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An ERP investigation of dichotic repetition priming with temporally overlapping stimuli

Jonathan Grainger and Phillip J. Holcomb

Abstract

The present study used event-related potentials to examine effects of prime-target repetition using a dichotic priming paradigm. Participants monitored a stream of target words in the right attended ear for occasional animal names, and event-related potentials (ERPs) were recorded to non-animal words that were either unrelated to, or a repetition of, prime words presented to the left ear. Prime words were spoken in a different voice and had a lower intensity than target words, and prime word onset began 50 ms before target word onset. Repetition priming effects were observed in the ERPs starting around 150 ms post-target onset, and continued to influence processing for the duration of target stimuli. These priming effects provide further evidence in favor of parallel processing of overlapping dichotic stimuli, at least up to the level of some form of sublexical phonological representation, a likely locus for the integration of the two sources of information.

Keywords

Spoken word recognition; dichotic priming; repetition priming; ERPs

Introduction

The vast majority of auditory priming studies investigating spoken word recognition have presented prime stimuli prior to target stimuli in close temporal proximity but with no overlap between the two (see Dufour, 2008, for a review). Although interesting patterns of behavioral priming have been observed and have been used to constrain current models of spoken word recognition, one might nevertheless question the sensitivity of this paradigm for revealing on-line processes related to speech perception, and particularly with respect to early perceptual processes. More precisely, the sequential priming paradigm might be useful for understanding processes involving time-invariant phonological representations (sublexical or lexical) that enable integration of information within words prior to word identification, and this is clearly an important goal for research. However, it may be less suited for the study of processing linked to lower-level time-specific phonological representations – that is, phonemes coded for their position in time rather than their position in a word. Given that one of the key questions for current research on spoken word recognition is precisely just how such time-specific phonological information makes contact

with time-invariant, word-centered phonological representations (Hannagan, Magnuson, & Grainger, 2013), the need for more appropriate methodology becomes obvious.

The present study provides an initial exploration of one possible methodology for examining such early processes in spoken word recognition. The three essential ingredients of the paradigm are: i) the dichotic presentation of prime and target stimuli - targets in the attended ear, primes in the other ear; ii) the temporal overlap across primes and targets, and iii) the use of millisecond-by-millisecond measures of priming effects using event-related potentials (ERPs). While earlier studies have demonstrated behavioral repetition priming using a dichotic listening procedure, the goal of the present study was to use ERPs to determine how quickly priming effects arise with temporally overlapping primes and targets. One seminal behavioral study is that of Dupoux, Kouider, and Mehler (2003), who were the first to use a “dichotic priming” paradigm in order to examine the type of information that can be obtained from the unattended ear in a dichotic listening situation. Dupoux et al. (2003) presented prime stimuli to the unattended ear and simultaneously presented target stimuli to the attended ear. Primes were presented at a reduced intensity and could either be surrounded by silence or could be embedded in a carrier sentence of the same spectral and energy levels as the prime. Participants made lexical decisions to targets in the attended ear, and robust inter-aural repetition priming was only found when primes were presented in isolation. Dupoux et al. argued that primes presented in isolation capture attention, enabling processing of the prime stimuli in the unattended ear, and giving rise to priming effects as well as to the conscious identification of primes. When primes were embedded in carrier sentences, there was no attentional capture, primes were not consciously identified, and there was no priming.

However, more recent work has shown that behavioral repetition priming can be obtained with unattended words presented in a continuous speech stream when there is a change in voice across prime and target (Rivenez, Darwin, & Guillaume, 2006). This might be due to the change in voice facilitating the tracking of distinct sound sources over time (Darwin, Brungart, & Simpson, 2003). In any case, the thorny issue of whether or not dichotic priming can be obtained in the absence of awareness of stimuli presented to the unattended ear (Holender, 1986) is orthogonal to the present enterprise. We are specifically interested in the kind of priming effects reported by Dupoux et al. (2003) in their Experiment 1, with isolated primes presented simultaneously with targets. The prime stimuli were temporally compressed such that phonemes in prime and target were not perfectly aligned, although they were spoken in the same voice. Even if prime stimuli were identified in these conditions, the priming effects that were found still require an explanation. According to Dupoux et al. (2003), in these specific conditions, attention might have rapidly switched to the unattended channel in order to enable lexical processing of primes. However, they did not specify how processing of target stimuli would then proceed in the absence of attention, under the assumption that only one channel can be attended at a time. As pointed out by Treisman (1971), it is not obvious how two simultaneously presented dichotic stimuli can be processed together, given the evidence that switching attention between the ears is difficult and takes time.

A number of studies have used event-related potentials (ERPs) to examine various kinds of effects in dichotic listening paradigms (e.g., Bentin, Kutas, & Hillyard, 1995; Hillyard, Hink, Schwent, & Picton, 1973), but to our knowledge the only prior study to investigate repetition priming effects is the one by Okita and Jibu (1998). These authors found a significant reduction in the N400 ERP component in the repetition condition, but only when primes were attended to. However, primes and targets were presented sequentially in that study. This is therefore further evidence for limited processing of unattended stimuli, but does not speak to the issue of how this limited processing can influence the simultaneous processing of attended stimuli. In the current study participants were presented with a spoken prime word in the left “unattended” ear and 50 ms later a spoken target word in the right “attended” ear.¹ The 50 ms SOA was designed to mimic the head start for prime processing in standard masked priming with visual stimuli (e.g., Holcomb & Grainger, 2006). Targets were either a repetition of the prime word (e.g., fire-FIRE, mouth-MOUTH), a completely unrelated word (e.g., mouth-FIRE or fire-MOUTH) or occasionally were “probe” words from a specific semantic category (animals). Participants were instructed to attend to all target words presented in the right attended ear and to press a button whenever such an item was an animal name. ERP recording was time-locked to the onset of all non-probe target words in the attended ear (i.e., target words for which there was no behavioral response, referred to here as “critical” targets).

The timing of the dichotic repetition priming effects to be investigated in the present study will provide important constraints on possible mechanisms driving such effects. Effects arising relatively early in the ERP signal would suggest that attentional switches are an improbable cause of dichotic repetition priming with temporally overlapping stimuli. According to attention-switch accounts of dichotic repetition priming effects, attention would be automatically attracted to the unattended ear upon prime presentation (an exogenous shift of attention), and would then rapidly switch back to the attended ear in order to respect task instructions (an endogenous shift of attention). Information from the unattended ear could then be integrated with on-going processing of target stimuli presented to the attended ear, hence generating priming effects. Given the lowest estimates of the timing of shifts of attention as being around 50 ms for an exogenous shift and 150 ms for an endogenous shift (Lachter, Forster, & Ruthruff, 2004), plus a minimum amount of time processing prime stimuli, one might not expect to see priming effects prior to the N400 time-window.

Method

Participants

Thirty-six volunteers (25 female, mean age = 19.9, SD = 1.6) who were all undergraduate students at Tufts University were paid \$25 to participate in this experiment. All were right-handed native speakers of English.

¹Given the evidence for a right ear advantage in prior research on dichotic listening (e.g., Kimura, 1961), we presented to-be-attended stimuli in that ear in order to further bias processing toward attended stimuli.

Stimuli

The *critical* stimuli for this experiment were 150 pairs of monosyllabic English words digitized at 22KHz and edited for precise word onset (Cooledit 2000k) and overall duration (primes mean duration = 411 ms, target mean duration = 412 ms). The non-critical *probe* stimulus pairs were formed by combining 25 monosyllabic animal names with 25 unrelated monosyllabic words using the same recording parameters. For both the critical and probe items, the first member of each pair was referred to as the *prime* and the second member as the *target*. Stimulus lists consisted of 125 trials each containing a prime-TARGET pair of items. In addition to ear of presentation, primes and targets were differentiated by intensity and speaker gender in order to minimize the physical similarity between repeated items and to enhance attentional separation. Targets were presented in the right ear at a normal conversational listening level (~60 dB SPL) in a female voice. Primes were presented in the left ear at a lower intensity level (-6dB) and were spoken in a male voice. There were 50 critical trials where the target was a repetition of the prime (e.g. fire-FIRE), and 50 other critical trials where the target was unrelated to the prime (e.g. mouth-FIRE). Across two lists, critical target words appeared once in each of the two conditions but within lists each target stimulus was presented once. For the 25 non-critical probe trials, five contained animal names in the unattended prime ear and filler words in the attended target ear while another 20 trials contained unrelated filler words in the unattended prime ear and animal names in the attended target ear.

Procedure

Spoken words were presented via headphones (Sennheiser model PC131) at normal listening levels (attended ear = 60 dB, unattended ear = 54 dB). Each trial began with the onset of the prime word spoken by a male speaker in the unattended ear and was rapidly followed 50 ms later by the onset of a target word spoken by a female speaker in the attended ear (i.e. SOA = 50ms). In order to keep the attentional demands of the task high, trials occurred in rapid succession with an average interval of prime onset between trials of 1 second. Every 30–35 trials there was a short (2 minute) rest break (see Figure 1 for a schematic of typical trial). Participants were asked to refrain from blinking and moving their eyes except during breaks. The animal names served as *probe* items in a go/no-go semantic categorization task in which participants were instructed to attend to the right ear and rapidly press a single button whenever they detected an animal name and to passively listen to all other stimuli (i.e., critical stimuli did not require an overt response). They were not told about the possible occurrence of animal names in the unattended left ear. A practice session was administered before the main experiment to familiarize the participant with the procedure.

EEG recording procedure

Participants were seated in a comfortable chair in a sound attenuated darkened room. The electroencephalogram (EEG) was recorded from 29 active tin electrodes held in place on the scalp by an elastic cap (Electrode-Cap International – see Figure 2). In addition to the 29 scalp sites, additional electrodes were attached to below the left eye (to monitor for vertical eye movement/blinks), to the right of the right eye (to monitor for horizontal eye movements), over the left mastoid bone (reference) and over the right mastoid bone

(recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 k Ω (impedance for eye electrodes was less than 10 k Ω). The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz and the EEG was continuously sampled at a rate of 250 Hz throughout the experiment.

Data analysis

Averaged ERPs were formed off-line from trials free of ocular and muscular artifact (less than 10% of trials). ERPs were calculated by averaging the EEG time locked to a point 50 ms pre-target onset and lasting until 800 ms post-target onset. The 50 ms pre-target period was used as the baseline. Separate ERPs were formed for the two target conditions (targets that were repetitions of their prime words and targets that were unrelated to their prime words). In order to carefully quantify the time-course of repetition effects, mean amplitudes in three contiguous post-target onset latency windows were measured: 150–300 ms (pre-N400), 300–600 ms (N400), and 600–900 ms (post-N400). Repeated measures analyses of variance (ANOVAs) were used to analyze the data from 15 electrode sites (see Figure 2) in each epoch separately. Each ANOVA included a factor of REPETITION (Repetition vs. Unrelated) and two distributional factors of LATERALITY (Left vs. Midline vs. Right) and ANTERIOR-POSTERIOR (FP vs F vs. C vs. P vs. O). We have used this analysis scheme in several previous ERP masked priming studies and it has been shown to provide the best balance between thorough analysis of the time-course and scalp distribution of priming effects with a simple straightforward presentation of results (e.g., Grainger, Lopez, Eddy, Dufau, & Holcomb, 2012). The Geisser-Greenhouse correction was applied to all effects with more than one degree of freedom in the numerator.

Results

Electrophysiological Data

150–300 ms Epoch—In the first epoch there was a main effect of REPETITION ($F(1,35) = 10.97$, $p = .0022$) with targets following unrelated primes producing more negative-going waves than targets following repeated primes. This effect was widespread across the scalp (with the exception of the most frontal sites) as can be seen in Figures 3 and 4 (left).

300–600 ms Epoch (N400)—In the second analysis time window there was no longer a main effect of REPETITION ($p > .46$) although there was a LATERALITY $\times$ REPETITION interaction ($F(2,70) = 4.98$, $p < .0129$) indicating a central-leftward distribution of the priming effect (see Figure 4 middle).

600–900 ms Epoch—In the final analysis window there was a marginal main effect of REPETITION ($F(1,35) = 3.1$, $p = .087$) and a LATERALITY $\times$ REPETITION interaction ($F(2,70) = 6.09$, $p = .0073$). Like the previous epoch the priming effect was somewhat left lateralized (see Figures 3 and 4).

Time-course Analysis—In order to more precisely characterize the temporal properties of repetition priming we also ran a series of analyses on contiguous 50 ms mean amplitude epochs from 100 to 900 ms. These results are presented in Table 1.

Behavioral Data

Post-experiment debriefing of participants revealed that they were aware of words occurring in the unattended ear, but none reported that they had noticed the presence of animal words in this ear. These informal reports are backed up by the animal detection task results.

Participants detected an average of 90% ($SD = 7.6$) of the animal name probe words in the right attended ear. However, no participant pressed to any of the animal names in the left unattended ear.

Discussion

In the present study we presented participants with clearly audible target words in the right (attended) ear and asked them to press a response button as soon as they heard an animal name. Fifty ms before each word presented to the right ear, a prime word was presented to the left (unattended) ear at a lower intensity and spoken in a different voice. Prime words could be the same as targets or totally different words. Animal names were also presented to the unattended ear, and although participants were aware of words being presented to the unattended ear, they never responded to the presence of an animal name in that ear. Our results showed a robust repetition priming effect that emerged about 150 ms post-target onset, and that was present for the entire duration of the target word, although the spatial distribution of priming effects did change slightly over time, becoming more left lateralized in later time windows. This clearly suggests that phonological information was obtained from the unattended ear and influenced the on-line processing of target words in the attended ear. Most important, the relatively early onset of these priming effects, prior to the N400 component, suggests that they are unlikely to be due to attention switches enabling sequential processing of primes and targets.

It is interesting to compare the present findings with those found previously in more traditional dichotic listening experiments with simultaneous presentation of stimuli to each ear, and in particular with respect to the phenomenon known as “phonological fusion” (Cutting, 1976; Sexton & Geffen, 1981). This phenomenon refers to the kind of errors participants make in a dichotic listening paradigm with simultaneous presentation, such as reporting hearing “black” upon presentation of “back” and “lack”. Cutting (1976) observed that phonological fusion is sensitive to phonetic characteristics but is relatively insensitive to nonlinguistic acoustic factors, and therefore concluded that it involved the combination of phonemes from both ears into a unitary percept. Later work by Kolinsky, Morais, and Cluytens (1995) provided further support for a relatively high-level locus of such phonological fusions. Kolinsky et al. presented pseudoword stimuli simultaneously to both ears, and asked their participants to indicate whenever they heard a word. A large number of illusory words were reported when the word was formed as a re-combination of the syllables of the pseudowords, such as reporting “cotton” when hearing “collan” and “bitton”. Kolinsky et al. argued that their results pointed to syllables as the key representation involved in inter-aural integration (see Mattys & Mellhorn, 2005, for further evidence).

What might be the mechanism(s) behind dichotic priming and phonological fusion effects? Dupoux et al. (2003) suggested that attention switches might be driving the dichotic priming effects they observed, with attention directed to the prime being a necessary condition for

obtaining these effects. However, the timing of the dichotic repetition priming effects found in the present study point to attention switches as an unlikely locus of these effects, even when applying the lowest estimates of the timing of such switches. Treisman (1971) had already nicely summarized the key issue here in reference to research described in Treisman (1970; 1971) and earlier work on dichotic listening: “If switching between the ears with alternating stimuli is difficult, as the present experiments suggest, how can it lead to so many spontaneous, apparently unavoidable errors in experiments with simultaneous presentation?” Today, many would agree that the answer lies in the quite extensive processing that is performed on information arriving in the unattended ear, and the way this information can be integrated with simultaneously processed information in the attended ear. Here we tentatively propose a straightforward extension of a recent model of spoken word recognition, the TISK model (Hannagan et al., 2013), as a possible solution to Treisman’s paradox, and as an account of the present findings.²

The backbone of our tentative explanation is the work performed by low-level speech analyzers that receive the auditory signal as input and generate output representations (probably phonemes) that are both *time-specific* (as postulated in TISK) and *source-specific* (an extension of TISK). Thus a given phoneme /p/ is tagged for its temporal location in echoic memory (/p/ at time-slot t in the memory loop) and tagged for the source that generated the input (/p/ from source x). The source-specific nature of such analyzers would enable parallel processing of different speech inputs at a cocktail party. Attention then determines how much this information is used for conscious identification of the speech signal by modulating the relative weight assigned to the different sources as time-specific and source-specific phonemes are mapped onto higher-order time-invariant and source-invariant sublexical phonological representations that code for the order of phonemes in a word rather than their position in time, or the location of their source. It is at this higher-level of representation that phonological fusions arise, and that processing of target words in the attended ear in the present study is influenced by phonological information extracted from the unattended ear.

In conclusion, we examined repetition priming effects in a dichotic priming paradigm where prime stimuli were presented to the unattended ear, at lower intensity, spoken in a different voice, and 50 ms prior to target stimuli presented to the attended ear. We found an early priming effect starting at around 150 ms post-target onset, as well as prolonged effects of repetition priming on the N400 component. The early effect of prime-target relatedness suggests that sublexical phonological information is extracted from the unattended ear and either integrated with sublexical phonological information extracted from the attended ear, or at the very least used to determine whether or not these two sources of information match or not. One obvious next step would be to examine the effects of different types of prime-target overlap (e.g., onset vs. rime overlap) in the dichotic priming paradigm. In general, we expect this future work to provide valuable insights with respect to describing the

²It has not gone unnoticed that the early dichotic repetition priming effect found in the present work resembles the mismatch negativity (MMN) effect found in ERP studies using the so-called oddball paradigm (e.g., Näätänen, 1999), both in terms of the timing and the spatial distribution of these effects. The MMN is thought to require habituation to a standard (i.e., massively repeated) stimulus prior to presentation of the deviant stimulus that generates an increased negativity. Clearly this is not the case in the present study where repeated and different stimuli were equiprobable.

mechanisms that enable speech information that is initially represented in time, to make contact with time-invariant phonological representations.

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Figure 1.

The dichotic priming paradigm (top). A sequence of six trials (bottom). Lowercase is used to represent the lower intensity of stimuli presented to the unattended (left) ear, and the slightly higher location of these stimuli represents their earlier (50 ms) onset compared with stimuli in the attended (right) ear. In the top panel, the animal name probe words are shown in red (in the right attended ear these were the to-be-responded to items).

Figure 2.
Electrode montage and sites used in the analyses (darker circles).

Figure 3.

Grand average ERP waveforms from the 15 scalp sites used in the analyses of the data. The X-axis represents milliseconds from target word onset, and negative values are plotted up on the Y-axis.

Priming Effect in 3 Epochs

Figure 4.

Topographic maps showing average voltage differences (unrelated condition minus repetition condition) across all electrode sites for the three analysis epochs. The colorbar is a microvolt scale.

p-values from a time-course analysis showing main effects of Repetition and interactions of this factor (R) with the Laterality (L) and Anterior-Posterior (AP) distributional factors at consecutive 50 ms epochs from 100 ms to 900 ms post-target onset.

Table 1

	100–150	150–200	200–250	250–300	300–350	350–400	400–450	450–500	500–550	550–600	600–650
REPETITION	0.350	0.002	0.006	0.090	0.280	0.690	0.950	0.530	0.880	0.280	0.
R × L	0.260	0.500	0.044	0.080	0.037	0.150	0.190	0.027	0.036	0.003	0.
R × AP	0.760	0.250	0.100	0.320	0.310	0.120	0.530	0.210	0.400	0.360	0.