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Effects of acoustic distortion and semantic context on event-related potentials to spoken words

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Abstract

This study examined the neurophysiological effects of acoustic degradation on auditory semantic processing. Event-related potentials were recorded to target words presented in a sentence context. Targets were semantically congruent or incongruent with the context, which was acoustically intact or low-pass filtered. In unaltered contexts, N400 amplitude was significantly greater for incongruent than congruent words. Filtering significantly reduced this effect, even though participants were highly accurate in interpreting the degraded stimuli, as shown by an anomaly detection task. This reduction in the N400 effect appeared to be driven by decreased N400 amplitudes over posterior electrode sites for incongruent targets. These results demonstrate that acoustic degradation influences the neural response to words in context by reducing the availability of semantic information in on-line sentence comprehension.

Descriptors: Event-related potentials (ERPs), Language, Lexical access, Semantic priming, Speech perception, Hearing

To comprehend spoken language, the listener must rapidly extrapolate higher-level linguistic representations (such as words and sentences) from a complex acoustic signal. The results of numerous behavioral studies suggest that listeners use meaningful context to aid in the perception of words. For instance, normal adult listeners are faster to respond to words that are preceded by semantically congruent contexts in lexical decision (Aydelott & Bates, 2004; Meyer & Schvaneveldt, 1976; Neely, 1991; Stanovich & West, 1983), picture naming (Carr, McCauley, Sperber, & Parmelee, 1982), and pronunciation (reading or cued shadowing; Bates & Liu, 1996; Seidenberg, Waters, Sanders, & Langer, 1984) tasks. Conversely, listeners are slower to make lexical decisions in response to words preceded by semantically incongruent contexts (Aydelott & Bates, 2004; Neely, 1991; Stanovich & West, 1983). Thus, the semantic context facilitates the processing of congruent words, resulting in speeded responses, and inhibits the processing of incongruent words, resulting in slowed responses.

These behavioral effects mirror the component processes of word recognition and lexical access that have been proposed in a number of models of spoken word comprehension (e.g., Aydelott & Bates, 2004; Faust & Gernsbacher, 1996; Marslen-Wilson, 1993; Marslen-Wilson & Warren, 1994). According to these models, the listener must first activate a set of possible word candidates on the basis of the acoustic input, and the appropriate candidate must then be selected from among these active word representations based in part on expectancies generated by the sentence meaning. The selected target must then be integrated into the semantic context. That the semantic context produces both facilitation and inhibition effects on responses to word targets suggests that the language processing system makes use of contextual information in both the activation and selection of compatible word candidates, and that the speed of processing of individual words is influenced by the ease with which they may be integrated into the contextual meaning.

The processes of lexical activation, selection, and integration depend crucially upon the quality of the acoustic input. Studies of priming in single words have demonstrated that even minute acoustic variations that do not change the perceptual identity of a phonetic segment can influence word recognition and semantic processing (Andruski, Blumstein, & Burton, 1994; Aydelott Utman, Blumstein, & Burton, 2000). However, spoken language comprehension is rarely accomplished under ideal listening conditions. The speech signal may be masked by environmental noise or filtered by electronic communication devices, such that portions of the acoustic spectrum are not available for perceptual analysis. As a consequence, the initial activation of lexical–

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semantic representations may be disrupted, and the increased attentional demand imposed by the need to disambiguate a degraded signal may also interfere with later processes of lexical selection and integration.

Recent studies have shown that acoustic distortion affects both the facilitation and inhibition of spoken words in a semantic context. In a lexical decision task, Aydelott and Bates (2004) examined response times to target words that were congruent or incongruent with a strongly biasing auditory sentence context, relative to a neutral baseline condition. Sentence contexts were presented in three conditions: acoustically intact (no distortion); reduced intelligibility, in which 1-kHz low-pass filtering was applied to the signal; and reduced processing time, in which the signal was subject to 50% temporal compression. Target words were acoustically intact in all conditions. The results revealed that low-pass filtering affected both the facilitation of congruent targets and the inhibition of incongruent targets, whereas time compression reduced inhibition without affecting facilitation. Similar results have also been obtained for other types of acoustic distortion, such as competing speech (Moll, Cardillo, & Aydelott Utman, 2001). These findings suggest that reduced processing time affects the suppression of lexical information that is incompatible with the context, whereas reducing the intelligibility of the acoustic signal disrupts both lexical activation and contextual selection. Thus, the ability to make use of semantic context to aid in lexical processing is particularly vulnerable to perceptual stress. Further, the distinct patterns of vulnerability to perceptual stress shown by facilitation and inhibition effects in behavioral reaction time studies may reflect the operation of more than one process involved in the comprehension of words in context.

Interestingly, contextual effects on lexical access are also disrupted in populations with endogenous processing disturbances, including elderly individuals and patients with neurological damage. Studies of inhibitory control in normal adults have suggested that the ability to suppress irrelevant contextual information during language comprehension declines with age (e.g., Hartman & Hasher, 1991; Sommers & Danielson, 1999). Further, Blumstein, Milberg, and colleagues (Aydelott Utman, Blumstein, & Sullivan, 2001; Milberg, Blumstein, & Dworetzky, 1988; Milberg, Blumstein, Katz, Gershberg, & Brown, 1995) have observed that patients with Broca's aphasia show weak and unreliable facilitation effects with spared inhibition effects in auditory priming tasks. In contrast, Wernicke's aphasics show the reverse pattern, demonstrating robust facilitation with reduced or absent inhibition. Thus Broca's aphasics appear to suffer from insufficient activation of lexical information on the basis of semantic context, whereas Wernicke's aphasics fail to suppress irrelevant information during lexical access. Taken together, these findings provide further support for the vulnerability of lexical activation and suppression in word recognition in response to cognitive stress, and may suggest underlying neural mechanisms associated with these processes. In addition, the similarities in performance between individuals with endogenous language disturbances and normal adults under stress indicate that the use of perceptual degradation in normal language comprehension may provide a means of evaluating the role of domain-general factors in language disorders (cf. Dick et al., 2001; Miyake, Carpenter, & Just, 1995).

The behavioral findings cited above indicate that perceptual degradation has a direct influence on the semantic processing of words in context. However, this interpretation is subject to the limitations of reaction time (RT) data as a measure of on-line language processing. Although behavioral methods have revealed much about the nature of word recognition and lexical access, these methods rely upon extraneous tasks such as lexical decision, which may involve the operation of task-specific strategies that do not necessarily reflect the normal functioning of the language processing system. In contrast, neuroimaging techniques provide a more direct measure of neural responses to language stimuli and allow for the use of more ecologically valid experimental tasks. In particular, event-related brain potentials (ERPs) have been used extensively in studies of language comprehension and offer better temporal resolution than other neuroimaging methods.

Studies using ERPs have demonstrated that contextual information can modulate certain aspects of the neural response to words. The processing of lexical–semantic information in particular is reflected in a negative component that peaks in amplitude 400 ms after the presentation of a word stimulus (the N400). The N400 is observed in response to visual or spoken words presented in isolation, suggesting that this component reflects the normal response to words irrespective of the context in which they occur, and may be associated with the activation of information in semantic memory (Kiefer & Spitzer, 2000; Kutas & Federmeier, 2000). Nevertheless, the amplitude of N400 is highly sensitive to semantic context, such that N400 is typically larger for words that are incongruent with a preceding word or sentence context and smaller for words that are congruent with the context, than for words presented in isolation or in a neutral context (Holcomb & Neville, 1990, 1991; Kutas & Hillyard, 1983, 1984; Van Petten & Kutas, 1990).

The observed difference in N400 amplitude between congruent and incongruent words is referred to in the literature as the *N400 effect*, and the magnitude of the effect is modulated by the extent to which the target word is semantically related to previously presented words or is expected or predictable in a particular sentence context (for a review, see Kutas & Federmeier, 2000). For this reason, the N400 effect has been interpreted as an index of contextual integration, that is, the ease or difficulty with which words may be incorporated into the overall meaning of the context (Brown & Hagoort, 1993). However, the amplitude of the N400 component is also reduced for implausible sentence completions that share semantic features with expected words, suggesting that ease of integration alone cannot account for the N400 effect (cf. Kutas & Federmeier, 2000). Instead, the reduction in N400 amplitude observed for congruent words may reflect a predictive process, in which the context serves to anticipate upcoming information by activating features of compatible items in semantic memory. Based on a study showing hemispheric differences in the processing of semantically implausible items, Kutas and Federmeier (2000) argue that the language system uses *both* predictive and integrative strategies in the comprehension of words in context, and that these two aspects of processing are reflected in the neural response to words in different brain regions.

This distinction between predictive and integrative processing strategies mirrors the component processes of activation and integration proposed in the behavioral literature. According to both accounts, contextual information serves to activate semantic features of congruent words, facilitating response times and decreasing N400 amplitude for compatible word candidates. Subsequently presented words must be integrated with the context, with more effortful integration of incongruent words thought to be due to the suppression of incompatible candidates. These processes of suppression result in the inhibition of response times and increased N400 amplitudes for incompatible word candidates (cf. Aydelott & Bates, 2004). Thus, in both the behavioral and ERP literature, separate mechanisms have been posited to account for the different roles of context in the processing of lexical–semantic information.

Similarly, the anomalous semantic facilitation and inhibition effects obtained in previous behavioral studies of elderly and aphasic populations are reflected in the N400 response to words in context observed in these groups. Specifically, normal elderly individuals show a reduced N400 effect (i.e., a smaller difference in N400 amplitude between congruent and incongruent words) in response to strongly biasing sentence contexts, relative to younger adults (Cameli & Phillips, 2000; Federmeier & Kutas, 2005; Federmeier, McLennan, De Ochoa, & Kutas, 2002; Kutas & Iragui, 1998). The N400 effect is also reduced in aphasic patients with impaired language comprehension (as assessed by the Aachen Aphasia Test), but not in aphasic patients with spared comprehension (Hagoort, Brown, & Swaab, 1996; Swaab, Brown, & Hagoort, 1997). Morevover, the amplitude of the N400 effect is abnormally small in a variety of other clinical populations with deficits in processing contextual information, such as individuals with Alzheimers (Iragui, Kutas, & Salmon, 1996), schizophrenia (Kiang & Kutas, 2005), autism (Strandburg et al., 1993), and alcoholism (Ceballos, Houston, Smith, Bauer, & Taylor, 2005; Schmidt & Neville, 1985). Reduction of the congruency effect in these populations is typically due to larger amplitude N400s to congruent targets, rather than smaller N400 amplitudes to incongruent targets. As the N400 amplitude becomes smaller with increasing contextual constraints in normal young adults, the increased N400 amplitude to congruent targets in these populations is consistent with a deficit in the ability to use context to constrain word meaning. In contrast, the N400 effect is abnormally large in groups that show a strong dependence on context for language processing, such as language impaired children (Neville, Coffey, Holcomb, & Tallal, 1993) and individuals with Williams Syndrome (Bellugi, Lichtenberger, Mills, Galaburda, & Korenberg, 1999; Mills, 1998).

Thus, the N400 component provides a reliable measure of the influence of contextual information on lexical–semantic processing that is sensitive to endogenous comprehension disturbances. This component is therefore of considerable potential interest as a means of evaluating the influence of perceptual stress on normal language comprehension. The extent to which abnormalities in N400 amplitudes in the populations described above are linked to processing versus structural deficits can be examined by manipulating task demands in healthy individuals. For example, reductions in the N400 effect and increased N400 latencies are observed under high working memory load conditions in normal adults (D'Arcy, Service, Connolly, & Hawco, 2005). Working memory has been shown to be an important factor in N400 reduction due to normal aging (Gunter, Jackson, & Mulder, 1995). In an ERP study using degraded visual targets, Holcomb (1993) found that the latency of the N400 was delayed in the degraded condition, but there was no effect on the amplitude of the N400 for either the congruent or incongruent condition. In the present study, we predict that by degrading the context as opposed to the target, the magnitude of the N400 effect will be diminished and the latency of the N400 will delayed.

The purpose of the present study was to examine the effects of acoustic distortion on the neural response to spoken words in a semantic context. ERPs were measured in response to target words presented in semantically biasing sentence contexts, which were either congruent or incongruent with the meaning of the target. Context sentences were either acoustically intact or low-pass filtered at 1 kHz to introduce perceptual stress in the form of reduced signal intelligibility (cf. Aydelott & Bates, 2004). As in previous studies (Aydelott & Bates, 2004; Moll et al., 2001), target words were always acoustically intact.

Two types of response to the acoustic degradation were therefore predicted: (1) a *perceptual* response, reflecting the change in the auditory stimulus from filtered to unfiltered speech, and (2) a *semantic* response, reflecting reduced semantic activation of congruent targets and reduced difficulty in the integration of incongruent targets due to the degradation of the context. Previous ERP studies have shown that abrupt changes in the perceptual characteristics of an auditory signal result in an enhanced N1 component followed by a positivity in the 200–500-ms time window (Escera, Alho, Winkler, & Näätänen, 1998; Näätänen & Picton, 1987), which may reflect the orienting of attention in response to the acoustic difference. Thus, similar perceptual effects were expected to emerge in the present study. The primary focus of the present study was the semantic response, which was evaluated by examining the effects of acoustic degradation on the N400 component elicited by target words in congruent and incongruent contexts. Acoustic degradation was expected to reduce the N400 effect in two ways: (1) by disrupting the activation of semantic features associated with contextually compatible words, thus increasing N400 amplitudes for congruent targets in filtered contexts relative to unaltered contexts[1], and (2) by interfering with integrative strategies that make the processing of contextually incompatible items more difficult, thus decreasing N400 amplitude for incongruent targets in filtered contexts relative to unaltered contexts. To ensure that any effect of acoustic degradation on the N400 component could not be attributed to participants being unable to perceive or comprehend the degraded stimuli due to reduced intelligibility, a semantic anomaly detection task was administered in which participants were asked to indicate whether the meaning of the target was compatible with the meaning of the sentence context.

Methods

Participants

Fifteen undergraduates at the University of California, San Diego, participated in the experiment. All were right-handed native speakers of American English between 18 and 30 years of age. None of the participants reported any history of hearing impairment,[2] neurological disease, or substance abuse.

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[1]Note that the N400 response is observed to words irrespective of context, and that biasing contextual information significantly *reduces* N400 amplitudes to congruent words *relative* to words presented in isolation or in a neutral context. We therefore predicted that N400 amplitudes would be *increased* for congruent words in degraded contexts relative to intact contexts, that is, that degradation of the context would result in N400 amplitudes that more closely resembled the neural response to words observed in the absence of semantic bias.

[2]Although none of the participants reported any hearing impairment, it is worth noting that there is some variation in hearing sensitivity within the non-hearing-impaired population. This was taken into account in the present study by using a within-subject design in which each participant heard all of the sentence contexts and targets in both unaltered and degraded conditions. Thus, an individual baseline response to all stimuli in the absence of acoustic degradation was effectively obtained for each participant, which could then be compared to that participant's response to filtering.

Stimuli

Each test trial consisted of an auditory sentence 6–10 words long (mean = 8 words) containing a target word that was either congruent or incongruent with the overall meaning of the sentence context, for example, "The cat is catching *mice* in the back yard" (congruent) versus "The cat is catching *plates* in the back yard" (incongruent). All target words were presented in sentence-medial position. The sentences were spoken by a female native speaker of American English in a sound-attenuated chamber. The speaker was told to use a natural intonation and to articulate each word clearly. The stimuli were digitized directly onto an IBM-compatible PC at an 11.025 kHz sampling rate with an 8-bit quantization. In addition to these unaltered stimuli, distorted versions of the sentence contexts were created by applying low-pass filtering at 1 kHz to each word in the sentence context using the equalizer function in the SoundEdit 16 software package (cf. Aydelott & Bates, 2004). No degradation was applied to any of the target words. Thus, the target words were always acoustically intact, irrespective of the distortion applied to the semantic context. All targets were one to three syllables long, with an average duration of 843 ms. As all sentence contexts and targets appeared in all experimental conditions, there were no differences in stimulus duration or content across filtering or congruency manipulations.

All participants heard 80 unfiltered sentences and 80 sentences in which all words except for the target words were filtered. Half of the sentences in the filtered and unfiltered conditions contained a target word that was semantically congruent with the sentence context and half contained a target word that was incongruent with the context. Two sentence lists were constructed and counterbalanced across subjects as to which sentences would be heard in the filtered and unfiltered conditions. Each sentence stem (all words but the target) was repeated twice in both filtered and unfiltered conditions, once with a congruent target and once with an incongruent target; thus, each sentence stem was heard four times altogether, with the order of presentation of filtering and congruency conditions counterbalanced across stems. The incongruent targets consisted of target words that were congruent in a different sentence. Thus the congruent and incongruent targets were the same, that is, physically identical stimuli, that varied only in terms of the sentence context in which they appeared. In total, each participant received 40 trials per condition (40 unfiltered sentences, each presented once with a congruent target and once with an incongruent target, and 40 filtered sentences, each presented once with a congruent target and once with an incongruent target), with order of presentation counterbalanced across conditions. Because the target words appeared in sentence-medial positions, the target words were not as highly constrained as would be typical of an N400 paradigm using sentence-final words with a high cloze probability.[3] Two norming studies were conducted to verify that the targets in the incongruent condition were in fact interpreted as semantically incongruent. An online reaction time study was conducted in which 20 undergraduate students were asked to press a button as soon as they detected an anomaly. Sentences in which anomaly detection reaction times were significantly longer than the overall mean for incongruent trials or in which the anomaly was not detected were eliminated from the stimulus set. Additionally, an open-ended stem-completion questionnaire presented a separate group of 20 undergraduate students with the words in each sentence preceding the target. The answers were scored for word class, and 95% of the responses were nouns. Cloze probability was not determined because the sentence-medial position allowed for multiple semantic fits in each sentence. However, no targets classified as incongruent were given as responses in the stem completion task.

Procedure

The sentences were delivered one word at a time with a 200 ms ISI between words. The ISI was inserted to facilitate time-locking to the onset of each word while preserving the prosody of the sentence (for a similar procedure, see Holcomb, Coffey, & Neville, 1992). Participants were asked to listen carefully to each sentence. Both the intact and distorted versions of each sentence were presented in random order to each participant. To ensure that participants were able to detect the semantic anomalies in both the intact and distorted sentences, participants were asked to indicate whether the sentence "made sense" by pressing one of two buttons marked "YES" and "NO" on a response box after the end of each sentence.

ERP Recording

The electroencephalogram (EEG) was recorded using tin electrodes from 14 sites affixed to a cap (Electro-cap International) and two electrooculogram (EOG) sites. Eight of the sites were from standard 10/20 placements over left and right frontocentral (Fp1/Fp2), frontal (F7/F8), occipital (O1/O2), and midline (Cz, and Pz) positions, and six were nonstandard sites designed to be located over areas along the perisylvian fissure, including anterior temporal (L/R22, which was situated one-half the distance between F7/F8 and T3/T4), temporal (L/R41, which was situated 33% of the distance from T3/T4 to C3/C4), and left and right temporo-parietal (WL/WR, which was 50% of the distance between T3/T4 and P3/P4). Additionally, the EOG from over (Fp1) and under (Le) the left eye was recorded to monitor blinks and vertical eye movements and from the right outer canthus (He) to monitor horizontal eye movements. Impedances were maintained below 5 KΩ. The EEG was amplified at a gain of 10,000 using SA Instrument amplifiers (input impedances of 1000 MΩ per channel), recorded at 250 Hz, and filtered with a bandpass of 0.01 to 100 Hz. The averaged ERPs were also digitally filtered off-line with a 60-Hz low-pass filter. All electrodes were referenced to linked mastoids.[4]

[3]The target words occurred in sentence-medial positions because these sentences were also used in a study of infants comparing word order and semantic violations. Sentence-medial violations were chosen to control for position in the sentence. Semantic violations in the middle of a sentence also produce an N400 effect (Van Petten & Kutas, 1990), although the N400s to the congruent targets are likely to be larger than for sentence final targets.

[4]We are aware of the controversies surrounding the use of linked mastoids (Picton et al., 2000). Linked mastoids were used here to increase the number of active sites available given hardware constraints and to provide consistency with previous studies. The impedances were matched within 1 μV to reduce shorting problems associated with mismatched impedances. A pilot study using similar auditory stimuli was conducted to examine possible distortions in the distribution of scalp activity resulting from forced linkage. This was determined by recording from one mastoid, using the other as a reference, and linking the mastoids off-line. These pilot data were compared with the data recorded using linked mastoids and did not yield significant differences (see Zangl & Mills, in press).

ERP Data

EEG was time-locked to the onset of each word. Artifact rejection was conducted off-line using a computer program in the data analysis system. Criteria for rejection of trials containing eye-blinks, horizontal eye movement, muscle movement, or amplifier blocking were set for each subject individually based on visual inspection of the data on a trial-by-trial basis. Setting the same criteria for each participant can be problematic due to individual variability in EEG amplitudes (Luck, 2005). The individual thresholds were entered into a computer program for averaging only artifact-free trials. This method has been shown to be very effective in separating real artifact from EEG noise (Luck, 2005). A mean of 87% of the trials per condition (i.e., 35 out of 40, range 31–40) were artifact free and retained for analysis. There were no differences in the percent of artifact-free trials per condition. ERPs were averaged separately for filtered and unaltered sentences and for congruent and incongruent targets.

Measurement of ERP Components

All measurements were relative to a 100-ms prestimulus baseline. ERP condition effects were characterized using sequential 200–300-ms time windows from 0 to 600 ms after the beginning of each word, that is, 0–200, 200–400, and 300–600 ms. Consistent with previous ERP studies, a negative-going component, peaking at approximately 100 ms (N1) was observed in the first 200 ms. Because the N1 was a discrete peak, it was measured as the local minimum peak amplitude within the first 200 ms after stimulus onset rather than as a mean amplitude over that window. The local minimum peak was defined as the largest negative peak surrounded on both sides by more positive points. This type of measure reduces distortion due to high frequency noise and avoids errors due to minimum voltage at the edge of the time windows (Luck, 2005). All other measures used mean amplitudes for the subsequent epochs. The N1 was followed by a positivity between 200 and 400 ms (P200–400). Of specific interest was whether the filtered context would influence the amplitude of the N400. Although the N400 is typically measured between 300 and 500 ms (e.g., Federmeier et al. 2002), some of the N400 activity elicited in this paradigm extended past this epoch. Therefore, a 300–600-ms window was used to measure the N400.

Amplitude data were analyzed separately for each time window in repeated measures ANOVAs with semantic congruency (congruent, incongruent), acoustic distortion (unaltered context, filtered context), hemisphere (left, right), and electrode site (frontal, anterior temporal, temporal, temporo-parietal, and occipital sites) as within-subjects factors. Huynh–Feldt corrections were used for the repeated measures. Simple effects analyses (planned comparisons) were conducted to examine the effects of distortion at each electrode site.

Results

Behavioral Data

Percent correct responses in the semantic anomaly detection task for each subject in each condition are shown in Table 1. Participants were highly accurate at judging whether each sentence made sense, irrespective of the presence of acoustic distortion. Paired *t* tests revealed no significant effect of distortion on anomaly detection, $t(1,14) = 1.52, p > .1$, although distortion did reduce accuracy slightly for semantically plausible sentences, $t(1,14) = 2.47,\ p < .05$. For both semantically plausible and anomalous sentences, accuracy was above 90%. In all cases,

Table 1. *Mean (and Standard Deviation) Percent Correct Responses in the Semantic Judgment Task*

Bias	Distortion	% Correct (*SD*)
Congruent	Unaltered	96.33 (2.09)
	Filtered	92.67 (5.86)
Incongruent	Unaltered	91.83 (10.20)
	Filtered	93.83 (7.25)

ERPs were analyzed only for those trials in which a correct response was produced in the anomaly detection task. Thus, any modulation of the ERP signal in response to targets in filtered contexts cannot be attributed to participants' being unable to hear and interpret the filtered sentences or to detect semantic congruency or anomaly in the filtered sentences.

ERP Data

Averaged ERP waveforms for congruent and incongruent targets are shown in Figures 1 (unaltered contexts) and 2 (filtered contexts).

N1 (0–200 ms)

Visual inspection of the ERP response in the 0–200-ms window revealed a distinct negative peak (N1) that was more pronounced for targets in filtered contexts (see Figure 2) than unfiltered contexts. A repeated measures ANOVA and simple effects means comparisons confirmed that N1 amplitude was significantly larger for targets in filtered contexts than unaltered contexts, main effect of distortion, $F(1,14) = 13.52$, $p < .01$, $\eta_p^2 = .49$, but

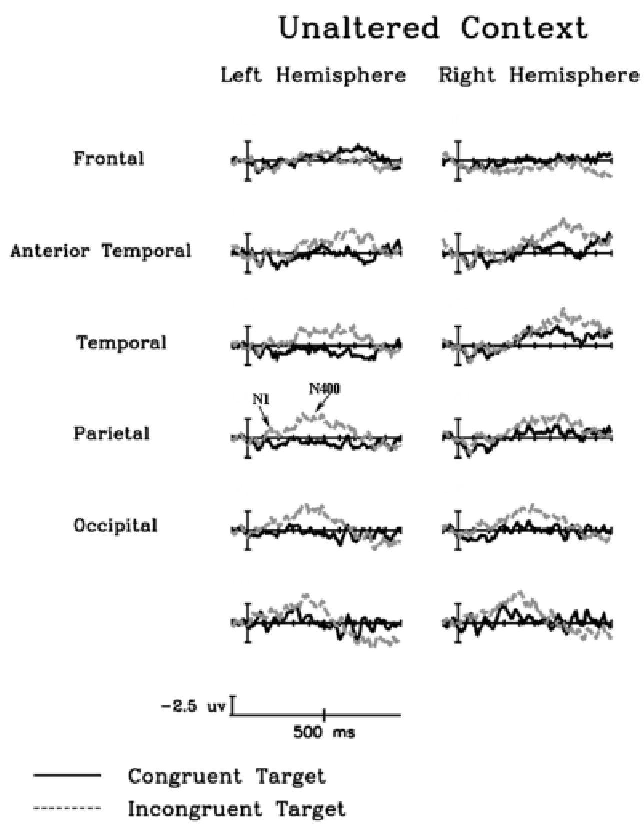

Figure 1. Averaged ERP responses to congruent and incongruent spoken word targets in acoustically intact sentence contexts.

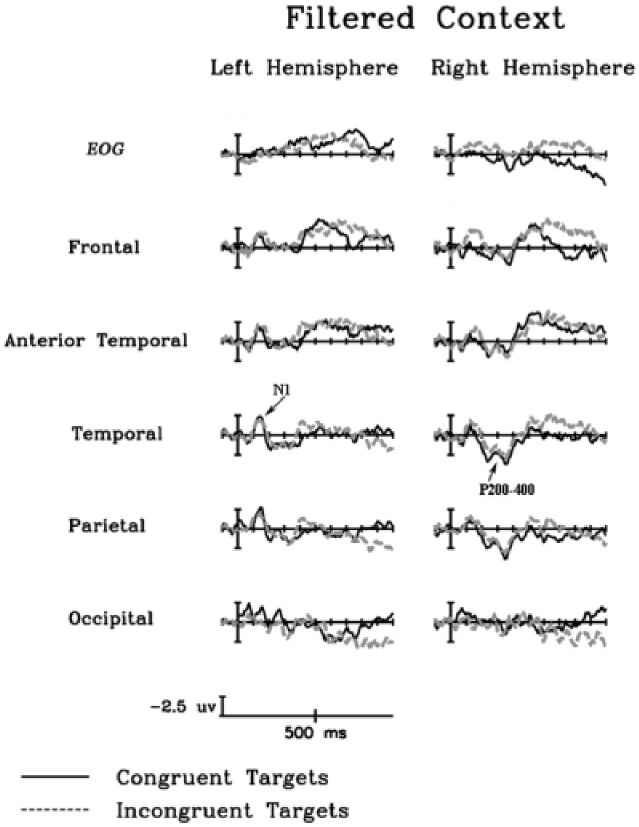

Figure 2. Averaged ERP responses to congruent and incongruent spoken word targets in low-pass filtered sentence contexts.

only over regions anterior to the occiput, Distortion × Electrode Site, $F(4,56) = 4.44$, $p < .05$, $\eta_p^2 = .34$, simple effects for distortion at each electrode site, frontal, $F(1,14) = 10.06$, $p < .01$, $\eta_p^2 = .42$, anterior temporal, $F(1,14) = 10.21$, $p < .01$, $\eta_p^2 = .42$, temporal, $F(1,14) = 15.85$, $p < .001$, $\eta_p^2 = .53$, parietal, $F(1,14) = 7.79$, $p < .01$, $\eta_p^2 = .36$, occipital, $F(1,14) = 0.01$, $p = .93$. Thus, as predicted, the presentation of an unaltered target in a filtered context produced a perceptual ‘‘pop-out’’ effect, resulting in an enhanced N1 response over frontal and temporal electrode sites. This response is illustrated in the bar plot in Figure 3, which shows the peak N1 amplitude in each experimental condition, averaged across all electrode sites. No other significant main effects or interactions emerged.

P200–400

The N1 was followed by an increased posterior positivity to targets in filtered contexts. A repeated measures ANOVA and simple effects comparisons confirmed that the ERP signal was significantly more positive in response to targets in filtered contexts than unfiltered contexts but only over posterior electrode sites, as shown in the bar plot in Figure 4, main effect of distortion, $F(1,14) = 10.52$, $p < .01$, $\eta_p^2 = .43$, Distortion × Electrode Site, $F(4,56) = 5.14$, $p < .05$, $\eta_p^2 = .29$, simple effects for distortion at each electrode site, frontal, $F(1,14) = 0.21$, $p = .65$, anterior temporal, $F(1,14) = .66$, $p = .43$, temporal, $F(1,14) = 19.48$, $p < .001$, $\eta_p^2 = .58$, parietal, $F(1,14) = 39.64$, $p < .001$, $\eta_p^2 = .74$, occipital, $F(1,14) = 21.92$, $p < .001$, $\eta_p^2 = .61$. As in the case of the N1, this positivity was interpreted as a response to the abrupt change in the perceptual characteristics of the target stimulus for unaltered words presented in a filtered context, possibly reflecting the orientation of attention (Escera et al., 1998; Näätänen & Picton, 1987).

A significant Congruency × Hemisphere × Electrode Site interaction also emerged in this analysis, $F(4,56) = 3.48$, $p < .05$, reflecting a more negative response to incongruent targets at left anterior temporal and temporal electrode sites, simple effects for congruency at each electrode site, left hemisphere: frontal, $F(1,14) = 0.54$, $p = .21$, anterior temporal, $F(1,14) = 5.67$, $p < .01$, $\eta_p^2 = .29$, temporal, $F(1,14) = 4.63$, $p < .01$, $\eta_p^2 = .50$, parietal, $F(1,14) = 2.50$, $p < .14$, occipital, $F(1,14) = 0.01$, $p = .93$; right hemisphere: frontal, $F(1,14) = 0.44$, $p = .52$, anterior temporal, $F(1,14) = 0.81$, $p = .38$, temporal, $F(1,14) = 0.45$, $p = .51$, parietal, $F(1,14) = 1.85$, $p = .20$, occipital, $F(1,14) = 0.67$, $p = .43$. As the 200–400-ms time window overlaps with the predicted N400 effect, this interaction was thought to reflect the onset of the N400 response, which is discussed in detail below.

N400 (300–600 ms)

The plot of the ERP response to targets in unaltered contexts (Figure 1) showed a negative component in the 300–600-ms region in the incongruent condition across all electrode sites, which was attenuated in the congruent condition, consistent with previous studies showing an N400 congruency effect for words in a semantic context (Kutas & Hillyard, 1983, 1984). The reduction in N400 amplitude for congruent targets was most apparent over

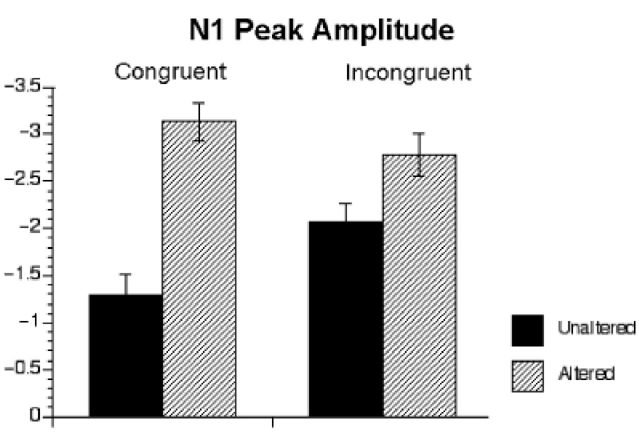

Figure 3. Effect of congruency and low-pass filtering on peak ERP amplitude in the N1 time window (0–200 ms) across all electrode sites.

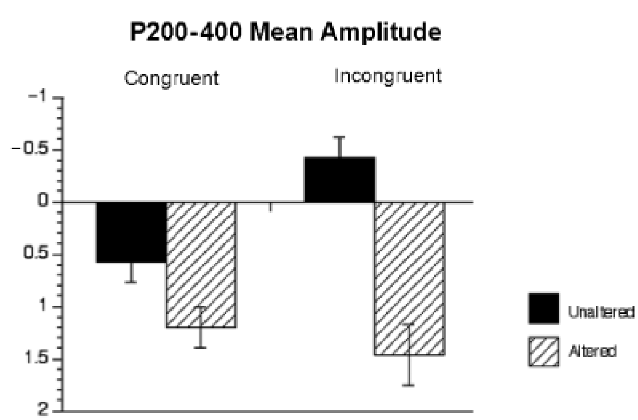

Figure 4. Effect of congruency and low-pass filtering on mean ERP amplitude in the 200–400-ms window across all electrode sites.

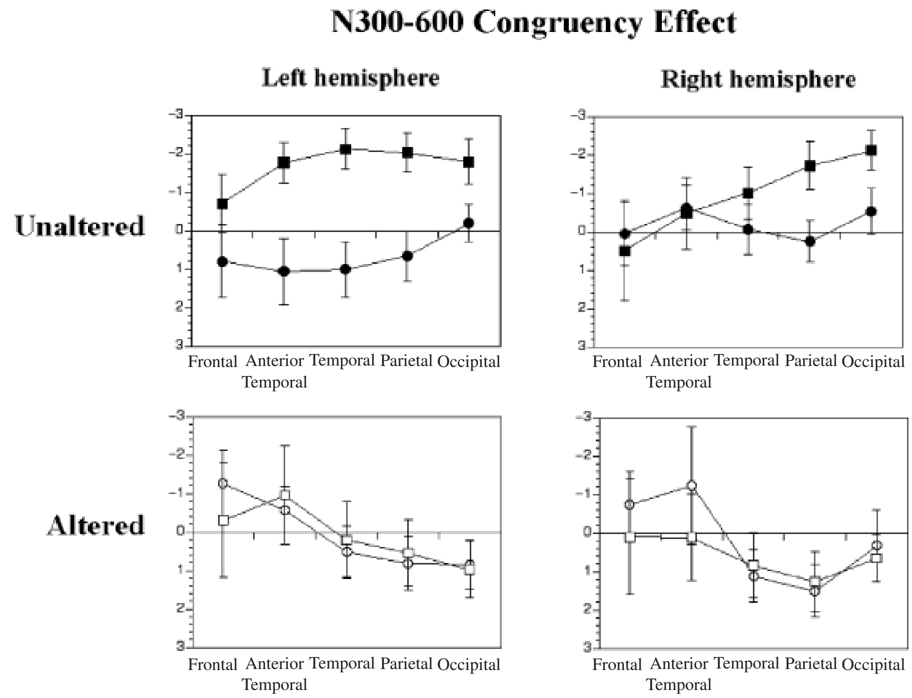

Figure 5. Effect of congruency on mean ERP amplitude in the 300–600-ms window for targets in unaltered (top panel) and filtered (bottom panel) contexts across all electrode sites. Circles: congruent targets, squares: incongruent targets; filled shapes: unaltered contexts, unfilled shapes: altered contexts.

the left hemisphere. A similar, slightly later negative response was observed in the same time window for targets in filtered contexts (Figure 2), but N400 amplitudes for congruent and incongruent targets were less clearly differentiated than in unaltered contexts—this modulation is revealed most clearly in the N400 effect (see below). Targets embedded in the distorted sentences elicited smaller mean amplitude N400s overall than did targets within the undistorted sentences but only over posterior regions, Distortion × Electrode Site, $F(4,56) = 7.62$, $p = .001$, $\eta_p^2 = .35$, simple effects of distortion at each electrode site: frontal, $F(1,14) = .95$, $p = .35$, anterior temporal, $F(1,14) = 0.10$, $p = .76$, temporal, $F(1,14) = 6.43$, $p = .02$, $\eta_p^2 = .31$, parietal, $F(1,14) = 13.30$, $p = .001$, $\eta_p^2 = .49$, occipital, $F(1,14) = 10.85$, $p = .01$, $\eta_p^2 = .44$.

As predicted from previous studies (D'Arcy et al., 2005; Holcomb, 1993), the N400 peaked later in the filtered (486 ms) than the unfiltered (446 ms) condition, main effect of distortion, $F(1,14) = 8.12$, $p = .01$, $\eta_p^2 = .37$. There was no main effect of congruency on N400 latency, $F(1,14) = 0.04$, $p = .84$; nor a Distortion × Congruency interaction, $F(1,14) = 0.38$, $p = .55$.

The apparent difference in the magnitude of the N400 effect between filtered and unaltered sentence contexts was examined in a repeated measures ANOVA. We predicted that the N400 effect would be reduced for filtered contexts relative to unaltered contexts. Line plots showing the average effect of congruency at each electrode site for unaltered and filtered targets are shown in Figure 5. Although the expected Distortion × Congruency interaction was not significant, $F(1,14) = 2.39$, $p = .14$, planned comparisons for the unaltered versus filtered contexts supported the prediction that the N400 effect was reduced in filtered contexts relative to unaltered contexts. In unaltered contexts, N400 amplitudes were significantly larger for incongruent target words than congruent targets, simple effects for unaltered context: congruency $F(1,14) = 5.21$, $p = .04$, $\eta_p^2 = .27$. This effect was larger over the left than the right hemisphere, Congruency × Hemisphere, $F(1,14) = 6.37$, $p = .02$, $\eta_p^2 = .31$. However, in filtered contexts, no significant difference emerged between congruent and incongruent targets at any electrode site, $F(1,14) = 0.07$, $p = .79$ (simple effects of congruency at each

Table 2. *Simple Effects Analysis of Congruency on N300–600 Mean Amplitudes at Each of the 10 Lateral Electrode Sites (Targets in Unaltered Contexts)*

	Left hemisphere			Right hemisphere		
	$F\,(1,14)$	P value[a]	η_p^2	$F\,(1,14)$	P value[a]	η_p^2
Frontal	1.76	.21	.11	0.09	.76	.01
Anterior temporal	9.90	**.01**	.41	0.02	.90	.001
Temporal	21.04	**.001**	.60	1.23	.29	.08
Parietal	18.72	**.001**	.57	7.53	**.02**	.35
Occipital	6.22	**.03**	.31	7.20	**.02**	.34

[a]Bold entries indicate that result is statistically significant at .05 level.

Table 3. *Simple Effects Analysis of Congruency on N300–600 Mean Amplitudes at Each of the 10 Lateral Electrode Sites (Targets in Filtered Contexts)*

	Left hemisphere			Right hemisphere		
	$F\,(1,14)$	P value	η_p^2	$F\,(1,14)$	P value	η_p^2
Frontal	0.45	.51	.03	0.41	.53	.03
Anterior temporal	0.08	.78	.005	0.80	.38	.05
Temporal	0.07	.80	.005	0.14	.72	.01
Parietal	0.07	.79	.005	0.09	.77	.01
Occipital	0.02	.88	.0002	0.11	.74	.01

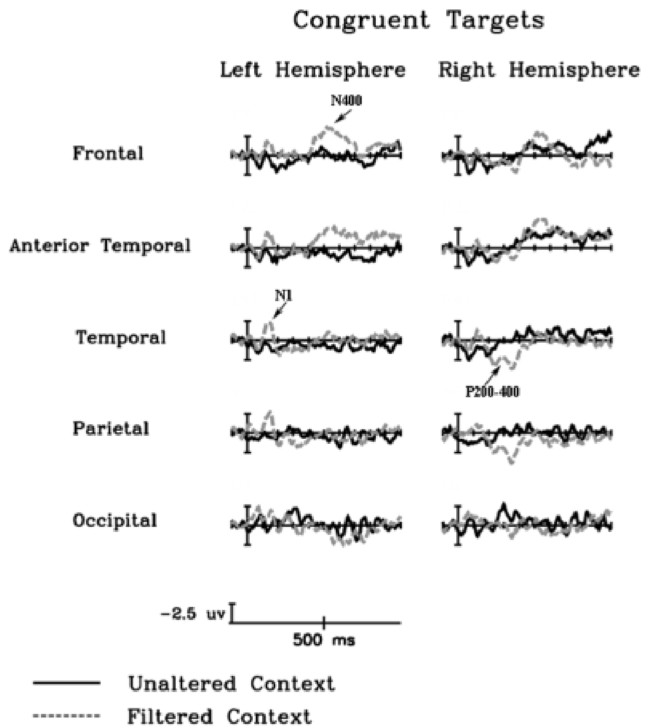

Figure 6. ERPs to congruent targets in the low-pass filtered and acoustically intact contexts.

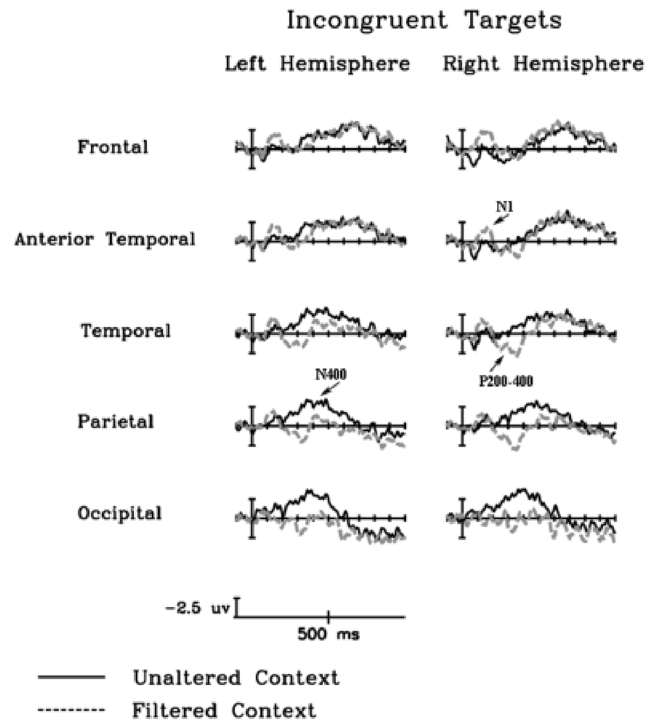

Figure 7. ERPs to incongruent targets in the low-pass filtered and acoustically intact sentence contexts.

electrode site for targets in unaltered and filtered contexts are shown in Tables 2 and 3), and no other interactions were significant. Thus, low-pass filtering of the semantic context eliminated the N400 effect, despite participants' ability to perceive and interpret the filtered sentences (as shown in the anomaly detection task).

To determine whether the effects of filtering of the context differed for congruent and incongruent targets, ERP responses to

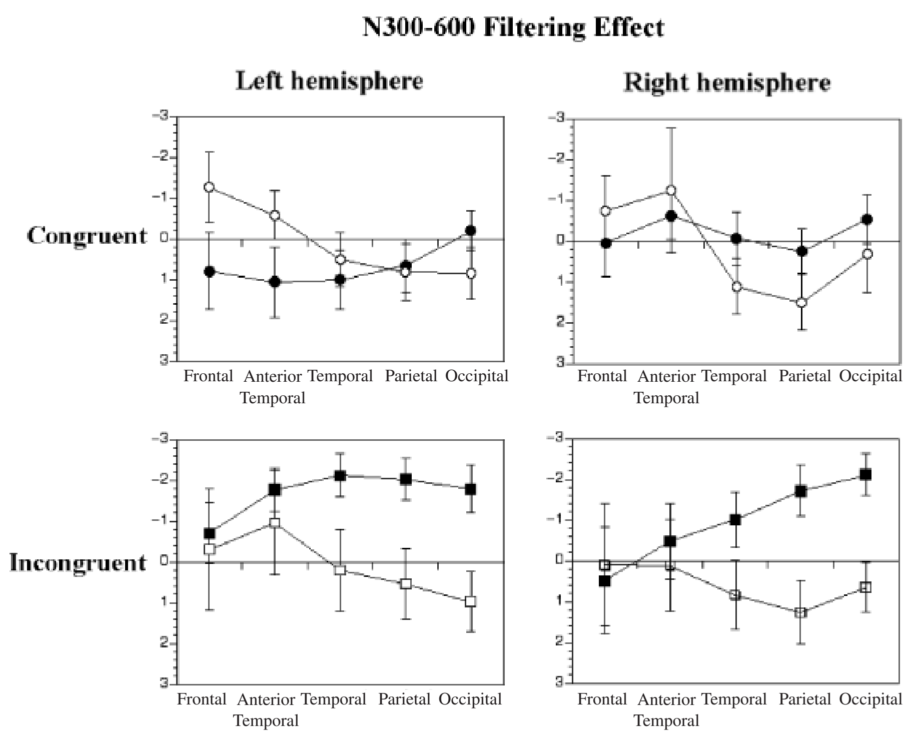

Figure 8. Effect of filtering on mean ERP amplitude in the 300–600-ms window for congruent (top panel) and incongruent (bottom panel) targets across all electrode sites. Circles: congruent targets, squares: incongruent targets; filled shapes: unaltered contexts, unfilled shapes: altered contexts.

Table 4. *Simple Effects Analysis of Filtering on N300–600 Mean Amplitudes at Each of the 10 Lateral Electrode Sites (Congruent Targets)*

	Left hemisphere			Right hemisphere		
	F(1,14)	P value	η_p^2	F(1,14)	P value	η_p^2
Frontal	3.02	.10	.18	0.61	.45	.04
Anterior temporal	2.05	.17	.13	0.13	.72	.01
Temporal	0.26	.62	.02	2.09	.17	.13
Parietal	0.03	.86	.002	2.43	.14	.15
Occipital	3.53	.08	.20	1.46	.25	.09

targets in unaltered and filtered contexts were compared within each semantic congruency condition. The ERP waveform data for congruent and incongruent targets are plotted in Figures 6 and 7. Line plots showing the average congruency effect at each electrode site for unaltered and filtered targets are shown in Figure 8. For congruent targets (Figure 8, top panel), a repeated measures ANOVA Distortion × Electrode Site interaction, $F(4,56) = 4.26$, $p = .02$, $\eta_p^2 = .23$, suggested that filtering of the context modulated the N400 effect over electrode site. Visual inspection of the waveform suggested that the ERP signal was more negative in response to targets in filtered than unaltered conditions over anterior regions of the left hemisphere. However, planned comparisons of the effect of filtering over electrode site showed only a very marginal filtering effect for the left anterior electrode in the 300–600-ms time window (see Table 4 for simple effects by electrode).

In contrast, the ERP response to incongruent targets was *less* negative in the filtered than the unaltered condition in this time window, most notably over posterior regions (Figure 8, bottom panel). This suggests that, as predicted, filtering of the semantic context reduced N400 amplitudes to incongruent targets. Planned simple effects comparisons for the incongruent targets confirmed that the N400 was significantly diminished for targets in the filtered versus unaltered condition over posterior regions bilaterally, simple effects for incongruent context: distortion, $F(1,14) = 5.17$, $p = .04$, $\eta_p^2 = .27$, Distortion × Electrode Site, $F(4,56) = 4.54$, $p = .03$, $\eta_p^2 = .24$; see Table 5 for simple effects by electrode.

Discussion

As predicted, acoustic distortion of the sentence context influenced both the perceptual and semantic response of the ERP signal to target words. The pattern of activity associated with the perceptual response may reflect a shift in attention due to the abrupt change from filtered to intact speech. It is well known that within auditory oddball paradigms, shifts in a variety of different acoustic properties elicit a mismatch negativity (MMN; Takegata, Roggia, & Näätänen, 2003). It is possible that in the current paradigm the filtered speech set up a particular acoustic context that created a mismatch to the unfiltered target. In oddball paradigms requiring a response, the MMN is often followed by a P300. In the present study, intact words in filtered contexts produced an enhanced N1 (MMN), as well as an increased positivity in the 200–400-ms time window relative to words in unaltered contexts. The positivity is most likely a P3 in response to the lower probability of the unfiltered targets embedded in the filtered sentence context. Of particular interest was the semantic response, that is, that the N400 effect to words in context was modulated by acoustic distortion. As the focus of the present study was the effects of perceptual stress on semantic comprehension, this finding will be discussed in greater detail.

Table 5. *Simple Effects Analysis of Filtering on N300–600 Mean Amplitudes at Each of the 10 Lateral Electrode Sites (Incongruent Targets)*

	Left hemisphere			Right hemisphere		
	F(1,14)	P value[a]	η_p^2	F(1,14)	P value[a]	η_p^2
Frontal	0.07	.79	.004	0.06	.80	.004
Anterior temporal	0.47	.50	.03	0.26	.62	.02
Temporal	5.51	**.03**	.28	6.50	**.02**	.32
Parietal	8.29	**.01**	.37	17.97	**.001**	.56
Occipital	9.62	**.01**	.41	11.41	**.001**	.45

[a]Bold entries indicate that result is statistically significant at .05 level.

In accord with previous studies, in the unaltered context the amplitude of the N400 was larger to incongruent than congruent targets (the N400 effect). In contrast, when sentential context was distorted, the N400 effect was significantly attenuated, despite the fact that participants were highly accurate in detecting the semantic anomaly. Thus, these findings demonstrate that acoustic degradation reduces the availability of semantic information in on-line sentence comprehension and directly influences the neural response to words in context, even when the degraded speech is sufficiently intelligible to allow successful off-line interpretation of the sentence meaning.

A similar attenuation of the N400 effect is also reported in aging adults and atypical populations. In neurologically intact elderly individuals, reductions in the magnitude of the N400 effect (also in the auditory modality) are observed, where the N400 to incongruent targets is diminished relative to young adults (Cameli & Phillips, 2000; Kutas & Iragui, 1998). Such a result may be due to less effective and/or slower processing of contextual information—a hypothesis consistent with the results of the present study. The diminution of the N400 effect is more dramatic in the case of low-comprehending aphasic patients with left hemisphere damage (Swaab, Brown, & Hagoort, 1998). Interestingly, such an aphasia-related diminution also appears in tandem with a loss of the Early Left Anterior Negativity (ELAN), associated with early sentential and syntactic processing anomalies (Friederici, von Cramon, & Kotz, 1999). Furthermore, a dramatic reduction of the ELAN amplitude in a very similar paradigm was reported in conjunction with degradation of the acoustical signal, a result complementary to the one we report here (Herrmann, Oertel, Wang, Maess, & Friederici, 2000).

The reduction of the N400 effect in response to acoustic degradation observed in the present study appeared to be driven primarily by the diminished N400 amplitude to incongruent targets in the filtered condition. This suggests that the reduced availability of semantic information as a result of acoustic degradation produces fewer demands on semantic integration in the incongruent condition, such that N400 amplitude is decreased. This interpretation should be taken with some caution, as there was substantial temporal overlap in the perceptual and semantic response to acoustic degradation, particularly for the 200–400- and 300–600-ms time windows. Thus, N400 amplitudes to incongruent targets in degraded contexts are likely to have been influenced to some degree by the P3 response, which was particularly apparent over posterior electrode sites.

In conclusion, the results of this study demonstrate that distortion of the speech signal directly influences the neural response to spoken words presented in a sentence context. Specifically, acoustic degradation decreases the availability of semantic information that would otherwise affect the on-line processing of lexical items by increasing the demand of semantic integration for incongruent targets. Similar patterns have been observed in behavioral and ERP studies of elderly individuals and patients with acquired aphasia, providing further support for the present findings and suggesting that both exogenous perceptual factors and endogenous processing disturbances can produce similar effects on language comprehension. Future studies that utilize the same task to compare the performance of healthy adults processing degraded stimuli to clinical populations should be useful for better understanding the domain-general processing deficits underlying language disorders.

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