical value, the ratio of intensity remains constant. These CBWs always correspond to a specific portion of the basilar membrane that is .5 mm in length. Fletcher went on to talk about loudness levels and the loudness scale. Fletcher explained various experiments that have been used to develop the loudness scale. One such experiment, though hypothetical at that time, was described as a way of obtaining this type of scale. Typical listeners would be presented a sound in one ear, with a loudness level of L_1. Then tones of this same intensity would be presented in both ears and this loudness measure labeled L_2. Each level would correspond with a loudness unit on the scale, and these would correspond with N_1 and N_2 respectively. Then the process would be repeated except that the intensity of the tone presented in the one ear would be raised to that of L_2. This tone would then be presented in both ears, and this level would be measured as L_4, which would correspond with N_4. In creating a reliable loudness scale, the intensity of N_4 should be four times as great as that of N_1. This and other experiments were discussed as methods of quantifying loudness levels. Fletcher finished by addressing the process of measuring and mapping auditory patterns in deaf individuals. Fletcher concluded that similar to typical hearers, the auditory patterns of deaf individuals can also be drawn quantitatively. *Relevance to current work:* This article was one of the earliest mentions of the CBW in audiology literature. It is the foundational document for the use of CBW in countless future studies, including the current work. *Level of evidence:* Level IV.

Fletcher, H. (1953). *Speech and hearing in communication.* New York, NY: D. Van Nostrand Company, Inc.

Objective: This book was one of the early guides to hearing and speech sciences. The chapter of focus discussed the bases of auditory masking and what is required to mask various types of sounds. *Conclusions:* Fletcher discussed early investigations of the critical bandwidth (CBW), as they relate to masking sounds. Fletcher defined value *k* as the number of dB above the spectrum level of noise that the level of a pure tone must be raised before it is masked by the noise. When the width of a noise around a tone becomes very small, the value of *k* becomes large, in that the maskee tone can be raised to higher levels. However, there must be a bandwidth above which the value of *k* will become constant and equal to the difference between the level of the maskee tone and the spectrum level for the noise. That bandwidth is defined as the CBW. Fletcher summarized that only a relatively small band of frequencies around a tone contribute to masking that tone. These frequencies correspond to CBWs. Fletcher also presented evidence indicating that certain frequency bands stimulate specific sections along the basilar membrane. This further supports the concept of critical bands in the human auditory system. *Relevance to current work:* This chapter, as well as the book in general, was a major contributor to current knowledge of audiology. This chapter gave some of the earliest and most fundamental information on CBWs and how the ear perceives sounds in the presence of other sounds. This is a key principle in the current work, which also looked at how the ear perceives and the brain processes complex sounds. *Level of evidence:* IIIc.

Friederici, A. D. (2004). Event related brain potential studies in language. *Current Neurology and Neuroscience Reports, 4*, 466-470. doi: 10.1007/s11910-004-0070-0

Objective: In this article, Friederici reviewed the four relevant language-related components in event-related potentials (ERPs) in the brain. These are the N400, the early left anterior negativity (ELAN), the P600, and the closure positive shift (CPS). Event related potentials are measured in the brain using either electroencephalography (EEG) or magnetoencephalography (MEG), which are measured on the scalp and able to register brain activity millisecond by millisecond. This ability is a strength of EEG and MEG when compared to other imaging techniques, such as functional magnetic resonance imaging and positron emission tomography. *Conclusions:* The N400 component is a negative waveform that peaks around 400 ms after the critical stimulus onset. It has been observed to be correlated with lexical-semantic processes. The N400 is distributed broadly over both hemispheres, and MEG studies have shown that it likely generates in the region of the auditory cortex. This component has been observed in the presentation of sentences with semantically mismatched final words and in other similar settings. The N400 amplitude is greater with presentation of semantically unrelated words in a sentence than with semantically related words. There is also some evidence that the N400 reveals some aspects of lexical integration as well. Syntactic processes are shown in two phases, the ELAN and the left anterior negativity (LAN) components. The ELAN is correlated with early structure-building processes and is present between around 100 and 200 ms. This component has been shown to be supported by the superior temporal gyrus and the frontal operculum. The LAN component reflects the processes of assigning the grammatical relations between words and their thematic roles. The LAN is typically present between 300 and 500 ms. The P600 is a late-syntax related ERP component that is observed as a positive wave after 600 ms following stimulus onset. Violations of structural preferences, outright syntactic violations, and difficulty of syntactic integration have all led to the presence of the P600. Lastly, the CPS component is directly related to prosodic elements of speech. The CPS is correlated with the processing intonational phrase boundaries and is observed as a positive shift at the end of a phrase boundary. Interestingly, the CPS is still present when the intonational phrase boundary is omitted and only indicated by pitch contour variation, as well as in the absence of segmental information. This suggests that the CPS is strictly related to prosodic processes. *Relevance to current work:* This article reviewed the primary components in ERPs in the brain related to language, which was discussed in the current study. These components are observed via EEG and MEG. These imaging methods are functional methods of viewing brain-activity in a more real-time manner. *Level of evidence:* Level IIIc.

Jurcak, V., Tsuzuki, D., & Dan, I. (2007). 10/20, 10/10, and 10/5 systems revisited: Their validity as relative head-surface-based positioning systems. *NeuroImage, 34,* 1600-1611. doi: 10.1016/j.neuroimage.2006.09.024

Objective: The purpose of this article was to examine the effective spatial resolution of the 10/20, 10/10, and 10/5 electrode placement systems for multi-participant studies. The goal was to assess the potential of each of these systems as relative head-surface-based positioning systems. *Method:* The researchers reanalyzed magnetic resonance imaging data sets from 17 healthy participants (9 males, 8 females, ages 22-51). Researchers determined the 10/20, 10/10, 10/5 positions and analyzed and compared the reference points and curves, uses, and validity of each system. *Conclusions:* The authors stated that although the 10/20 system has been proven to be effective and beneficial, there is still a need for further research to increase the accuracy of the system. There is no clear indication of any of the three systems being superior to another. The authors concluded that as long as a detailed rule for a particular method is provided, it will yield precise landmarks that can be probabilistically described. *Relevance to current work:* This article provided foundational material on the 10/20 system. This is the system that was utilized for applying electrodes for EEG data collection in the current study. *Level of evidence:* IIIb.

Kim, S., Richter, W., & Ugurbil, K. (1997). Limitations of temporal resolution in functional MRI. *Magnetic Resonance in Medicine, 37*, 631-636. doi: 10.1002/mrm.1910370427

Objective: The goal of this study was to examine temporal resolution aspects of fMRI using approaches focused on motor areas of the brain. *Method:* Study members included healthy volunteers who participated in fMRI scans. Two temporal fMRI experiments were conducted, both involving finger movements in response to lighted visual stimuli. In each experiment, four circles corresponding with four fingers would light up in randomized sequences, and participants were instructed to move their fingers in the corresponding order. The first experiment involved an immediate response and determined temporal resolution and reproducibility in one single area. The second experiment involved a delayed response and determined hemodynamic responses in multiple regions simultaneously. Functional MRI data were processed and hemodynamic response times were calculated. *Results:* The authors were able to measure hemodynamic responses and temporal resolution results. During repeated tasks, the upper level of the hemodynamic response in the motor area was about 5 seconds. To determine the upper limits of the temporal resolution, the inter-peak time was plotted against the inter-epoch time. The correlation of these lines was high, at $R^2 = 0.89$, the slope of this line was close to 1. *Conclusions:* The authors summarized various methods that may be useful in improving temporal resolution in fMRI. However, they concluded that although fMRI is a useful tool and the temporal resolution is not unreasonable, methods such as EEG or MEG may prove more useful and accurate in measuring neural processes that operate in a domain of tens of milliseconds and faster. *Relevance to current work:* The authors demonstrated some of the strengths and limitations of fMRI and incidentally EEG. This article served to illustrate the reasoning behind using EEG in the current study, despite the strengths of fMRI. *Level of evidence:* Level IIIa.

Lee, A., Kannan, V., & Hillis, A. E. (2006). The contribution of neuroimaging to the study of language and aphasia. *Neuropsychology Review, 16,* 171-183. doi: 10.1007/s11065-006-9014-6

Objective: The authors of this article reviewed and discussed various methods of functional and structural imaging, including uses, strengths, and limitations. The included imaging techniques were magnetic resonance imaging (MRI), functional MRI (fMRI), diffuser tensor imaging, and briefly positron emission tomography (PET). Magnetic resonance imaging is a brain imaging method based on the magnetic properties of protons in the blood. The proportion of various types of magnetic signals received by the device allows the device to form a tissue contrast that produces a structural image of the body. Functional MRI is utilized based on the observation that increased activity in the brain will result in an increase in blood flow. This methodology is beneficial but not without limitations. Functional MRI relies on the assumption that the individual presents with a typical hemodynamic response to brain activation, which may be absent in cerebrovascular disease. Furthermore, fMRI, specifically neurovascular coupling in the brain, can vary based on the time of day, external factors such as caffeine or non-steroidal anti-inflammatory agents, head movements, and normal motion of the brain in the cardio-respiratory cycle. There are also various technical difficulties associated with fMRI. One significant example is the difficulty in testing specific cognitive functions without activating the brain in the resting state, which decreases the signal to noise ratio. This technical difficulty may be reduced by simple head restraints or motion-correction software, but these are often insufficient. Other methods of overcoming this limitation are conjunction analysis and event related designs. Conjunction analysis is a process that better allows for the incorporation of cognitive functions that interact with each other. Event related designs randomly intermix the brain activations or events of interest with other events, in order to prevent the systematic influence of preceding events on the events of interest. The authors went on to discuss the use of MRI scans with diffusion-weighted imaging and perfusion-weighted imaging in the study of language in the brain, particularly in individuals with aphasia. These methods are means of assessing lesions in stroke patients or those with other etiologies. The third method the authors discussed was diffuser tensor imaging, which is the process of determining the ability of water molecules to be diffused in the brain. Water molecules in a three dimensional space diffuse either in all three directions evenly (isotropic diffusion) or more in one direction than another (ansiotropic diffusion). Like all other modalities, diffuser tensor imaging has its limitations, yet it can still be of benefit to the study of language functioning by providing information about major fiber tracts. Lastly, the authors gave a brief comparison of PET and fMRI. The benefits of PET over fMRI include no loss of sensitivity or spatial localization of the anterior and medial temporal lobes; reduced chance of movement artifact in articulation tasks, due to lower spatial resolution; a quieter procedure, reducing activation of the cortex by external auditory stimuli; and arguably a more comfortable procedure. However, fMRI does not require as much time between scans, allowing for the comparison of repeated stimuli without transient responses between; greater spatial resolution; more rapid neurovascular coupling; higher availability; and a noninvasive nature. *Conclusions:* The authors concluded that all of these imaging methodologies complement each other, and a unique combination should be used for each individual case. *Relevance to current work:* This document effectively reviewed and compared several of the prevailing methods of imaging the brain used today. In particular, the process, benefits, and limitations of fMRI were discussed. *Level of evidence:* Level IIIc.

Lee, J. J., Lee, D. R., Shin, Y. K., Lee, N. G., Han, B. S., & You, S. H. (2013). Comparative neuroimaging in children with cerebral palsy using fMRI and a novel EEG-based brain mapping during a motor task – A preliminary investigation. *NeuroRehabilitation, 32,* 279-285. doi: 10.3233/NRE-130845

Objective: This study was designed to compare topographical maps produced using a novel electroencephalography (EEG) based brain mapping system with functional magnetic resonance imaging (fMRI) during a motor task in children with and without cerebral palsy (CP). *Method:* Five children participated in this study, one typical child (age 13) and four children with CP (mean age 10.25). No participants exhibited severe cognitive, visual-perceptual, or auditory impairment. The motor task involved grasping a small bag for 5 s each trial, with rest periods in between to prevent fatigue. The authors used an extension of the 10/20 system to create a novel EEG-based brain mapping system to look at cortical reorganization in regions of interest (ROIs) during the grasping task. The data from the EEG were used to create topographical power maps to better examine ROIs. Functional MRI measures were taken separately and involved a similar grasping task as was used in the first portion of the study. *Results:* In all five children, EEG activity was observed in the sensorimotor cortex (SMC) and the inferior parietal cortex (IPC). Additional areas of activation were observed in the children with CP, however. Two children showed activation in the premotor cortex (PMC) and superior parietal cortex. In the other two children with CP, activation was also observed in the prefrontal cortex. In the fMRI results, researchers observed activation in the contralateral SMC in the child without CP and in two of the children with CP. In another child with CP, the researchers found contralateral SMC activation during left hand movement and bilateral SMC and right PMC activation during right hand movement. In the final child with CP, activation was observed in the contralateral SMC during the less affected hand movement and some activation in the contralateral primary somatosensory cortex during movement of the affected hand. *Conclusions:* The researchers concluded that EEG-based topographical maps were equivalent to maps produced from fMRI during a hand motor task. They claimed that the EEG-based brain mapping system showed high potential as an alternative neuroimaging method to examine underlying neural control mechanisms, although additional studies with larger samples sizes are needed to further confirm this conclusion. *Relevance to current work:* This study compared the topographical maps produced using EEG with those produced using fMRI in children. It provided an important comparison in the technique that was used in the current study with other brain imaging methods. *Level of evidence:* Level IIIb.

Moore, B. C. J., & Glasberg, B. R. (1983). Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *The Journal of the Acoustical Society of America, 74,* 750-753. doi: 10.1121/1.389861

Objective: The authors examined and discussed auditory filter shapes, how they relate to the critical bandwidth (CBW), and possible adjustments to be made to the analysis of CBWs. They began by explaining and comparing two methods of determining the equivalent rectangular bandwidth (ERB) of the auditory filter. The two methods, the notch-noise method and the ripple-noise method, produce similar but not identical results. The authors also compared various results of these methods with those of accepted CBW measures and results. Finally, the authors discussed some of the limitations of using these ERB measures. Among other limitations, they mentioned that the results tend to apply to young listeners at moderate sound levels, the ERB typically increases with age, and the assumption of filter symmetry is not always valid. *Conclusions:* The authors concluded that using either method to obtain ERB measurements is practical and produces similar results to CBW measures. Both ERB and CBW are useful and functional measures. *Relevance to current work:* This article compared ERB to CBW and related aspects, reinforcing the validity of the CBW. It also gave additional information of the CBW. *Level of evidence:* Level IIIc.

Okamoto, H., Stracke, H., Pantev, C. (2008). Neural interactions within and beyond the critical band elicited by two simultaneously presented narrow band noises: A magnetoencephalographic study. *Neuroscience, 151,* 913-920. doi: 10.1016/j.neuroscience.2007.11.038

Objective: The purpose of this study was to investigate neural interactions elicited by two simultaneously presented noises. *Method:* Participants included 16 healthy individuals (eight females, mean age 24.4) with normal hearing. Test stimuli (TS) were presented binaurally at 45 dB above each participant's individual sensation level, and 150 trials for each stimulus were presented in random order. Each stimulus had a duration of 300 ms, with a 12.5 ms rise and fall time, and consisted of either one or two narrow band noises (NBNs) obtained from digitally filtered white noise. The first stimulus, TS1, consisted of one NBN of 40 Hz bandwidth, centered at 1000 Hz. The rest of the TS consisted of two NBNs of 20 Hz bandwidth, with center frequencies set equally apart from 1000 Hz in octave scale and center frequency differences as follows: TS2 at 40 Hz, TS3 at 80 Hz, TS4 at 160 Hz, TS5 at 330 Hz, and TS6 at 670 Hz. Test stimuli 1-3 were within the critical band, TS4 was at the critical band, and TS5-6 were beyond the critical band. The researchers gathered measurements of auditory-evoked fields. The authors also performed behavior measurements of loudness to assess the perceived loudness of all test stimuli. Additional two-forced-choice behavioral tests were performed on participants and sixteen additional participants, matched for age and gender. Pairs of two test stimuli were presented at a loudness of 45 dB sensation level in the same room that all other tests were performed. Participants were asked to press one of two buttons to indicate whether the first or second stimulus was louder. *Results:* In analyzing normalized N1m source strength, the researchers found there was a significant main effect of TS type. There were significant differences between TS1 and all other stimuli conditions, as well as between TS2 and TS4, TS3 and TS4, TS4 and TS5, and TS4 and TS6. The N1m source strength gradually increased until the frequency difference between NBNs reached the critical band and then decreased as the frequency difference continued to increase. In analyzing N1m latency, the researchers also found a significant main effect of TS type. There were significant differences between TS1 and TS4, TS1 and TS5, TS1 and TS6, and TS2 and TS6, as well. The N1m latency results contrasted the N1m source strength results in that the N1m latency became systematically shorter as the frequency differences between the two NBNs increased. The loudness comparison tests indicated no significant differences in perceived loudness among all TS. *Conclusions:* These authors concluded that their results confirmed that source strength and latency of the auditory evoked fields elicited by two simultaneously presented NBNs depended on the center frequency difference between these NBNs. They stated that these findings offer new insight into the neural mechanisms involved in spectral tuning of neural activities elicited by complex sounds. They also concluded that the neural interactions observed seem to have a strong relation to the critical band. *Relevance to current work:* This study touched on the influence of the critical band on auditory evoked fields, which was a major focus of the current work. It also indicated the need for further experiments in this region of study. *Level of evidence:* IIIa.

Orrison, W. W. (1995). *Atlas of brain function*. New York, NY: Thieme Medical Publishers, Inc.

Objective: This purpose of this book was to give an introductory explanation of the locations and functions of structures in the brain. *Conclusions:* This book provided a glossary of many of the structures and regions in the brain, explaining the locations and functions involved in those structures and regions. It also gave examples of images of the brain at different views (sagittal, axial, and coronal) and at different levels of depth. These maps display many of the structures and regions discussed from different angles, depths, and views and in relation to surrounding structures and regions. *Relevance to current work:* This book provided information regarding the location and function of relevant structures in the brain, which was used in the current study. *Level of evidence:* Level IIIc.

Patterson, R. D. (1976). Auditory filter shapes derived with noise stimuli. *The Journal of the Acoustical Society of America, 59,* 640-654. doi: 10.1121/1.380914

Objective: The author aimed to explore the different techniques for determining auditory filter shape and to test the accuracy of prior hypotheses regarding filter derivation techniques. *Method:* Ten individuals participated as what the author called "observers". All participants had audiometrically normal hearing in the range below 4.0 kHz. Two broad noise bands were positioned symmetrically about a tone (f_0). The tone threshold, P_s, was then measured as a function of the distance from the tone to the edge of the noise bands Δf. The researcher then repeated the experiment at three tone frequencies: 0.5, 1.0, and 2.0 kHz. The independent variable in this experiment was the relative distance between the tone and noise edge and was represented by the term $\Delta f / f_0$. Each band of spectrum masking noise was produced by low-pass filtering a broad-band noise with two Khronhite filters, then multiplying the resultant low-passed noise with a sinusoid. Tone thresholds were determined by using a blocked, two-alternative, forced-choice procedure, with the masking noise on continuously during the experiment. The participant was presented with 14 blocks of 20 trials. All thresholds were gathered for each tone frequency, then the next tone was presented. *Results:* Patterson found that when the notch in the band-noise was narrow, the tone threshold showed little variation as a function of the observer. However, as the notch widened, a consistent and significant difference emerged. The most sensitive observer produced the filter with the most severe skirt. *Conclusions:* The auditory filter shapes derived using the notched noise masker revealed a filter whose skirts fell steadily from about 6 dB down at $\Delta f / f_0 = 0.1$ to around 35 dB down at $\Delta f / f_0 = 0.4$. Patterson also concluded that data range did not predict bandwidth well, and the ability of the average filters to predict the masking data of a specific observer or participant will decrease as the distance between the tone and the masker increases. *Relevance to current work:* Patterson explored the shape of the auditory filter in humans, which provided early yet important background information for the current study. *Level of evidence:* Level IIIa.

Picton, T. W. (2011). *Human auditory evoked potentials.* San Diego, CA: Plural Publishing, Inc.

Objective: This book explored various aspects of auditory evoked potentials and how they relate to processing sounds, hearing, speech understanding, and more topics relevant to human audiology. *Conclusions:* The author of this book presented fundamental information about auditory evoked potentials. Picton addressed the various response waves that are observed in auditory processing. Picton also explained the relevance these responses have to various functions and areas in the brain. Other topics of discussion included infant hearing assessment, auditory neuropathy, and cochlear implants. *Relevance to current work:* This book provided valuable information on the response components studied in the current study as well as the areas and functions related to these components. *Level of eviedence:* Level IIIc.

Scharf, B. (1961). Complex sounds and critical bands. *Psychological Bulletin, 58,* 205-217. doi: 10.1037/h0049235

Objective: This article reviewed the critical bandwidth (CBW) and four types of experiments in which critical bands have been measured, namely absolute threshold of complex sounds, masking of a band of noise by two tones, sensitivity to phase difference, and loudness. *Conclusions:* The author of this article reviewed several articles regarding the topics of focus, all as they relate to the CBW. In the category of thresholds of complex sounds, Scharf cited an article that measured the threshold of a complex as the frequency range and number of tones was varied. The experiment concluded that, even despite the presence of background noise, when the frequency range exceeded a particular width, which depended on the center frequency, the threshold for the multitone complex would begin to increase. These widths approximated those indicated by the critical-band curve. In the subject of two-tone masking, the author referenced an experiment where the researcher measured the threshold of a narrowband noise in the presence of two tones, one on either side. As the frequency difference between the two tones increased, the masked threshold of the noise did not change until the difference reached a certain frequency, which evidently corresponded approximately with established CBWs, where the threshold dropped sharply. When addressing sensitivity to phase, the author discussed an experiment that looked at the difference in sensitivity to amplitude modulation (AM) and frequency modulation (FM) in the human ear. The ear showed more sensitivity to AM modulation than FM at lower modulation rates, but as the rate of modulation gradually increased, the difference in sensitivity to AM and FM decreased until there was essentially no difference in sensitivity. This point also corresponded with the critical-band curve. The author then addressed loudness of complex sounds as a function of CBW, which Scharf stated had been the aspect most measured in related studies. Several experiments produced results generally indicating that the loudness of a complex sound is independent of bandwidth until the CBW is reached. The author went on to discuss the question of the presence of a masking band. Scharf cited several experiments on the matter and concluded that there most likely is a masking band, and it may correspond with the width of the critical band. Finally, Scharf addressed other correlates of the critical band, including the interesting observation that the critical band seems to correspond to a constant distance of about

1.3 millimeters along the basilar membrane. The author went as far as to state that all of these results suggest that the CBW may even be regarded as a fundamental unit of hearing. *Relevance to current work:* This article demonstrated not only the existence of the CBW in the human auditory system, but it's pervasive and important nature in the study of hearing. This information is foundational to the further research that was completed in the current study. *Level of evidence:* Level IIIc.

Seghier, M., Lazeyras, F., Momjian, S., Annoni, J., de Tribolet, N., & Khateb, A. (2001). Language representation in a patient with a dominant right hemisphere: fMRI evidence for an intrahemispheric reorganisation. *NeuroReport, 12*, 2785-2790. doi: 10.1097/00001756-200109170-00007

Objective: The goal of this study was to determine via functional magnetic resonance imaging (fMRI) paradigms if inter- or intrahemispheric language reorganization was present in a patient before and after surgery related to a right frontal opercular arteriovenous malformation (AVM). *Method:* This study involved six control participants and one patient. The control participants were healthy right-handed males with a mean age of 29 years. The patient was a 36-year-old ambidextrous woman. The controls were native French speakers, and the patient was fluent in French. The patient, prior to surgery, presented with headache and word-finding difficulties. Computed tomography, magnetic resonance imaging (MRI), and fMRI scans revealed a right fronto-opercular hemorrhage and a superficial right fronto-opercular AVM. Following surgical excision of the AVM, the patient demonstrated apraxia of speech and a severe non-fluent aphasia. Functional MRI scans were used during data collection to analyze activity during the paradigms. All participants underwent phonological (rhyming) and semantic (categorization) language tasks using concrete, imaginable, high frequency nouns. Data was processed using MEDX software via cross-correlation analysis after motion correction. The cross-correlation was exhibited as a Z-value, with a probability assigned to each Z-value, and each value was calculated pixelwise between a delayed boxcar function and the set of measurements. Researchers only considered clusters of > 4 pixels showing a statistically significant Z-score (at $p = 0.01$). *Results:* In the six healthy participants, brain imaging maps revealed activation in various areas, but virtually all responses were localized to the left hemisphere (with the exception of one participant who showed, primarily during the semantic task, additional right hemisphere activations). Results from the patient revealed activation in different areas, both prior to and following surgery. Pre-surgery, activations were observed primarily in the right hemisphere. Post-surgery, fewer areas of activation were observed, and activation was restricted to the right hemisphere exclusively. *Conclusions:* The authors observed the unexpected presence of language processing in the right hemisphere for a patient with a congenital right opercular malformation, concluding through fMRI paradigms and other tests that language control likely shifted from the classically language-dominant left hemisphere to the right hemisphere during early development. The authors also noted the absence of interhemispheric reorganization following the excision of the AVM and concluded that interhemispheric transfer of language may not be necessary for language development and recovery of patients following this type of malformation and procedure. *Relevance to current work:* This study used fMRI as an effective and non-invasive method to observe and assess brain activity in various language tasks. *Level of evidence:* IIIa.

Soeta, Y., & Nakagawa, S. (2006). Complex tone processing and critical band in the human auditory cortex. *Hearing Research, 222,* 125-132. doi: 10.1016/j.heares.2006.09.005

Objective: This experiment examined physiological correlates of the critical bandwidth (CBW) in the human auditory cortex. It was intended to better understand critical bands and related auditory evoked potentials (AEP) in the brain. *Method:* Ten right-handed, normal hearing individuals, ages 22-35 years, participated in this study. This experiment included two portions, including a two-tone portion and a three-tone portion. In the two-tone portion, the tone frequencies were geometrically centered at 1 kHz with frequency separations of 20, 50, 100, 200, 500, and 1000 Hz. For the three-tone complexes, a quasi-frequency-modulation stimulus was used. The three-tone bandwidths were selected as 8, 50, 100, 200, 500, and 1000 Hz. Stimuli were presented diotically to both ears at 55 dB sound pressure level, and all stimuli were presented for a 500 ms duration with 10 ms rise and fall times. Stimuli for both the two- and three-tone complexes were presented in a randomized order with a consistent inter-stimuli interval of 1.5 s. Auditory-evoked fields were recorded and analysis performed to provide estimates of the location and strength of auditory cortical activity. *Results:* The N1m component was observed about 100 ms after stimulus onset, and the magnitude of the N1m was significantly affected by frequency separation in the two-tone complexes and bandwidth in the three-tone complexes, especially when the separation or bandwidth was larger than 500 Hz. Clear N1m responses were recorded in the temporal region of both hemispheres. Furthermore, the effects of two-tone frequency separation and three-tone bandwidth on the equivalent current dipole (ECD) (N1m amplitude) moments were significant. When the two-tone frequency separation or three-tone bandwidth was less than the CBW, the ECD moments were approximately constant, but when the separation or bandwidth increased beyond the CBW, the ECD moments increased with increasing separation or bandwidth. The authors also found significantly greater ECD moments in the right hemisphere than in the left hemisphere for both two-tone and three-tone complexes. *Conclusions:* The authors found results directly supporting various prior experiments in the same area of study. They concluded that the human auditory cortex does exhibit critical band-like behavior, in that the N1m response was significantly affected by tonal separation or bandwidth. *Relevance to current work:* This experiment measured event related potentials in the human auditory cortex for two- and three-tone complexes, as related to the CBW, which directly relates to the procedures of the current work. Although slightly different measures were taken, the premise is similar and many of the same principles were used in the current study. *Level of evidence:* Level IIIa.

Soeta, Y., Nakagawa, S., & Matsuoka, K. (2005). Effects of the critical band on auditory-evoked magnetic fields. *NeuroReport, 16,* 1787-1790. doi: 10.1097/01.wnr.0000185961.88593.4f

Objective: The purpose of this experiment was to examine the auditory-evoked magnetic fields (AEFs) of the human auditory system in response to changes in the critical bandwidth (CBW). *Method:* Twelve right-handed individuals with normal hearing (ages 22-35) participated in this study. Auditory stimuli included pure tone and bandpass filtered noises with a center frequency of 1000 Hz. Stimulus duration was 0.5 s, with a 10 ms rise and fall time, and each stimulus was cut out of a 10-s-long bandpass filtered noise. The bandwidths were set at 40, 80, 160, 320, and 640 Hz. All stimuli were presented at 55 dB sound pressure level. The N1m wave was measured for each participant at each stimuli. *Results:* Clear N1m responses were observed in all participants from all stimuli types in both the left and right temporal regions. The main effect of the bandwidths on N1m peak latency was not significant, but the main effect of the hemispheres was significant. The N1m latency in the left hemispheres was significantly shorter than that of the right hemispheres. There were no significant interactions between bandwidth and hemisphere. The researchers also observed that the equivalent current dipole moments (or N1m magnitudes) decreased with increasing bandwidth when the bandwidth was less than the CBW and increased with increasing bandwidth when the bandwidth was greater than the CBW. *Conclusions:* The authors concluded that the N1m magnitude was significantly affected by CBW, but the latency and source location of N1m in the cortex did not significantly relate to bandwidth. Furthermore, the main effect of hemisphere on N1m latency was also significant. *Relevance to current work:* This experiment studied the response of the N1m latency to changes in bandwidth, particularly in response to the CBW. The current work sought to study similar aspects of auditory evoked potentials. *Level of evidence:* IIIa.

Sosa, M. C. R., Martinez, M. I. F., Gomez, J. L. O., & Jauregui-Renaud, K. (2009). Early auditory middle latency evoked potentials correlates with recovery from aphasia after stroke. *Clinical Neurophysiology, 120,* 136-139. doi: 10.1016/j.clinph.2008.10.011

Objective: This study was designed to examine the relationship between the latency of Pa and Nb peaks of the middle latency auditory responses and scores on the Boston Diagnostic Aphasia Examination (BDAE) in stroke patients. The authors were assessing if there is a correlation between middle latency responses and recovery following stroke. *Method:* Forty individuals participated in this study. Ten right handed patients (3 males and 7 females, ages 39-55) hospitalized because of stroke were assessed. Thirty controls that were age, sex, and health (excluding stroke) matched, also participated. Patients were tested at the time of hospital discharge and 2, 4, and 6 months following. Controls were tested at day 1, as well as 2, 4, and 6 months afterwards. Electrophysiological testing was administered to all participants at each testing period, and the BDAE was administered to the patients at each testing period as well. *Results:* All patients showed improved scores on the BDAE upon each trial, with the greatest increase at 2 months post-discharge. The control group showed no significant change in middle latency auditory responses over time. All patients showed a gradual decrease in Pa and Nb latencies, although high variability among patients was observed. The largest change in latency of Pa and Nb peaks between consecutive measures was between discharge and 2 months following. At the time of hospital discharge, the BDAE scores of the patients were related to the latency of the Nb peak (shorter Nb latencies related to higher exam scores), but not the Pa peak. Over time, however, covariance analysis showed a relationship between Nb latency, BDAE score, and time of evaluation. *Conclusions:* The authors stated that the results of this study suggest that successful regeneration from post-stroke aphasia seems to depend more on the interaction of available language-related brain regions than on recruiting new brain regions during the rehabilitation process. The results of the BDAE testing were in agreement with prior studies showing widespread improvement in stroke victims on this exam over the months following the incident. The authors also conclude that the results indicate that the latency of the auditory electrical response recorded at hospital discharge following stroke is related to the recovery from aphasia, as evaluated by the BDAE. *Relevance to current work:* This study examined auditory evoked potentials as related to other brain functions, similar to the procedure of the current work. This article also provided important background information on auditory evoked potentials. *Level of evidence:* IIIb.

Voets, N. L., Adcock, J. E., Flitney, D. E., Behrens, T. E. J., Hart, Y., Stacey, R., . . . Matthews, P. M. (2006). Distinct right frontal lobe activation in language processing following left hemisphere injury. *Brain, 129,* 754-766. doi:10.1093/brain/awh679

Objective: This study was intended to localize language activity in the right inferior frontal gyrus (RIFG) in patients with left temporal lobe epilepsy (LTLE) and healthy control participants. This was to help further explore functional reorganization of language, specifically the role of the RIFG in this process. The study also involved functional magnetic resonance imaging (fMRI) analysis of language activation in the RIFG of a patient prior to and following anatomical left hemispherectomy treating Rasmussen's encephalitis. *Method:* Twelve preoperative right-handed patients with LTLE (seven males, mean age 33.4 years, range 15-53 years) and twelve healthy, right-handed, neurologically typical controls participated in this study. The researchers used fMRI to observe participants during verbal fluency tasks, including phonemic and semantic tasks, to localize language activity in the RIFG. For the phonemic fluency task, participants viewed 10 alternating 30 second blocks of a flashing fixation cross (rest condition) and a letter of the alphabet (active condition), and they were instructed to think of words beginning with that letter throughout its presentation. During the semantic fluency task, a category name was presented for 30 seconds, during which participants were to think of members of that category, and a 30 second rest period followed. After all of these trials were completed, the same procedure was repeated with different stimuli, with the participants then naming the members of each category out loud. The researchers also analyzed regions of interest (ROIs), using fMRI, in order to further identify localization of language functions. Researchers also used anatomical localization to locate specific anatomical regions of RIFG activation. This helped to determine whether activations in the RIFG were in homologous locations to those in the left inferior frontal gyrus (LIFG). In the individual case study, the patient RC was a male diagnosed with Rasmussen's epilepsy at the age of six. RC further developed epilepsia partialis continua and a progressive right hemiparesis. At the age of twelve, he underwent fMRI analysis during phonemic and semantic fluency tasks to localize language functions in the brain. Two years later, he successfully underwent a left anatomical hemispherectomy. Two additional years later, at the age of 16, RC again completed phonemic and semantic fluency tasks during fMRI analysis. *Results:* The LTLE patients generated on average significantly fewer words than controls in both phonemic ($t = 4.835$, $p < 0.001$, mean words) and semantic fluency ($t = 7.387$, $p < 0.001$) tasks. In the phonemic fluency tasks, the controls showed significant levels of activation in more areas of the brain than in LTLE patients, as shown in fMRI results. Healthy controls showed increased activation, compared to LTLE patients, in the left thalamus and insular cortex, while LTLE patients showed increased activation in the right medial frontal gyrus and bilateral posterior cingulate gyri and precuneus. During the semantic fluency tasks, the control participants demonstrated activation in a similar network as that in the phonemic tasks, with significantly increased activation in the left inferior frontal, left hippocampal, left inferior occipital, bilateral thalamus, putamen, and anterior cingulate regions, as compared to LTLE patients. In the ROI analysis, no significant difference was found between the controls and the patients in the fMRI signal change for phonemic or semantic tasks. In the localization analysis, LTLE patients showed activation in a significantly more posterior region during phonemic tasks than control participants, but there was no significant difference in any other direction. With respect to the patient RC, the researchers found interesting results. Preoperatively, RC displayed bilaterally distributed language-related activation on fMRI results, with particular activation in bilateral inferior frontal and superior temporal regions, in both phonemic and semantic fluency tasks. Following the hemispherectomy, activation was limited almost exclusively to the RIFG. Additionally, mean word generation scores were similar pre- and postoperatively. *Conclusions:* The authors concluded that it is likely that verbal fluency after left hemisphere damage does not rely on typical right hemisphere regions, but rather recruits a more posterior RIFG region. They also stated that RIFG regions in language processing are not simple anatomical homologues of LIFG language regions in either left hemisphere damaged or healthy control populations. This lead to the conclusion that the RIFG plays a critical role in reorganizing language functions following left hemisphere damage, but the relationship between reorganized right hemisphere language functions and normal right hemisphere processes is yet to be completely determined. *Relevance to current work:* Functional MRI was used throughout this study to successfully localize language functions in the RIFG and other areas of the brain. This imaging methodology is beneficial in mapping areas of activation during various language tasks. This concept can be carried over into other language and auditory-related functions. *Level of evidence:* IIIb.

Warren, J. D., & Griffiths, T. D. (2003). Distinct mechanisms for processing spatial sequences and pitch sequences in the human auditory brain. *The Journal of Neuroscience, 23*, 5799-5804. Retrieved from http://www.jneurosci.org/

Objective: The purpose of this study was to investigate the human brain areas engaged in the analysis of pitch sequences and sequences of acoustic spatial locations. The authors sought to test the hypothesis that there are distinct cortical substrates responsible for the processing of pitch patterns and the location of sounds in space. *Method:* Participants included five males and seven females ages 23-38 years. Stimuli were presented at 70 dB SPL and included regular interval noises with variable pitch. The stimuli varied according to seven conditions: (1) iterated ripple noise (IRN) with fixed pitch and spatial location, (2) IRN with changing pitch and fixed spatial location, (3) IRN with fixed pitch and changing spatial location, (4) IRN with changing pitch and changing spatial location, (5) fixed amplitude random phase noise with fixed spatial location, (6) fixed amplitude random phase noise with changing spatial location, and (7) silence. Functional MRI was used, and blood oxygenated level-dependent images were acquired. This study assessed each participant's ability to detect changes in pitch pattern, changes in spatial pattern, or simultaneous changes in both pattern types. *Results:* The primary findings of this study regarded the areas of activation in the processing of pitch and spatial location. A bilateral anterior network of areas observed to be dedicated to processing pitch sequences included the regions of Hechel's gyrus, superior temporal gyrus, anterior planum temporale, and planum polare. A bilateral posterior network dedicated to processing spatial sequences included the posteromedial planum temporale. No significant differences were found between hemispheres. *Conclusions:* The authors concluded that there are distinct human auditory mechanisms simultaneously and specifically engaged in processing the different properties of sound sequences, with the mechanism for processing pitch pattern located anteriorly and the mechanism for processing spatial pattern located posteriorly. These results generally supported prior hypotheses on this subject, although further research is still needed. *Relevance to current work:* The results of this study identified specific areas involved in pitch perception, which is directly relevant to the current study. The current study used this and other relevant functional information to draw conclusions regarding the processing of complex sounds. *Level of evidence:* Level IIIb.

Zerlin, S. (1986). Electrophysiological evidence for the critical band in humans. *The Journal of the Acoustical Society of America, 79,* 1612-1616. doi: 10.1121/1.393297

Objective: This experiment measured the amplitude changes in wave V of the auditory brainstem response as a function of frequency in order to further explore the physiological correlates of the critical band in humans. *Method:* Seven young adult females with normal hearing participated in this study. Two-tone complexes were presented monaurally to participants through earphones. The two-tone complexes were centered around 2 and 4 kHz. Each tone was presented at 85 dB SPL and in random phase at 20 ms bursts with a 1.5 ms rise and fall, presented at a 10/s rate. Using electrodes on the head, the researcher recorded evoked potentials for each listener.

Results: For complexes centered around 4 kHz, three participants showed an abrupt increase in the amplitude of wave V when the tonal separation was between 800 and 1200 Hz, three additional participants showed an increase between 600 and 800 Hz, and one showed an increase between 800 and 1000 Hz. Repeated measures were performed for four participants with complexes centered around 2 kHz. All four listeners showed an increase in wave V amplitude at the frequency separation range of 200 to 400 Hz. *Conclusions:* The author concluded that these results are in agreement with other similar studies and current ideas on auditory evoked potentials. The results confirmed the presence of critical band-like behavior in the auditory system. More specifically, the author summed up the results by indicating that there is a critical band at about 700 Hz for a complex centered around 4 kHz and at about 300 Hz for a complex centered around 2 kHz. *Relevance to current work:* This study looked at the effect of frequency separation and the critical bandwidth on physiological correlates in the brain, specifically wave V. The current study aimed to do just that, although it focused more on other auditory evoked potentials. *Level of evidence:* Level IIIa.

Zhang, C., & Zeng, F. (1997). Loudness of dynamic stimuli in acoustic and electric hearing. *The Journal of the Acoustical Society of America, 102,* 2925-2934. doi: 10.1121/1.420347

Objective: In this article, the authors addressed the issue of traditional loudness models which use steady-state sounds, as opposed to more realistic dynamic stimuli, such as speech and other environmental sounds. They adapted and replicated a classic experiment by Fastl and Zwicker and completed two additional experiments to study the effects of the temporal envelope on the loudness sensation of dynamic stimuli. The whole discussion is motivated by questions regarding fitting prosthetic devices to hearing-impaired listeners. *Method:* All experiments included six normal hearing participants (three males, ages 25-35 years) and three cochlear implant listener participants (ages 35-65 years). In all experiments, participants were to judge which one of the two intervals presented contained the louder sound by pressing one of two buttons on a PC mouse. Experiment one was a replication of the Fastl and Zwicker experiment. In it, these authors presented to participants two tones geometrically centered on 1 kHz and with a frequency separation of 2, 5, 10, 20, 50, 100, 200, 500, 1000, and 2000 Hz. Each of the two tones was presented at fixed level of 60 dB sound pressure level. Next, they presented three-tone stimuli that were amplitude-modulated and quasi-frequency-modulated. Experiment two used sinusoidally amplitude-modulated (SAM) noise in a similar procedure. In the third experiment, the researchers obtained for each cochlear implant participant a threshold and an uncomfortable level of both zero-phase and Schroeder-phase (phase manipulations) stimuli at specified harmonic locations. This experiment was designed to separate the critical band analysis from the temporal envelope effects on loudness sensation of dynamic stimuli. *Results:* In experiment one, the authors found similar results to those of Fastl and Zwicker, with three notable deviations. First, Fastl and Zwicker found a 6 dB effect for frequency separations below 10 Hz, while this study found only a 3.5 dB effect. Next, Fastl and Zwicker found an intensity summation effect of exactly 3 dB for frequency separations between 10 and 100 Hz, while Zhang and Zeng found a 2 dB effect in this aspect. Third, for frequency separations above the 133 Hz critical bandwidth, Zhang and Zeng observed a steep loudness growth and a maximal 12 dB effect at the 1000 Hz separation, while Fastl and Zwicker observed a shallower loudness growth and a maximal 10 dB effect at the greatest frequency separation. In experiment two, the authors observed that the temporal effect on the loudness was nonmonotonic as a function of the overall level. They also observed that the louder sensation produced by the amplitude-modulated noise, when present, occurred well beyond the 10 Hz range observed in Fastl and Zwicker's original two- and three-tone experiments. In the third experiment, the authors found that the temporal effect of loudness in electric hearing is level dependent, such that the threshold is determined more by the root-mean-square level, and the uncomfortable loudness level is determined by the peak level of the temporal envelope. *Conclusions:* The authors of this article concluded that, according to their results, there is a need to reassess the design of the compression circuit in hearing aids and cochlear implants. It is important that the design takes into account dynamic noises, particularly speech sounds, in restoring normal loudness levels for hearing impaired listeners. They also concluded that there is a good deal of room for further research in this area, as particularly noted by discrepancies in the results of similar experiments. *Relevance to current work:* This article presented issues that could have potentially been present in the current study and which should be acknowledged and accounted for. These are important considerations in a valid and realistic hearing study. *Level of evidence:* Level IIIa.

Zhang, F., Anderson, J., Samy, R., & Houston, L. (2010). The adaptive pattern of the late auditory evoked potential elicited by repeated stimuli in cochlear implant users. *International Journal of Audiology, 49,* 277-285. doi: 10.3109/14992020903321759

Objective: The purpose of this experiment was to study the adaptive pattern of the late auditory evoked potential (LAEP) in cochlear implant (CI) users. *Method:* Nine right-handed individuals participated in this study (ages 31-77). All participants were postlingually deafened adult CI users. Stimuli were presented through a loudspeaker 50 cm from the ear of the participant. Stimuli were presented at each individual's most comfortable loudness level, according to a point numerical scale, and consisted of 1 kHz tone bursts of 60 ms with a 10 ms rise and fall time. The tones were presented in 30 trains consisting of 10 bursts per train. Electroencephalography (EEG) data were collected via electrodes placed on the scalp based on the 10/20 system. At least two recordings were obtained from each participant. *Results:* The LAEP results showed the largest response for the first tone burst and a decreased response for the rest of the tone bursts. This demonstrated an adaptive pattern. The researchers used an adaptation index to quantify adaptation amount across participants, and they compared good performers versus poor performers. This measure of "good" or "poor" performance was based on performance in measures for word recognition scores, hearing in noise in quiet conditions, and hearing in noise in noisy conditions. The adaptive pattern in CI participants with good performance appeared to be more prominent than that in CI participants with poor performance. The LAEP exhibited amplitude reduction during the presentation of tone-burst trains. The amount of LAEP adaptation in good CI performers is similar to that of normal hearers, but much less prominent in poor CI performers. *Conclusions:* The authors of this study concluded that CI users showed adaptive behaviors in LAEP responses, particularly so in users that demonstrated good speech perception performance. They pointed out that this study did not provide a sufficient amount of trials nor was it able to remove enough contamination due to external movements in order to make any definitive statements. However, the results offered valuable insight regarding the effects of deafness on the neural generators of the LAEP and on how to better restore normal adaptation in CI users to improve their speech perception. *Relevance to current work:* The authors used EEG to study auditory evoked potentials in CI users. This study demonstrated the importance and versatility of EEG in brain imaging studies, including the current study. *Level of evidence:* Level IIIb.

Zwicker, E., & Fastl, H. (1990). *Psychoacoustics: Facts and models.* Berlin, Germany: Springer-Verlag.

Objective: The purpose of chapter six of this book was to discuss the critical bandwidth (CBW) and related aspects. Specifically, the author examined the origins of the CBW concept, methods for obtaining CBW, the critical band rate scale, critical band level as it relates to excitation level, and excitation level versus critical band rate versus time pattern. *Conclusions:* The concept of critical bands in the auditory system was first presented by Fletcher and has grown and developed over the years. Critical bandwidths are important in auditory masking as well as in understanding the auditory system and the processing of sounds. The author presented and explained five methods for determining a CBW. These include using threshold measurements, masking in frequency gaps, the ability to detect phase changes, loudness measurement as a function of bandwidth for constant sound pressure level, and localization of impulses in binaural hearing. The author also described the critical band rate scale. The importance of the critical band in describing hearing sensations led to the creation of the critical band rate scale. The scale is based on the fact that our hearing system analyzes a broad spectrum of frequencies into portions that correspond with critical bands. The first critical band spans from 0 to 100 Hz, the second from 100 to 200 Hz, and so on up to 500 Hz, where the frequency range of each critical band increases. All scale figures were included in the chapter. The author went on to discuss excitation in the auditory system, as it relates to the CBW. *Relevance to current work:* This chapter provided important information on the CBW and excitation in the human auditory system, which was a central focus of the current work. The critical band rate scale was the foundation for the current experiment. *Level of evidence:* Level IIIc.

Zwicker, E., Flottorp, G., & Stevens, S. S. (1957). Critical band width in loudness summation. *The Journal of the Acoustical Society of America, 29,* 548-557. doi: 10.1121/1.1908963

Objective: The purpose of this document was to investigate how the critical bandwidth (CBW) affects loudness summation in various presentations. The authors explored how the loudness of a group of tones depends on the spacing of the tones, as well as how the loudness of a band of noise depends on the width of the band. They also discussed the relation of the CBW to other functions. *Method:* There were two experiments discussed in this article. In the first experiment, participants were presented with four tones centered around the frequencies 500, 1000, and 2000 Hz, in turn. The participants were to adjust the level of the complex to match the loudness of the single pure tone, the center frequency. The researchers determined the adjusted level by measuring the sound pressure level of one component in the complex. In the second experiment, the researchers designed sets of filters with different pass bands centered about a given frequency, which they used to produce bands of various widths centered about the frequencies 440, 1420, and 5200 Hz. The filtered bands were presented as white noise to groups of 12 participants, and each was instructed to adjust a comparison signal to match the loudness of each filtered band. *Results:* In the first experiment regarding loudness and tonal separation, the researchers found strong evidence to support the proposed hypothesis that within a critical band, loudness is independent of the spacing of the tones, but when the overall spacing of the tones exceeds a critical value, the loudness increases. In the second experiment regarding loudness and band width, the researchers stated that their results provided strong evidence for another proposed hypothesis, that is that within the CBW, the loudness of a band of noise of constant sound pressure level does not change with bandwidth, but will increase when the band width is increased beyond that critical value. *Conclusions:* The researchers found evidence supporting prior ideas and concepts regarding the effect of the CBW. The authors went on to briefly discuss the relation between critical bands and other relevant functions, including the difference limen for frequency, the function relating frequency to subjective pitch in mels, and the function relating frequency to the position of stimulation on the basilar membrane. They concluded that there likely is a relationship among these functions, but further research on the subject is necessary. *Relevance to current work:* This article related important early information regarding the CBW and its significance in audiology. It also discussed the relationship between critical bands and position of stimulation on the basilar membrane, which was a subject of direct interest in the current study. *Level of evidence:* Level IIIa.

Appendix B

Informed Consent to Act as a Human Research Subject

Neurophysiological Correlates of the Critical Bandwidth in the Human Auditory System

David L. McPherson, Ph.D.
Communication Science and Disorders
Brigham Young University
(801) 422-6458

Name of Participant: ___________________________________

Purpose of Study

The purpose of the proposed research project is identify to what extent there is neurophysiological response to auditory stimuli of specific frequency bandwidths. This will be accomplished by measuring brain activity during the presentation of auditory stimuli of various frequency bandwidths, with the simultaneous measuring of loudness judgments by the participant.

Procedures

You have been asked to participate in this study by Grace Bentley, B.S., a student conducting research under the direction of David L. McPherson, Ph.D. The study will be conducted in room 110 of the John Taylor Building on the campus of Brigham Young University. The testing will consist of one session, including orientation and testing, and will last for no more than 3 hours. You may ask for a break at any time during testing. Basic hearing tests will be administered during the first half-hour of the session.

Surface electrodes (metal discs about the size of a dime) will be used to record electrical activity of your brain. These discs will be applied to the surface of the skin with a liquid. They are easily removed with water. Blunt needles will be used as a part of this study to help apply the electrode liquid. They will *never* be used to puncture the skin.

Brain processing of hearing will be measured using an electrode cap, which simply measures the electrical activity of your brain and *does not* emit electricity; no electrical impulses will be applied to the brain. These measurements of the electrical activity are similar to what is known as an "EEG" or brain wave testing. These measurements are of normal, continuous electrical activity naturally found in the brain.

You will wear the electrode cap while being presented various tones. You will be asked to determine which tone is louder and indicate your response by pressing a button. During the time of your responses, the electrical activity of your brain will be recorded on a computer. The sound will be presented through insert earphones and will not exceed a comfortable listening level. You will be seated comfortably in a sound treated testing room. You will be asked to give responses during the hearing test and portions of the electrophysiological recording by pressing a series of buttons.

The procedures used to record the electrophysiological responses of the brain are standardized and have been used without incident in many previous investigations. The series of tones presented is experimental, but the recording procedure is not.

Risks/Discomforts

There are very few potential risks from this procedure, and these risks are minimal. The risks of this study include possible allergic reactions to the liquid used in applying the electrodes. Allergic reactions to the liquid are extremely rare. There is also a possibility for an allergic reaction to the electrodes. If any of these reactions occur, a rash would appear.

Treatment would include removing the electrodes and liquid and exposing the site to air, resulting in removal of the irritation. If there is an allergic reaction, testing procedures would be discontinued. Another unlikely risk is a small abrasion on the scalp when the blunt needle is used to place electrode gel. Treatment would also include removing the electrode and gel, exposing the site to air and testing procedures would be discontinued.

Benefits

You will receive a copy of your hearing assessment at no charge. You will be notified if any indications of hearing loss are found in this area. The information from the study may help further the understanding of neurological processing of sounds, which will be beneficial to professionals in the corresponding field.

Confidentiality

All information obtained from testing is confidential and is protected under the laws governing privacy. All identifying references will be removed and replaced by control numbers. Data collected in this study will be stored in a secured area accessible only to personnel associated with the study. Data will be reported without individual identifying information.

Compensation

You will be given $10 compensation at the completion of this portion of the study; you will receive this compensation whether or not you complete the study in its entirety.

Participation

Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without affecting your standing with the University.

Questions about the Research

If there are any further questions or concerns regarding this study, you may ask the investigator Grace Bentley, via phone at (530) 515-5842, or via email at graceannbentley@gmail.com. You may also contact David McPherson, Ph.D, Communication Science and Disorders, at (801) 422-6458; Taylor Building Room 129, Brigham Young University, Provo, Utah 84602; e-mail: david_mcpherson@byu.edu.

Questions about your Rights as a Research Participant

If you have questions regarding your rights as a research participant, you may contact the BYU IRB Administrator at (801) 422-1461; A-285 ASB, Brigham Young University, Provo, UT 84602; e-mail: irb@byu.edu.

Other Considerations

There are no charges incurred by you for participation in this study. There is no treatment or intervention involved in this study.

The procedures listed above have been explained to me by: ____________________________ in a satisfactory manner and any questions in relation to such risks have been answered.

I understand what is involved in participating in this research study. My questions have been answered and I have been offered a copy of this form for my records. I understand that I may withdraw from participating at any time. I agree to participate in this study.

Printed Name:_________________________

Signature:____________________________

Date:_______________________________