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Discrimination of Speech Sound Contrasts Determined with Behavioral Tests and Event-Related Potentials in Cochlear Implant Recipients

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Abstract

Cortical potentials evoked with speech stimuli were investigated in ten experienced cochlear implant (CI, type Nucleus 24M) users using three different speech-coding strategies and two different speech contrasts, one vowel (/i/-/a/) and one consonant (/ba/-/da/) contrast. On average, results showed that, compared to subjects with normal hearing, P300 amplitudes were smaller; however, most latencies were within the normal range. Next, individual P300 measures in response to the two speech contrasts were compared to behavioral discrimination scores. Significant within-subject differences in P300 amplitudes and latencies were found for the three speech coding strategies. These differences were in agreement with the behavioral, strategy-dependent discrimination of the speech contrasts.

Key Words: Cochlear implantation, cortical responses, discrimination, electrophysiological measurements, event-related potentials, objective measurements, P300, speech coding strategies

Sumario

Se investigaron los potenciales corticales evocados con estímulos de lenguaje en diez usuarios experimentados de implante coclear (CI tipo Nucleus 24M) utilizando tres diferentes estrategias de codificación del lenguaje, y dos diferentes contrastes de lenguaje, el contraste de una vocal (/i/-/a/) y una consonante (/ba/-/da/). En promedio, los resultados mostraron que, comparados con sujetos normo-oyentes, las amplitudes de las ondas P300 fueron menores; sin embargo, la mayor parte de las latencias estuvieron dentro de límites normales. Luego, se compararon las medidas individuales de la P300, en respuesta a los dos contrastes, con los puntajes de discriminación. Se encontraron diferencias significativas intra-sujeto en las amplitudes y latencias de la P300, en las tres estrategias de codificación del lenguaje. Estas diferencias correlacionaron con las discriminaciones conductuales, estrategia-dependientes, de los contrastes de lenguaje.

Palabras Clave: Implantación coclear, respuesta cortical, discriminación, medidas electrofisiológicas, potenciales relacionados con el evento, medidas objetivas, P300, estrategias de codificación del lenguaje

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Auditory processing of electrical stimuli in cochlear implant (CI) users can be studied by electrophysiological measurements. Several groups have studied evoked potentials in CI users at various neural levels, ranging from the peripheral part of the auditory system (using neural response telemetry, e.g., Abbas et al, 1999, or electrically evoked brainstem responses, e.g., Kileny et al, 1994), the subcortical regions (middle latency responses, e.g., Kileny, 1991; Groenen et al, 1997) up to the auditory cortex (event-related potentials, Kileny, 1991; Micco et al, 1995; Groenen et al, 2001). Several of these studies focused on the relation between electrophysiological data and behavioral performance (Kileny, 1991; Micco et al, 1995; Makhdoum et al, 1998). The underlying idea is that auditory processing can be studied in more detail with evoked potential data, which might help to understand better individual speech perception performance.

Nowadays, it is possible to stimulate the cochlea in various ways with CI systems. The Nucleus cochlear implant system has implemented three different speech-coding strategies. For the greater part, these speech-coding strategies differ with respect to the stimulation rate per electrode and the total number of active electrode sites. It has been shown that on an individual level, the different strategies might lead to significant variation in speech perception performance (Parkinson et al, 1998; Kiefer et al, 2001; Beynon et al, 2003). It is assumed that this is due to differences in the processing of speech sounds per coding strategy.

To study auditory responses on a cortical level, the so-called mismatch negativity (MMN) responses (e.g., Kraus et al, 1993; Groenen et al, 1996) or P300 responses (Micco et al, 1995; Kileny et al, 1997) have been applied. MMN measurements have the advantage that the MMN can be obtained in a passive listening condition (e.g., Näätänen, 1995). However, MMN data are not easy to obtain owing to problems with the signal-to-noise ratio. This limits its clinical application (Groenen et al, 1996; Dalebout and Fox, 2001). The P300 response as a measure for discrimination has the relative disadvantage that it requires an active attention. The advantage of the P300 response is that it is a rather robust cortical response (Donchin and Coles, 1988; Coles et al, 1997). Therefore, we chose P300 measurements for the present study.

It has been shown that P300 amplitude is primarily related to unexpectedness of a stimulus and thus to its probability of occurrence and its discrimination from a more frequent stimulus. The P300 latency is an index for stimulus evaluation processes, including activities that involve encoding and proper categorization of the stimulus (Coles et al, 1997). Although there is controversy regarding the specific relation between P300 amplitude and the complexity of the task, there is consistency in the literature regarding the P300 latency as an index of the processing time of the stimulus (Donchin and Coles, 1988; Gratton et al, 1990). Earlier research by Kutas et al (1977) has shown longer processing times, or "stimulus evaluation times," when the behaviorally determined discrimination of the stimulus contrast was more difficult. They advocated the use of the peak latency instead of the amplitude of the P300. Nevertheless, in most P300 studies, two outcome measures are investigated, that is, amplitude and latency.

The Nucleus 24 cochlear implant system has 22 intracochlear electrodes and implements three different speech coding strategies. These speech-coding strategies differ with respect to the stimulation rate per electrode and the total number of active electrode sites. One of these strategies is mainly based on processing spectral information (SPEAK): the processor analyzes the acoustic waveform in the frequency domain (spectral "maxima") and activates the relevant electrodes with pulses at a mean stimulation rate of 250 Hz per electrode. Another strategy, "CIS," or continuous interleaved sampling, is based on processing in a time domain with a much higher stimulation rate per electrode (usually 1200 Hz) resulting in a higher temporal resolution compared to the spectral peak analysis. Usually, a number of predefined electrode sites are stimulated.

Finally, a third strategy combines various features to optimize the spectral and temporal processing of sounds: "ACE," or advanced combination encoding strategy. An extensive description of the ACE strategy has been given by Vandali et al (2000).

The aim of the present study is to assess whether the P300 measurement is a valid objective tool to study speech understanding with speech-coding strategy as a variable.

Thereto, P300 potentials were obtained with two selected speech contrasts in CI users and, for matters of comparison, in subjects with normal hearing. Next, it was studied whether individual behavioral discrimination scores for the speech contrasts obtained for each of the three coding strategies were related with corresponding P300 latencies and/or amplitudes. Measurements were performed in experienced CI users using a vowel and a consonant contrast.

METHODS

Subjects

Event-related potentials (ERPs) were obtained from ten experienced cochlear implant users; they were all postlingually deaf adults using a Nucleus 24M system. They participated on a voluntary basis. In all ten subjects, the complete array of electrodes had been inserted into the cochlea without any complications. The stimulation mode was monopolar (MP1+2) in all cases. For the ACE strategy a stimulation rate of 900 Hz per electrode was chosen with eight maxima; for the SPEAK strategy a mean stimulation rate of 250 Hz per electrode was chosen with an average of six maxima, and for the CIS a stimulation rate of 1200 Hz per electrode was chosen with 12 fixed electrode sites. The pulse width of the stimuli was 25 μsec in all three coding strategies. At the time of ERP recording, stable maps were available for the three coding strategies. All subjects had been using the speech processor full-time for more than one year. Some subject characteristics are shown in Table 1.

To study possible differences in ERPs compared to subjects with normal hearing, data were obtained from a control group of ten adults in the same age range as the CI users (mean age 45 years, ranging from 21 to 66 years; 4 women, 6 men). Subjects in the control group had normal hearing (thresholds at 0.5, 1, 2, and 4 kHz ≤20 dB HL) and no pathological otoneurological history. The ERP measurements in the control group were performed under the same conditions as in the CI group.

Stimuli

Auditory cortical potentials were evoked using speech stimuli. As one of the aims was to generate the endogenous P300 component, responses were elicited using an "oddball paradigm," that is, a stimulation paradigm in which a relative unexpected stimulus occurred in a series of much more frequently occurring and thus expected stimuli (Coles et al, 1997). Two speech contrasts were used: one vowel contrast with the vowel /i/ as the standard stimulus and the vowel /a/ as the deviant stimulus, and one consonant contrast with /ba/ as the standard and /da/ as the deviant stimulus. Standard stimuli occurred at a probability rate of 85%, while in 15% of the cases deviant stimuli were randomly presented. Construction, manipulation, and

Table 1. Subject Demographics of the CI Group

Subject	Gender	Age (yrs)	Etiology	Duration Deafness (yrs; months)	Duration CI use (yrs; months)
1	f	36	progressive	10;8	4;8
2	m	59	progressive	24;3	4;4
3	f	24	meningitis	1;5	4;2
4	f	66	progressive	7;5	3;11
5	m	70	otosclerosis	11;4	3;10
6	m	72	sudden	1;9	3;8
7	m	35	progressive	13;1	3;1
8	m	75	Meniere	16;3	2;8
9	m	42	ototoxicity	2;3	2;8
10	f	46	progressive	1;7	2;11
mean		53		9;0	3;6
range		24–75		1;5–24;3	2;8–4;8

resynthesis of these stimuli have been described in detail elsewhere (Groenen et al, 2001).

The two speech tokens of the vowel contrast /i/ vs. /a/ differed in the central frequencies of the first, second, and third formants. In the consonant contrast, the two speech tokens /ba/ and /da/ differed in the starting value and slope of the transitions of the second and the third formants.

Test Procedure

The ERP measurements were performed in a double-walled sound-proof room with low reverberation. Subjects were seated in a comfortable chair. The loudspeaker that presented the speech sounds was placed at a distance of 1 m in front of the subjects. The interstimulus interval was fixed at 2 sec. Each deviant stimulus was followed by at least two standard stimuli before the next deviant stimulus was presented. Blocks consisted of 220 stimuli: the first 20 stimuli were standard stimuli, followed by 30 deviant stimuli randomly embedded in 170 standard stimuli. The loudness level of presentation was 70 dB SPL measured with the Bruel and Kjaer 2203 SPL meter at the ear of a subject with normal hearing, or at the microphone of a CI user.

The noninverting recording electrode was fixed at CPz, according to the 10-10 system (Nuwer et al, 1998). The inverting electrode was placed on the nose, and a common ground electrode was placed on the cheek contralateral to the implant in the CI subjects, or on the right cheek in the subjects with normal hearing. Evoked potentials were measured with a Medelec ER94 (Oxford Instruments, Oxford, UK) system. Analysis time was set at one second with on-line filter settings that ranged from 1 Hz (high pass) to 125 Hz (low pass). Measurements with artifacts caused by eye movements were excluded from the average. Averaged recordings were filtered digitally off-line with a cutoff frequency of 25 Hz (low pass). Each measurement was repeated once. Subjects were instructed to count the deviant stimuli aloud.

For accuracy purposes, electrical thresholds (T-levels) and comfortable loudness levels (C-levels) of the three coding strategies were updated separately and fine-tuned. ERP measurements were carried out after the speech processor was adjusted for each strategy and had been used for at least one week each prior to the ERP measurement with that specific strategy.

Behavioral Testing

Before the ERP recordings, standard and deviant stimuli were presented separately six times each as well as in pairs. The subject was then asked to give a rating on a 5-point scale, with 1 as “no difference perceived between standard and deviant” and 5 as “very clear distinction between the standard and deviant” stimuli. This was done to obtain the patient’s opinion about the degree of discrimination of the contrast with the three different speech-coding strategies. Additionally, the subject’s true and false positive/negative responses to the deviant stimulus were counted during the ERP measurements.

ERP Data Analysis

N1 and P2 components were identified visually on the average response trace of the standard stimulus in the 50–300 msec region after stimulus onset. The P300 peak was identified as a positive deflection in the difference wave, that is, the result of subtracting the response to the standard from that to the deviant stimulus. Per peak (N1, P2, and P300) two response parameters were determined, that is, their latency and amplitude. Latency was defined as the time between the stimulus onset (in msec) and the maximum deflection of the peak; the absolute maximum in the deflection itself was the amplitude (in μV). Per subject, this resulted in three latencies and three amplitudes, namely one latency and one amplitude for each of the peaks N1, P2, and P300 in the three speech-coding strategies.

To evaluate reproducibility and to be able to assess intra-individual differences in amplitudes and latencies, measurements were repeated once. This enabled a test-retest evaluation. Differences in amplitudes and latencies between recordings obtained with the different speech-coding strategies were considered to be statistically significant when they differed by more than twice the intra-individual standard deviation derived from the test-retest data (see Appendix).

RESULTS

Event-Related Potentials

Typical examples of ERP recordings obtained from a CI subject are shown in Figure 1. The averaged response to the standard stimulus is indicated by the thin line, while the averaged response to the deviant stimulus is indicated by the thick line. The positive deflection around 300 msec post stimulus is clearly recognizable in the deviant recordings of the two speech contrasts. When the two figures are compared, it can be seen that smaller ERP amplitudes and prolonged latencies are present for the consonant contrast when compared to the vowel contrast.

Figure 2 shows the amplitudes and the latencies of N1, P2, and P300 peaks obtained from the CI subjects using the vowel (left figure) and the consonant (right figure) contrasts. Most CI users showed reproducible peaks. The N1 component was identified in 28 out of the 30 responses to the vowel contrast (ten subjects x three coding strategies); a P2 component was found in 27 responses and a P300 component in 29 responses. The N1 was identified in 27 out of the 30 responses to the consonant contrast, a P2 component in 28 out of 30 responses, and a P300 in only 17 responses. All the subjects with normal hearing consistently showed reproducible ERPs to the two speech contrasts.

CI Users versus Controls

Table 2 shows group mean amplitudes and latencies for the controls and the CI group. For the vowel contrast, amplitudes of N1, P2, and P300 components were smaller in the CI subjects than in the controls. Statistical analyses revealed significant differences in amplitudes of the components N1, P2, P300 (unpaired t-tests after corrections for equal variances, two-tailed, $p < 0.05$) between the control and the CI group, except for the SPEAK N1 and P300 component, and the ACE P300 component.

Latencies were prolonged in the CI group with all three coding strategies. Statistically significant latency shifts were found for all three speech-coding strategies (unpaired t-tests, two-tailed, $p < 0.05$), except for the ACE P300 component and the SPEAK P300 component. When amplitude levels of the missing peak values ($n = 6$ out of 90 responses) were replaced by 0 and their latencies by the poorest value found plus 10% (arbitrary choice), correlations became higher, and, additionally, the SPEAK N1 amplitude became statistically different from the control group ($p < 0.05$).

Next, for the consonant contrast, a somewhat different picture emerges. First of all, the table shows a significant number of subjects with absent P300. N1 and P2 amplitudes were significantly smaller in the CI group than in the controls, except for the N1 amplitude with the CIS strategy. Most latencies for N1 and P2 were significantly delayed ($p < 0.05$). Statistical analysis for

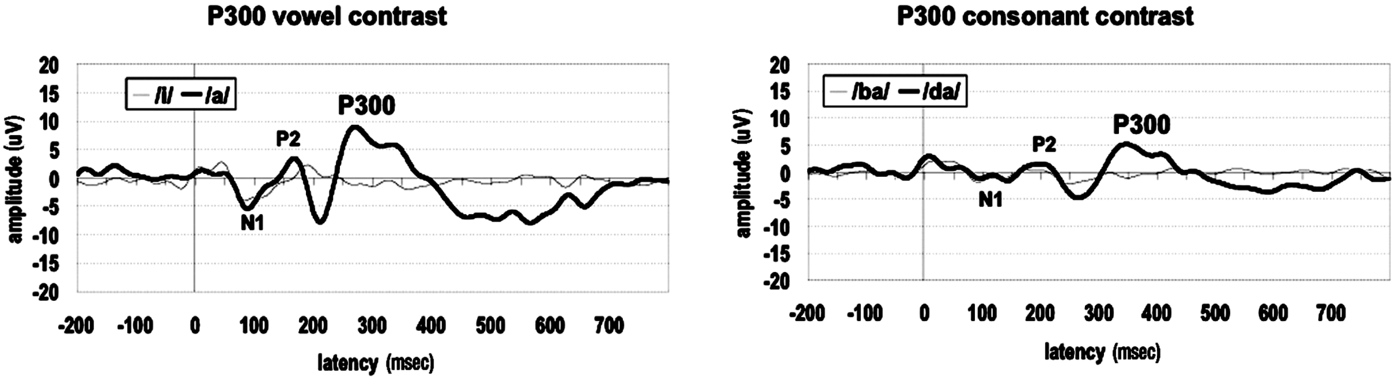

Figure 1. Typical ERP recordings from a CI subject (#2): The figures show averaged responses to the vowel contrast (left) and averaged responses to the consonant contrast (right). Thin line: response to standard; thick line: response to deviant stimulus. A positive P300 peak is recognizable in the response to the deviant stimulus.

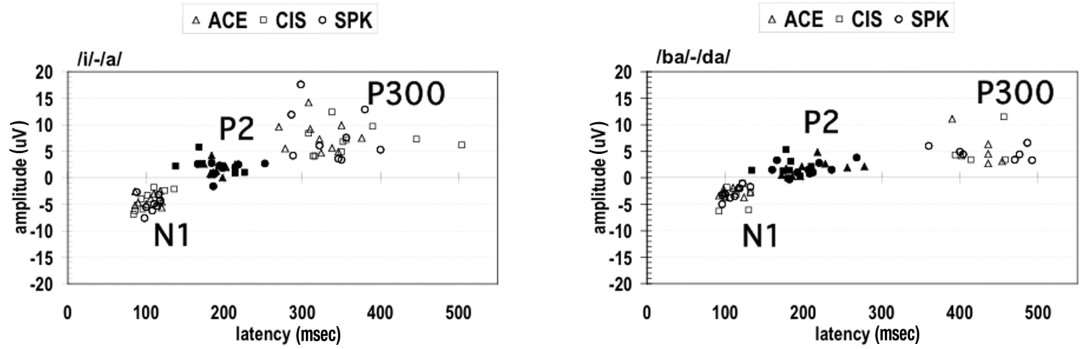

Figure 2. ERP peak latencies and amplitudes of 10 CI subjects to the vowel contrast (left) and the consonant contrast (right). Responses obtained with the ACE, CIS, or SPEAK are indicated with symbols: Δ for ACE, □ for CIS, and ○ for SPEAK. To distinguish N1 and P300 from P2 values, symbols for P2 are filled.

N1 and P2 with amplitude levels set at 0 and latencies at the unfavorable value (poorest value plus 10%) did not significantly change the results. The consonant data showed a tendency toward poorer P300 data in the CI users. However, the fact that the P300 could not be recognized with certainty in 13 out of 30 measurements should be taken into account.

Strategy-Dependent Differences

When analyzing within-subject differences for the three speech coding strategies, it is important to know whether a difference in amplitude or latency is statistically significant. For this purpose, we first determined the 95% critical value from the test-retest measurements. In the Appendix, the 95% critical values are presented for amplitude and latency. Using these critical values, Table 3 shows an overview of intra-individual P300 potentials that were significantly different. When significant interstrategy differences were found, the significantly smallest amplitude

Table 2. Group Means with Standard Deviations for the N1, P2, and P300 Amplitudes (in μV) and Latencies (in msec) for the Vowel Contrast (top) and Consonant Contrast (bottom)

	N1 standard		P2 standard		P300 difference	
	amplitude	latency	amplitude	latency	amplitude	latency
Vowel Contrast /i/-/a/						
ACE	-4.2**	105*	1.9**	192**	7.9	322
sd	1.2 (n = 10)	14	1.1 (n = 10)	12	3.1 (n = 10)	32
SPEAK	-5.0	108**	1.8**	198*	8.1	336
sd	1.6 (n = 8)	11	1.5 (n = 8)	26	5.0 (n = 9)	41
CIS	-4.2*	107*	2.0**	190*	7.3*	367*
sd	1.8 (n = 10)	17	1.6 (n = 9)	28	2.4 (n = 10)	63
Controls	-6.6	93	5.9	173	11.4	314
sd	2.3 (n = 10)	6	2.5 (n = 10)	18	4.1 (n = 10)	14
Consonant contrast /ba/-/da/						
ACE	-2.7*	109	1.7*	212	5.3*	426
sd	0.8 (n = 10)	13	1.4 (n = 10)	34	3.1 (n = 6)	24
SPEAK	-2.9*	110	1.7*	205	4.7*	441
sd	1.3 (n = 8)	13	1.3 (n = 10)	32	1.2 (n = 7)	52
CIS	-3.3	114	1.9*	180	4.7**	431
sd	1.8 (n = 9)	14	1.7 (n = 8)	22	3.4 (n = 4)	32
Controls	-5.0	106	4.2	193	9.5	404
sd	2.1 (n = 0)	17	2.9 (n = 10)	28	3.4 (n = 10)	32

*p < 0.05
**p < 0.01

or longest latency (poorest responses) for a speech-coding strategy is always indicated by an “o” symbol in this table. In addition, as an absent P300 is considered as poor result, the missing data are also indicated with that symbol. The speech coding strategy with the significantly largest amplitude or shortest latency (best responses) is indicated with an asterisk. In only one subject (#5), the latency of the consonant contrast with ACE was significantly better than with SPEAK, while the latency of the SPEAK responses was significantly better than CIS. In Table 3 (bottom) this is indicated with a double asterisk.

With the vowel contrast, P300 peaks could be identified in all ten CI subjects with at least two of the three speech-coding strategies. In nine subjects, it was possible to determine a P300 with all three coding strategies. In eight subjects, a P300 was recognized when using the consonant contrast with at least one speech coding strategy; in two subjects, #1 and #4, no reproducible P300 peaks were found with any strategy.

Table 3. Intra-individual Significant P300 Amplitude and Latency Differences between Speech-Coding Strategies in Individual CI Subjects for the Vowel (top) and Consonant (bottom) Contrast

Vowel Contrast /i/-/a/

	Amplitude P300			Latency P300		
	ACE	CIS	SPK	ACE	CIS	SPK
CI Subject						
1				*	†	*
2				*	†	*
3		†	*	*	†	*
4		†	*	*	†	†
5				*	†	*
6				*	†	†
7						
8	*		†	*	†	*
9						
10				*	†	*

Consonant Contrast /ba/-/da/

	Amplitude P300			Latency P300		
	ACE	CIS	SPK	ACE	CIS	SPK
CI Subject						
2						
3	*	*	†	*	†	*
5	*	†	*	‡	†	*
6						
7						
8	†	†	*	†	†	*
9	†	†	*	†	†	*
10				*	*	†

Note: Missing data indicates nonidentifiable peaks.
*Significant interstrategy differences at the 5% level with the largest amplitudes and shortest latencies
†Significant poorest responses
‡Significant difference was found between this strategy and both other strategies

Behavioral Responses: Individual Contrast Ratings and Subjective Responses to Speech Contrasts

The behavioral discrimination of the speech contrasts was quantified on a five-point scale. Individual ratings for the contrast between the standard and deviant stimuli varied from 1, that is, no contrast perceived, up to 5, that is, very clear contrast. As expected, the controls with normal hearing showed an optimal score of 5 for both the vowel and the consonant contrasts (not shown). Table 4 shows an overview of the individual ratings in the CI subjects for the three coding strategies and the two speech contrasts. The consonant contrast was less clearly perceived than the vowel contrast by the CI subjects.

During the ERP recordings, the deviants were counted aloud. Thus the number of correctly identified deviant stimuli (true positives) and incorrectly identified standard stimuli (false positives) were known. These data were used to calculate the percentages of true positives (sensitivity) and true negatives (specificity). For the vowel contrast, a considerable ceiling effect was found for all three coding strategies. The sensitivity and specificity scores were above 95%, most were 100%. This was also found for four of the ten subjects with the consonant contrast. Therefore, it was decided not to use these data but to use the behavioral discrimination ratings from Table 4 for comparison with the P300 data from Table 3.

Relation between Objective Responses and Behavioral Responses

As the number of CI users was limited, it was decided to analyze the P300 measurements only qualitatively by comparing the results of Tables 3 and 4. For each subject, it was examined whether the significant best P300 response with a specific strategy corresponded with the best behavioral contrast discrimination. A straightforward comparison for the vowel contrast showed that the significantly highest (i.e., best) amplitudes (obtained with the ACE from subject #8, and with the SPEAK from subjects #3 and #4: see Table 3) were not in conformity with the best discrimination scores (see Table 4). On the other hand, the significantly shortest (i.e., best) latencies were nearly all associated with high discrimination ratings of 4 or 5. A rating of 3 was never associated with the best P300 latency, except in subject #10: this subject had a significant shorter P300 latency for ACE and SPEAK compared to CIS, although the SPEAK strategy was judged as the most difficult-to-discriminate strategy.

For the consonant contrast, significant best amplitudes were found in subjects #3, #5, #8, and #9, which was in acceptable conformity with the behavioral discrimination of this contrast (viz. with the highest ratings, 3 or 4). The significantly best latencies, found

Table 4. Individual Ratings of the Discrimination of the Speech Contrasts

CI subject	Vowel contrast			Consonant contrast		
	ACE rating	CIS rating	SPEAK rating	ACE rating	CIS rating	SPEAK rating
1	5	3	4	3	2	1
2	5	5	4	3	3	3
3	5	3	4	4	3	2
4	5	3	4	3	1	2
5	5	3	4	4	1	3
6	5	3	4	4	3	2
7	5	3	4	3	1	2
8	4	3	5	2	1	3
9	5	4	3	4	3	4
10	5	4	3	2	1	1

in the same four subjects, were also associated with the highest discrimination scores, except in subject #3 for SPEAK.

Figure 3 presents these findings in a different way. The figure shows each patient's shortest P300 latency (filled symbol) and the longest (open symbol) as a function of the patient's behavioral discrimination ratings. If a P300 was not found, a latency of 550 msec was assigned. The lines in the figure connect the best and poorest score for a particular patient. All the lines have a negative slope, indicating that longer latencies are associated with poorer subjective ratings.

DISCUSSION

In the present study, ERP measurements were obtained from CI users using three different speech-coding strategies. First, the results were compared to those of subjects with normal hearing. Further, it was studied whether there was a relation between the P300 measures and the behavioral discrimination for the two speech contrasts.

The quality of the P300 recordings was satisfactory; reproducible P300 responses were found in the majority of the recordings. Two variables, amplitude and latency, were analyzed. In all CI subjects, a P300 could be identified with the vowel contrast with at least two speech-coding strategies. However, for the consonant contrast, a P300 could be identified in only eight out of the ten CI subjects with at least one strategy.

A difference in the latencies of the slow vertex potentials N1 and P2 was found between the control group and the CI group for the vowel and consonant contrast, for all three coding strategies: these prolonged latencies suggest that the CI subjects had longer stimulus evaluation times, that is, perception took longer than in the control subjects (Table 2). A similar conclusion is drawn for the P300 data when absent data are taken into account. The overall poorer results with the consonant contrast in both the CI subjects and the control group (lower amplitudes, longer latencies, see Table 2) suggest that cortical processing is different from that with the vowel contrast. A possible explanation might be that the consonant contrast simply represented a smaller acoustical difference than the vowel contrast. Previous studies on subjects with normal hearing have shown that P300 responses to difficult-to-discriminate contrasts have longer latencies than easy-to-discriminate contrasts (Kutas et al, 1977; Donchin and Coles, 1988). Further, the fact that the discrimination of vowels is mainly based on frequency information, while consonant perception makes use of temporal processing, might play a role. There might be two different phonetic processing mechanisms with different neural processing times.

The main research question aimed at

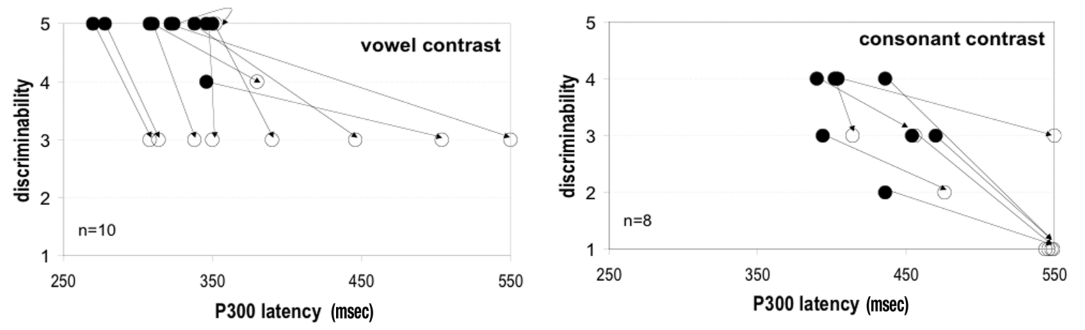

Figure 3. Discrimination scores versus P300 latencies for vowel (left) and consonant contrast (right). Intra-individual significant best scores are indicated with filled symbols and poorest scores with open symbols. Symbols at a latency of 550 msec indicate no P300 response.

the relation between P300 data, mainly its latency, and the behavioral discrimination of speech contrasts. Considering Figure 3, it is concluded that the subjective judgement of contrast discrimination using a rating scale was in agreement with P300 latencies for the vowel and consonant contrast.

It should be noted that it is not possible to draw any conclusions on the best of the three coding strategies for a particular CI user as most of the CI users were very familiar with one of the strategies (i.e., the strategy that they used daily). Besides CI processing by speech coding strategy, other factors might play a role in the intra-individual variability of speech recognition with a CI, such as the electro-neural interface (i.e., poor transmission of the CI output to the auditory nerve) or the neural processing (i.e., poor cortical representation of the speech sounds).

CONCLUSIONS

ERPs could be evoked readily in most CI users. In general, the morphology of the ERPs was similar to that found in the controls. However, the CI subjects showed longer stimulus evaluation times (i.e., prolonged latencies) for the vowel contrast and lower amplitudes for the vowel and consonant contrast than the control subjects. On an individual level, the present results indicated variation in auditory processing quantified by variation in the P300 data when different speech-coding strategies were used. P300 data were in acceptable agreement with behavioral discrimination ratings.

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Appendix. Mean Test-Retest Differences with Standard Deviations

Mean test-retest differences +/- sd		
contrast	amplitude (μV)	latency (msec)
vowel	0.0 +/- 2.4 (n = 29)	2.4 +/- 18.1 (n = 29)
consonant	0.9 +/- 2.2 (n = 17)	-2.5 +/- 29.6 (n = 17)

	N1		P2	
frequency	amplitude (μV)	latency (msec)	amplitude (μV)	latency (msec)
vowel	0.0 +/- 1.0 (n = 28)	-3.5 +/- 11.4 (n = 28)	-0.1 +/- 1.0 (n = 27)	1.7 +/- 12.3 (n = 27)
consonant	0.1 +/- 1.2 (n = 27)	7.4 +/- 18.8 (n = 27)	0.1 +/- 1.2 (n = 28)	4.1 +/- 24.5 (n = 28)

Note: Number of subjects in whom a reproducible N1, P2, or P300 peak was found is denoted by *n*.

Differences in amplitude and latency between the test and retest scores (signed differences) were determined and averaged over the ten CI subjects. This table presents the mean signed test-retest differences and standard deviations for N1, P2, and P300 amplitudes and latencies in response to the vowel and consonant contrasts. Assuming that the intra-individual variability in peak latencies and amplitudes was independent of speech coding strategy, test-retest differences for the three strategies were pooled. Data from those subjects in whom a reproduction of a specific peak was not possible were excluded. This resulted in less than three x ten (strategy x subjects) observations (the number is indicated between brackets). All the six mean test-retest values did not differ significantly from zero (t-test, 2-tailed, $p > 0.05$) for either contrast, implying no systematical order effects. Therefore, the standard deviation of this mean was used to define the measurement error: peak amplitude differences or peak latency differences of more than 2.26 times this standard deviation divided by $\sqrt{2}$ (repeated measurement) were considered significantly different (with a probability of 95%). For example, for P300 differences, these values were 3.9 mV and 29 msec for the vowel contrast, and 3.6 μV and 48 msec for the consonant contrast.