J Am Acad Audiol 18:107–116 (2007)

Effects of Stimulus Level on Cortical Auditory Event-Related Potentials Evoked by Speech

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Abstract

The effect of stimulus level on cortical auditory event-related potentials (ERPs) evoked by consonant-vowel (CV) contrasts, /ta/, /da/, and /sa/, was investigated. The lowest level at which CVs were discriminated with >95% accuracy was determined for 15 normally hearing adults. ERPs were obtained at 0, 20, and 40 dB SL above this level during active listening. ERP latencies decreased as level increased. P_{300} amplitude did not vary with CV level or type; however, obligatory ERPs decreased in amplitude as level increased. The effect of level on P_{300} latency is likely related to the cognitive processing speed needed to perform speech discrimination. Obligatory ERP amplitude results suggest that attention demands vary with level during discrimination of speech features.

Key Words: Adults, event-related potentials, P300, stimulus effects

Abbreviations: CV = consonant-vowel; ERP = cortical auditory event-related potential; VOT = voice-onset time

Sumario

Se investigó el efecto del nivel del estímulo en potenciales auditivos corticales relacionados con el evento (ERP) evocados por contrastes consonante-vocal (CV), /ta/, /da/ y /sa/. Se determinó en 15 adultos normoyentes el nivel menor al que se discriminaron los CV con > 95% de exactitud. Los ERP fueron obtenidos a 0, 20 y 40 dB SL por encima de este nivel durante audición activa. Las latencias de los ERP disminuyeron conforme los niveles aumentaron. La amplitud de la P_{300} no varió con el nivel o el tipo de los CV; sin embargo, las amplitudes siempre bajaron conforme subió el nivel. El efecto del nivel sobre las P_{300} parece estar relacionado con la velocidad de procesamiento cognitivo necesaria para realizar discriminación del lenguaje. Los resultados obligatorios de la amplitud de los ERP sugieren que las demandas de atención varían durante la discriminación de rasgos del lenguaje.

Palabras Clave: Adultos, potenciales relacionados con el evento, P300, efectos del estímulo

Abreviaturas: CV = consonante-vocal; ERP = potenciales auditivos corticales evocados relacionados con el evento; VOT = tiempo de inicio de la voz

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Portions of this work have been presented at the American Speech-Language-Hearing Association Convention, November 18–20, 2005, San Diego, CA, and the International Evoked Response Audiometry Study Group, June 12–16, 2005, Havana, Cuba.

Cortical auditory event-related potentials (ERPs) may be used to investigate the neural mechanisms involved in the detection, perception, and discrimination of sensory events. ERPs combined with psychophysical measures give an indication of the timing, strength, and location of cortical processes related to auditory perception (Oates et al, 2002). Studies are emerging that indicate the promise of these potentials as a measure of speech perception abilities (Tremblay et al, 2003) and the effects of sensorineural hearing loss (Oates et al, 2002) on speech perception and cognitive processes.

EVENT-RELATED POTENTIALS

Cognitive ERPs occur at latencies greater than 200 msec and may be used to document a listener's ability to discriminate between two auditory stimuli (Polich, 2004; Polich and Kok, 1995; Whiting et al, 1998). ERPs N_2 and P_{300} have been associated with "higher order" or "cognitive" processing of complex sensory events, such as discriminating speech sounds. The discrimination of speech sounds requires the integration of information processing subsystems, such as memory and attention. Cognitive ERPs are obtained using an "oddball" paradigm in which a "deviant" or "rare" stimulus is presented within a string of frequently occurring "standard" stimuli. N_2, the negative occurring potential following P_2, reflects the shift of attention towards a change in the stimulus string and the beginning of the stimulus classification process (Hillyard and Picton, 1987). P_{300}, a positive occurring potential with a latency of ≈300 msec, is an indicator of attention and memory processes occurring during the discrimination of two stimuli (Polich, 1987; Polich and Herbst, 2000). The latency and amplitude of N_2 and P_{300} are considered to be dependent upon these cognitive processes rather than on stimulus variables, insofar as the stimulus variables do not affect the task difficulty (Donchin et al, 1978). This is in contrast to "obligatory" ERPs, components occurring within the first 200 msec following stimulus presentation (i.e., P_1, N_1, and P_2), for which latency and amplitude are largely determined by stimulus parameters (Picton et al, 1974).

EVENT-RELATED POTENTIALS IN AUDIOLOGY

P_{300} has been used as a research tool for investigating central auditory processing disorders (Jirsa, 1992) and the auditory processing abilities of deaf adults who use cochlear implants to hear (Okusa et al, 1999; Beynon et al, 2005). Another application is the use of P_{300} as a measure of speech perception abilities. The effects of decreased audibility due to masking on speech perception and obligatory and cognitive ERPs have been evaluated. Martin et al (1997) investigated the effects of decreased audibility produced by high-pass noise masking on the P_{300} response to speech sounds /ba/ and /da/ presented at 65 and 80 dB SPL. Results from this study showed that as the masker cutoff was decreased below 2000 Hz, P_{300} amplitudes decreased and latencies increased in conjunction with decrements in discrimination performance. In a similar vein, Whiting et al (1998) investigated the effects of broadband noise masking on P_{300} evoked by speech. P_{300} amplitudes decreased and latencies increased when the noise masker level was greater than or equal to the speech stimulus level. These studies suggest that the P_{300} may provide insight about speech perception and discrimination skills, based on the presence, latency, or amplitude of the response. Recently, Martin and Stapells (2005) evaluated the effects of decreased audibility using low-pass noise masking on the P_{300} response to /ba/ and /da/. P_{300} amplitudes and latencies in this study were not significantly altered until the low-pass noise masker was raised to 2000 Hz. This study further established the strong correspondence between P_{300} and the ability to discriminate speech sounds, as was initially demonstrated in Martin et al (1997). Oates et al (2002) explored the effects of sensorineural hearing loss on P_{300} as subjects performed a speech discrimination task. Adult listeners with moderate hearing losses discriminated speech tokens /ba/ and /da/ at near threshold and suprathreshold levels. P_{300} latencies increased and P_{300} amplitudes decreased with severity of hearing loss. These outcomes showed that the P_{300} response properties could be related to the effects of hearing loss and stimulus level on speech discrimination abilities.

PRESENT STUDY

The purpose of the present study was to extend the application of ERPs, in combination with psychophysical measures, as an index of speech perception. In past research, the effects of stimulus level and audibility (and thus, discrimination ability) were intertwined. In the present study, level is varied but the listener's discrimination accuracy for speech contrasts /ta/, /sa/, and /da/ is held constant, and at a high level of >95%. Using this paradigm, the effects of level on obligatory and cognitive ERPs should be different. Obligatory ERPs should show stimulus-level related effects, with shorter latencies and larger amplitudes as level is increased. Because P_{300} indexes higher cognitive processes associated with discrimination, and not acoustic parameters of the stimulus, there should be no changes in P_{300} latency or amplitude as level is varied.

METHODS

Subjects

Fifteen adult participants were recruited for this study. Subjects were allowed to participate if they met the following criteria: (1) 18–38 years of age; (2) normal tympanograms using a 226 Hz probe tone; (3) normal (<20 dB HL) pure-tone thresholds for 500–4000 Hz for both ears; and (4) no recent history of using medications that would increase lethargy or affect cognitive function.

Stimuli

Consonant-vowel tokens /ta/, /da/, and /sa/ were used to evoke ERPs. These stimuli were chosen because they represented two different speech feature contrasts: manner of articulation /ta-sa/ (plosive vs. fricative) and voice-onset time /ta-da/ (voiceless vs. voiced). The Pratt Speech Analysis Program (version 4.3.01) was used to sample the tokens spoken by a female speaker into a Radio Shack dynamic microphone Model # 33-3018 interfaced with a Creative Labs Sound Blaster 16 Plug and Play (WDM) soundcard. Speech samples were digitized at a rate of 44 kHz. All tokens were truncated to a duration of 150 msec from the onset of the consonant. The digital wave files were played through the NeuroScan™ Stim program. The stimuli were presented to the subjects with an Etymotic ER3A insert earphone to the right ear only.

Calibration

Stimuli were calibrated using a Larson Davis System 824 sound pressure level (SPL) analyzer with a ½ in microphone Model #2540 and a 2CC coupler. The stimulus presentation levels ranged between 10 dB SPL and 80 dB SPL.

Procedure

All testing was performed in a double-walled sound-attenuating booth. The psychophysical and ERP data was generally collected during one test session with the psychophysical procedures completed first. If the subject became fatigued during ERP data collection, testing was immediately ceased and completed in a second session.

Speech Detection and Discrimination Threshold

The participants' perceptual detection thresholds were determined for each speech token presented at a rate of 0.4 Hz. Threshold was approached using a modified staircase procedure (down 10 dB for each correct detection, up 5 dB for each miss). The lowest level at which the participant could detect the token 50% of the time was taken as the speech detection threshold.

The "discrimination threshold" was then determined. Participants were asked to listen for the speech tokens and to press a response pad that had a button corresponding to each token. Each token was presented with equal probability, 33%, but pseudorandomly, at a rate of 0.4 Hz. There were 15 samples of each token in the 45-item test. The trials commenced at the detection threshold and were repeated at 5 dB steps of increasing intensity until the listener achieved a score of >95% for the 45-item test. The lowest level at which this score was achieved was designated the "discrimination threshold."

ERP Recording-Active Condition

Cortical auditory evoked potentials were obtained from a five-channel electrode montage at sites C_z, F_{pz}, P_z, C_3, C_4, with the nose as reference, and linked mastoids (M_1, M_2) as ground. An additional electrode was placed at the ipsilateral canthus of the right eye to monitor electro-oculographic (EOG) activity. Electrode impedances were held at a level of 5 kΩ or less. EEG filter settings were at 1–100 Hz (6 dB/octave slope), artifact rejection was set to ±75 uV, and the amplifier gain was 86 dB for all channels. ERPs were obtained using a Neuroscan "Scan" system with a Synamp amplifier. The recording epoch was 600 msec with a 100 msec pre-stimulus interval.

ERPs were obtained using an oddball stimulus paradigm, with the token /ta/ used as the standard at 70% probability and tokens /da/ and /sa/ each with 15% probability. The tokens were presented at a rate of .4 Hz. During this active listening condition, the subjects completed a three alternative forced-choice paradigm by pressing a response button corresponding to each token perceived. At least 60 samples each were obtained in response to each deviant token, /da/ and /sa/. ERPs were obtained at 0, 20, and 40 dB SL with regard to discrimination threshold, with stimulus level order randomized for each subject. These test levels were used to characterize the ERPs over a 40 dB dynamic range.

DATA ANALYSIS

ERP Analysis of Waveforms

Off-line processing of the EEG epochs included baseline correction, digital filtering (1 Hz high-pass, and 30 Hz low-pass filter, 12 dB/octave slope), artifact rejection (±75 μv for all channels), and averaging. After offline processing, responses to standard token /ta/, and deviant tokens /sa/ and /da/ were averaged separately. Latency and amplitude measures for obligatory components P_1, N_1, and P_2 were made using these averages. Difference waveforms for each condition were created by subtracting the averaged responses for the standard /ta/ from the averaged responses to deviant /sa/ and /da/. P_{300} latencies and amplitudes were measured from these difference waveforms.

The decision regarding response presence or absence required the agreement of two judges, that is, the coauthors. For a response to be considered present, the judges had to agree that an individual ERP peak (e.g., P_1, N_1, P_2, N_2, and P_{300}) was larger in amplitude than the level of the pre-stimulus baseline. Also, the peak had to fall within latency boundaries established for each component: P_1 had to occur between 50–150 msec, N_1 between 80–200 msec, P_2 at 150–300 msec, N_2 between 200–400 msec, and P_{300} between 300–500 msec. Latency and amplitude measures were obtained from each individual subject's responses. The judgments were made without knowledge of the consonant-vowel (CV) token type or stimulus level. Latency measures were taken at the highest point for a positive going component and at the most negative point for a negative component. Peak to trough amplitude measurements were then determined for each component, that is, P_1-N_1, N_1-P_2, and N_2-P_{300}. In instances of double peaks, latency was measured at the midpoint of the waveform.

The effects of stimulus level and type on ERP latency and amplitude were determined using repeated measures analysis of variance (ANOVA). Main effects and interactions were considered significant with a criterion of $p < 0.05$. Post hoc analyses were completed using Fisher's protected least significant difference (PLSD) tests.

RESULTS

Detection and Discrimination Thresholds

Detection and discrimination thresholds for the contrasts /ta/, /sa/, and /da/ were measured for each subject. The average detection threshold for each contrast was 10 dB SPL (SD = 1.38 dB) and the average discrimination threshold was 40 dB SPL (SD = 1.90 dB).

P_{300} Latency and Amplitude

Preliminary analyses showed that there were no statistically significant differences in ERP latencies or amplitudes when those obtained from the C_z montage were compared to those recorded from the P_z montage. Data from the C_z-nose montage will be reported. P_{300} latencies decreased systematically as level increased for each of the deviant contrasts /sa/ and /da/ (Figure 1). Analysis of variance (ANOVA) indicated a significant main effect of level ($F_{2,93} = 17.69$; $p < .0001$) on P_{300} peak latency. P_{300} latency for the /sa/

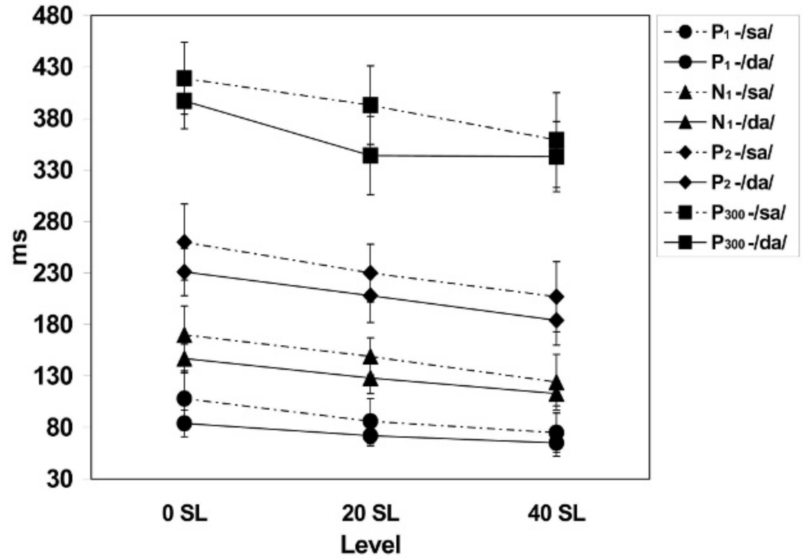

Figure 1. Mean latencies for P_1 (●), N_1 (▲), P_2 (◆), and P_{300} (■) are plotted as a function of level for the deviant contrasts /sa/ (dashed lines) and /da/ (solid lines). The error bars indicate standard deviations. Latencies decreased as level increased.

decreased from 420 msec at 0 dB SL to 355 msec at 40 dB SL. P_{300} latency for /da/ decreased from 400 msec at 0 dB SL to 345 msec at 40 dB SL. Post hoc analyses revealed significant latency differences between 0 and 20 dB SL (p = .0013), and 0 and 40 dB SL (p = .0001) for both /da/ and /sa/. Waveforms shown in Figure 2 illustrate these latency effects for the deviant contrast /sa/. There was a significant difference ($F_{1,92}$ =13.25; p = .0004) in latency as a function of CV type, with P_{300} latencies in response to /da/ shorter than those for /sa/, but with no interaction of level and CV type.

P_{300} amplitude was measured from the N_2 trough to P_{300} peak. The effects of level on token type on P_{300} amplitude were not significant. The mean amplitude of P_{300} was 5.67 µv (SD = 4.71) measured across level and CV type.

Obligatory Component Latency and Amplitude

The latencies and amplitudes of ERP obligatory components P_1, N_1, and P_2 were also measured as a function of level. As

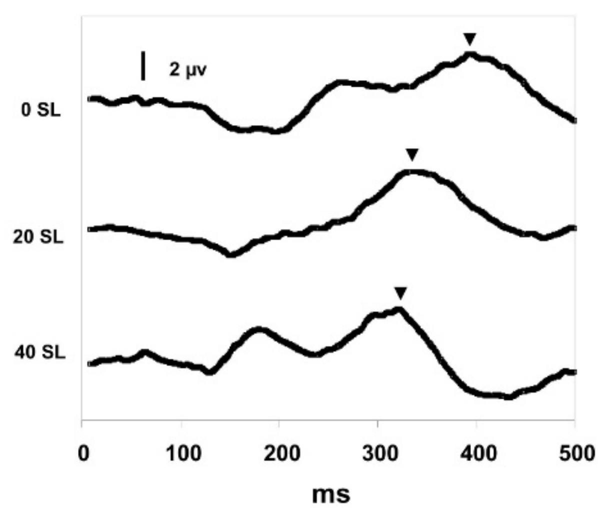

Figure 2. P_{300} waveforms as a function of level for the deviant contrast /sa/. The difference waveforms (response to /sa/ minus response to /ta/) for a representative subject are shown. The P_{300} is marked by the arrow symbol for each waveform.

expected, latency decreased with increasing level for each component (Figure 1). P_1 decreased from 100 to 70 msec, N_1 from 170 to 110 msec, and P_2 from 250 to 200 msec. ANOVA results indicated that the effect of level on latency was significant ($p < .0001$) for each of the components, P_1, N_1, and P_2. Latency differences as a function of CV token type, /da/ versus /sa/, were significant for N_1 ($p < .0001$) and P_2 ($p < .0001$) but not significant for component P_1. Also, P_1 latencies for /da/ were shorter than those for /sa/.

Peak-to-trough amplitude measurements were also made for P_1-N_1 and P_2-N_2. A surprising effect was found for the amplitudes of these obligatory components as a function of level. Amplitude *decreased* ($F_{2,92} = 3.96$, p = .022) with increasing level (Figure 3). Post hoc analyses revealed that the decrease in amplitude was significant ($p < .001$) between the 0 and 20 dB SL and 0 and 40 dB SL levels, but not between 20 and 40 dB SL. There were also amplitude differences owing to deviant CV type, /da/ versus /sa/, with responses to /da/ of larger amplitude than those for /sa/ ($F_{1,92} = 4.36$, p =. 039), but there was no interaction of CV type with stimulus level.

DISCUSSION

The purpose of the study was to evaluate the effect of stimulus level on obligatory and cognitive ERPs. Few studies have evaluated the effects of level on ERPs (Papanicolaou et al, 1985) or have used natural speech contrasts (Tremblay et al, 2003) to evoke ERPs. The approach in the present study was to evaluate the effect of level when discrimination ability was held constant at >95%. Two specific predictions were made, that (1) the P_{300} latency and amplitude would not be affected by changes in stimulus level, when discrimination performance was >95%; and (2) the P_1-N_1, N_1-P_2 latency would increase and amplitude would decrease as stimulus level was decreased. Prediction 1 was not supported by the results. Specifically, P_{300} latency decreased systematically as level was increased, although there was no effect of level on P_{300} amplitude. Prediction 2 was partially supported by the results. The obligatory components, P_1, N_1, and P_2, showed similar latency effects as the P_{300} when level was increased, but unlike P_{300}, their amplitudes *decreased* inversely with level.

P_{300}

P_{300} latency is typically interpreted as a measure of stimulus classification speed (Kutas et al, 1977; Donchin et al, 1978; Polich and Herbst, 2000). The present results suggest that as stimulus level is increased, processing time or the brain's ability to interpret the difference between the stimuli is decreased. A common understanding of P_{300} is that it reflects higher-order processing of sensory stimuli needed for the discrimination of sounds (Donchin et al,

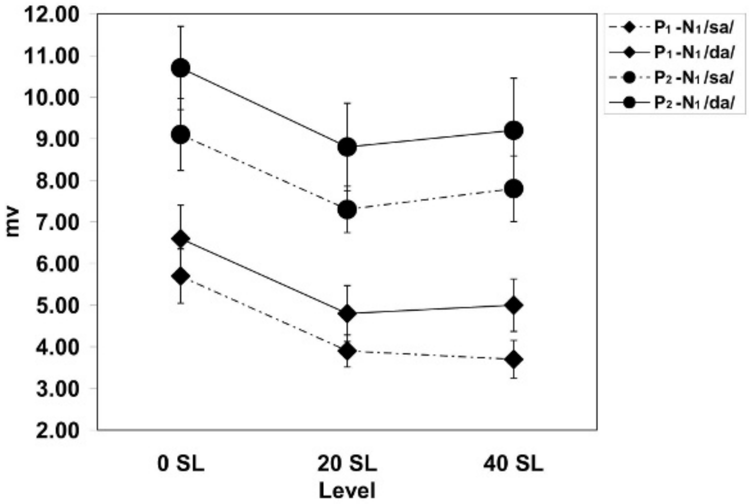

Figure 3. Mean amplitudes for P_1-N_1(◆) and P_2-N_1(●) for deviants /sa/ (dashed lines) and /da/ (solid lines) are plotted as a function of level. Error bars indicate standard error. Amplitudes decreased as level was increased.

1978). P_{300} is thought to reflect recognition and memory-updating processes while serving as a link between stimulus characteristics and attention (Patel and Azzam, 2005). Changes in stimulus characteristics will affect task difficulty (in this case, speech sound discrimination), thus influencing task performance that leads to these changes in ERP latencies (Johnson and Donchin, 1978; Polich, 1989). According to these constructs, the current latency results suggest that even though discrimination performance was >95% for each level tested (by design), it might have been easier to achieve this performance at the higher levels, leading to shorter latencies. Without an independent assessment of task difficulty, this interpretation cannot be ruled out.

Other studies investigating the effects of manipulating stimulus level on the P_{300} response have reported similar findings. Papanicolaou et al (1985) found that at high levels, P_{300} latency decreased by 20 msec when the level was varied from 15–75 dB HL. Polich (1989) demonstrated that P_{300} latencies decreased as stimulus levels were increased over a range from 30 dB SPL to 70 dB SPL. Garinis and Dille (2003) studied the effects of unequal and equal toneburst levels on P_{300}. P_{300} had shorter latencies and larger amplitudes when the target stimulus was higher in level than the standard. Most have interpreted this effect of stimulus level on latency as a reflection of the cortical processes needed to evaluate the stimuli necessary to perform a discrimination (Polich, 1989). Level may also affect the encoding resources related to the ease or difficulty of the task (Donchin et al, 1986).

Several cortical processes are activated while making a discrimination between CVs. Studies employing intracranial recording (Smith et al, 1990) have revealed the neural generators activated during the oddball discrimination task, such as the one used in the present study. During the initial perception of the standard stimulus, the cortical activation is most prominent in the paralimbic (cingulate, posteromedial, and temporal-frontal gyrus) and attentional (inferior parietal and dorsolateral prefrontal) cortices. Eventually, the standard and target stimuli are stored into working memory. When a different or target stimulus is perceived, discrimination occurs and the second stimulus is compared to the memory trace of the first stimulus (Romo et al, 2002). During this portion of the task, increased activity occurs in the hippocampal and parahippocampal regions (Kikuchi et al, 1997). Results from this stimulus comparison are subsequently reflected in the latency or amplitude of the P_{300}. The results of the present study, interpreted using this model, suggest that it took longer to process the stimuli, update auditory memory, and complete the discrimination task at lower stimulus levels than at higher levels, even when discrimination performance was >95% for all levels.

Yet, an alternative explanation exists, specifically, that stimulus level affects P_{300} in the same way as it affects obligatory components. As stimulus level is increased, more neurons are activated per unit of time, neural synchrony improves, and latencies decrease. There were modest correlations between P_{300} latency and the obligatory components, with the highest r^2, 0.43, for P_2 and P_{300}. In contrast, the highest r^2 was 0.61 for N_1 and P_2. The amount of latency change with level was slightly greater for P_{300}, at 1.38 msec/dB, compared to 0.62 msec/dB for P_1 and 1.1 msec/dB for N_1 and P_2. Covington and Polich (1996) have also shown that stimulus level can affect P_{300} latencies in a similar manner as for obligatory potentials. Again, without an independent measure of task difficulty, one that goes beyond the control of discrimination performance as was used in the present study, it is not possible to rule out an “exogenous” (i.e., stimulus-mediated) effect on this “endogenous” or cognitive ERP.

P_{300} latency was also affected by CV token type. While P_{300} latencies decreased systematically as level increased for both of these contrasts, P_{300} latency for the deviant /sa/ was longer compared to /da/. This difference may be due to the cognitive demands necessary to distinguish the dissimilar acoustic qualities of the initial consonants during discrimination. The deviant tokens differed from the standard in terms of voicing (/ta/ vs. /da/) and manner (/ta/ vs. /sa/). Voice-onset time (VOT) is the time interval between consonant onset and the onset of low-frequency periodicity generated by rhythmic vocal cord vibration (Steinschneider et al, 1999). The consonant /s/, an unvoiced fricative, has a longer onset to offset duration than the VOT of the voiced plosive /d/. Measurement of the consonant duration from a spectrographic display in this study indicated that the /s/ was approximately 68 msec. Tremblay et al (2003) measured the VOT patterns of the contrasts /bi/, /pi/, /shi/, and /si/ and found that the contrast /si/ resulted in the longest VOT compared to the other speech sounds. This acoustic distinction was reflected in the ERP latency data, for which longer latencies were obtained for the contrast /si/ compared to latencies in response to the other tokens (Tremblay et al, 2003). These investigators speculated that the length of consonant frication is significantly longer for the /s/ sound, thus indicating more processing time may be necessary for categorization during an auditory discrimination task. The data from this study support that interpretation.

The range of spectral differences between contrasts may also have played a role during discrimination. The listening task required the subject to discriminate between the contrasts /ta/ versus /da/, /da/ versus /sa/, and /ta/ versus /sa/. The spectral energy for the initial consonant differed for each token. The noise burst for /d/ has most energy at 350 Hz, compared to the noise burst for consonant /t/, which is around 2500 Hz, and the frication for /s/ is higher still, at around 4500 Hz. In the discrimination of /ta/ versus /da/ and /da/ versus /sa/ there is a larger frequency difference than /ta/ versus /sa/. It may be that it took longer to discriminate sounds closer in frequency, resulting in a more difficult task, than those for which the initial consonant contrasts represented a greater frequency difference. Similar results were reported by Vesco et al (1993), who found reduced latencies for tonal stimuli differing farther apart in frequency than stimuli closer in frequency.

P_{300} amplitude did not change with level or CV token type. P_{300} amplitude is thought to be related to the amount of attentional resources given to the task (Picton, 1992; Alford et al, 1997), the expectation of the stimulus (Hruby and Marsalek, 2003), and as an index of brain activity during working memory (Polich and Herbst, 2000). In our listening task, although stimulus levels increased, discrimination performance was at >95% for all levels. Because the sounds were audible enough for an individual to discriminate accurately, attention resources do not appear to change with level. In previous work (Martin et al, 1997; Oates et al, 2002), P_{300} amplitude changed with stimulus or masking level as audibility and discriminability also varied. The present results, along with the previous work, suggest that P_{300} amplitude can be used to index discrimination abilities. The results also support the hypothesis that stimulus level, per se, should *not* have an effect on the P_{300}.

Obligatory ERPs

Results from this study confirmed the well-known effect of level on the obligatory potentials P_1, N_1, and P_2: as level increased, latency decreased. The latencies of these components are determined by the acoustic characteristics of the stimulus (Näätänen and Picton, 1987; Cone-Wesson and Wunderlich, 2003). Earlier work by Picton et al (1974) investigated the effects of stimulus parameters, including level, on these obligatory ERPs. When clicks are used to evoke these components, P_1, N_1, and P_2 latencies decrease systematically when stimuli level is increased from 0 to 60 dB SL, and then asymptote. We found that latency also decreased steadily when intensities were increased from 0 dB SL to 40 dB SL with regard to discrimination threshold, that is, from 30 to 70 dB SPL. Picton et al (1974) indicated that P_2 latency decreased systematically from 280 msec to 220 msec (60 msec change) when evoked by clicks at 0–40 dB SL. In our results, P_2 latency decreased from 260 msec to 196 msec when levels increased from 0 to 40 dB SL, similarly showing a 64 msec change in latency, for a 40 dB level change. Although the latencies reported for the present study are prolonged in comparison to those of Picton et al (1974), this is due to the stimulus differences (click vs. speech sound).

A surprising effect of level on the amplitude of the obligatory potentials was apparent. The amplitudes of these components *decreased* as stimulus level was increased. Because the obligatory component response parameters are determined by acoustic parameters, an increase in amplitude would be expected. Input-output functions determined in response to clicks or tones show that P_1-N_1 and N_1-P_2 amplitudes increase monotonically with level over the range of 0–40 dB SL and then plateau at high intensities (i.e., >50 dB SL) (Madell and Goldstein, 1972). There are, however, some effects of attention on N_1 and P_2 (Näätänen and Picton, 1987), in that attention increases the amplitude of these components. The present results suggest that greater attention may have been engaged by the lower level stimuli, that is, that listeners have to pay close attention to achieve >95% discrimination scores at 0 dB SL (re: detection threshold). As level increased, less attention may have been needed to maintain discrimination performance. Thus, P_1-N_1 and N_1-P_2 amplitudes would decrease as level increased. Although attention is also needed to make the discriminations that evoke the P_{300}, apparently, these modulate the obligatory and cognitive ERPs in different ways. Perhaps there is a different attention "threshold" that needs to be reached before the P_{300} amplitudes are affected, and this may be higher than for obligatory components. Connections between frontal lobe and primary cortex would be involved in the effects of attention on obligatory responses, whereas the hippocampus and thalamus are also activated for the cognitive task that evokes the P_{300}.

Latency differences as a function of stimulus type were found for N_1 and P_2 components. As discussed previously, the VOT for /sa/ is longer than that for /da/. Because obligatory ERP component latencies are sensitive to acoustic parameters of a stimulus, latency differences as a function of initial consonant duration are expected. The obligatory ERP response latencies appear to follow a similar trend as noted in Tremblay et al (2003).Consonant duration differences for the deviant tokens /da/ and /sa/ used in the present study are the likely source of ERP latency effects.

CONCLUSION

This study used an experimental paradigm in which discrimination performance was held constant and the effect of level on obligatory and cognitive ERPs was determined. The results of the present study revealed a systematic effect of level on P_{300} latency, likely related to the cognitive demands of performing a speech discrimination task at low versus moderate stimulus levels. The effect of level on obligatory ERPs suggested a relationship between the attentional resources needed to discriminate speech at low levels and their amplitude. Furthermore, latency differences exist for both P_{300} and obligatory ERPs that appear to be related to the acoustic parameters of speech, including the spectral content and duration of the initial consonant. It is a long-term goal to map out the stimulus, subject, and pathological variables that would allow use of ERPs as an objective measure of speech perception.

Acknowledgments. The authors gratefully acknowledge the comments and critique provided by Dr. Jerger and two anonymous reviewers on a previous version of this manuscript.

REFERENCES

Alford BR, Jerger J, Jenkins HA. (1997) Electrophysiologic evaluation in otolaryngology. *Adv Otorhinolaryngol* 53:1–20.

Beynon AJ, Snik AF, Stegeman DF, Van Den Broek P. (2005) Discrimination of speech sound contrasts determined with behavioral tests and event-related potentials in cochlear implant recipients. *J Am Acad Audiol* 16:42–53.

Cone-Wesson BK, Wunderlich J. (2003) Auditory evoked potentials from the cortex: audiology applications. *Ear Hear* 11(5):372–377.

Covington JW, Polich J. (1996) P300, stimulus intensity, and modality. *Electroencephalogr Clin Neurophysiol* 100:579–604.

Donchin E, Karis D, Bashore TR, Coles MGH. (1986) Cognitive psychophysiology and human information processing. In: Coles MGH, Donchin E, Porges SW, eds. *Psychophysiology: Systems, Processes, and Applications.* New York: Guillford Press, 244–267.

Donchin E, Ritter W, McCallum C. (1978) Cognitive psychophysiology: the endogenous components of the ERP. In: Callaway E, Tueting P, Koslow SH, eds. *Event-Related Potentials in Man*. New York: Academic Press, 348–410.

Garinis AC, Dille M. (2003) Stimulus intensity effects on the cognitive P300 response. MA thesis, University of Arizona.

Hillyard SA, Picton TW. (1987) Electrophysiology of cognition. In: The nervous system. Sec. 1 of *Higher Functions of the Brain*, pt. 2. Vol. 5 of *Handbook of Physiology: Higher Functions of the Nervous System*, ed. Plum F. Bethesda: American Physiological Society, 519–584.

Hruby T, Marsalek P. (2003) Event-related potentials: the P3 wave. *Acta Neurobiol Exp* 63(1):55–63.

Jirsa R. (1992) The clinical utility of the P3 AERP in children with auditory processing disorders. *J Speech Hear Res* 3:903–912.

Johnson Jr R, Donchin E. (1978) On how P300 amplitude varies with the utility of the eliciting stimuli. *Electroencephalogr Clin Neurophysiol* 44:424–437.

Kikuchi Y, Endo H, Yoshizawa S, Kait M, Nishimura C, Tanaka M, Kumagai T, Takeda T. (1997) Human cortico-hippocampal activity related to auditory discrimination revealed by neuromagnetic field. *Neuroreport* 8:1657–1661.

Kutas M, McCarthy G, Donchin E. (1977) Augmenting mental chronometry: the P300 as a measure of stimulus evaluation time. *Science* 197:792–795.

Madell JR, Goldstein R. (1972) The relation between loudness and the amplitude of the *J Speech Hear Res* 15(1):134–141.

Martin BA, Sigal A, Kurtzberg D, Stapells DR. (1997) The effects of decreased audibility produced by high-pass noise masking on cortical event-related potentials to speech sounds /ba/ and /da/. *J Acoust Soc Am* 101(3):1585–1599.

Martin B, Stapells D. (2005) Effects of low-pass noise masking on auditory-event related potentials to speech. *Ear Hear* 26(2):195–213.

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

Oates PA, Kurtzberg D, Stapells DR. (2002) Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hear* 23(5):399–415.

Okusa M, Shiraishi T, Kubo T, Nageishi Y. (1999) Effects of discrimination difficulty on cognitive event-related brain potentials in patients with cochlear implants. *Otolaryngol Head Neck Surg* 121(5):610–615.

Papanicolaou AC, Loring DW, Raz N, Eisenberg HM. (1985) Relationship between stimulus intensity and the P300. *Psychophysiology* 22:326–329.

Patel SH, Azzam PN. (2005) Characteristics of N200 and P300: selected studies of the event-related potential. *Int J Med Sci* 2:147–154.

Picton TW. (1992) The P300 wave of human event-related potential. *J Clin Neurophysiol* 9(4):456–479.

Picton TW, Hillyard SA, Krausz HI, Galambos R. (1974) Human auditory evoked potentials: I. Evaluation of components. *Electroencephalogr Clin Neurophysiol* 36(2):179–190.

Polich J. (1987) Comparison of P300 from a passive tone sequence paradigm and an active discrimination task. *Psychophysiol* 24(1):41–46.

Polich J. (1989) Frequency, intensity and duration as determinants of P300 from auditory stimuli. *J Clin Neurophysiol* 6:277–306.

Polich J. (2004) Clinical application of the P300 event-related brain potential. *Phys Med Rehabil Clin N Am* 15(1):133–161.

Polich J, Herbst KL. (2000) P300 as a clinical assay: rationale, evaluation, and findings. *Int J Psychophysiol* 38:3–19.

Polich J, Kok A. (1995) Cognitive and biological determinants of P300: an integrative review. *Biol Psychol* 41(2):103–146.

Romo RA, Hernandez A, Zainos L, Lemus, Brody CD. (2002) Neuronal correlates of decision-making in secondary somatosensory cortex. *Nat Neurosci* 5:1217–1225.

Smith ME, Halgren E, Sokolik M, Baudena P, Musolino A, Liegeois-Chauvel C, Chauvel P. (1990) The intracranial topography of the P3 event-related potential elicited during auditory oddball. *Electroencephalogr Clin Neurophysiol* 76(3):235–248.

Steinschneider M, Volkov IO, Noh MD, Garell PC, Howard MA. (1999) Temporal encoding of the voice onset time phonetic parameter by field potentials recorded directly from human auditory cortex. *J Neurophysiol* 82:2346–2357.

Tremblay KL, Friesen L, Martin BA, Wright R. (2003) Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear Hear* 24(3):225–232.

Vesco K, Bone R, Ryan J, Polich J. (1993) P300 in young and elderly subjects: auditory frequency and intensity effects. *Electroencephalogr Clin Neurophysiol* 88:302–308.

Whiting KA, Martin BA, Stapells DR. (1998) The effects of broadband noise masking on cortical event-related potentials to speech sounds /ba/ and /da/. *Ear Hear* 19(3):218–231.