

ERP correlates of the irrelevant sound effect

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Abstract

The irrelevant sound effect refers to a decrement in serial-recall performance when auditory distractors are played during encoding or retention of the to-be-remembered items. We examined the event-related brain potentials (ERPs) that were elicited in response to the auditory distractors during encoding and retention of visually presented target sequences. Changing-state distractor sequences that consisted of several different distractor items interfered more with serial recall than steady-state sequences that consisted of repetitions of a single distractor item. The ERP responses that were elicited in response to the distractors comprised the exogenous N1 component and were further characterized by a subsequent positive wave, and a late negativity. The changing-state effect was associated with an increased N1 and a P3a. The results support the attention-capture account of the irrelevant sound effect.

Descriptors: Auditory evoked potentials, Auditory distraction, Attentional capture, Working memory

The irrelevant sound effect refers to the disruption of serial recall due to the presentation of auditory distractors. In the standard paradigm, participants are required to recall lists of items (digits, consonants, or words) that are sequentially presented in the visual modality. During presentation of these items or during a short retention phase, irrelevant sounds are played. Participants are required to recall the items in the order of their presentation. Typically, irrelevant sound decreases serial recall considerably relative to a silent-control condition. It is well established that the main determinant of the size of the irrelevant sound effect is the number of “changing states” (roughly defined as abrupt changes in pitch and amplitude) in the auditory channel (Campbell, Beaman, & Berry, 2002; Jones & Macken, 1995; Jones, Madden, & Miles, 1992). For instance, continuous random pitch glides fail to disrupt serial recall, but the same glides when interrupted by periods of silence interfere with recall (Jones, Macken, & Murray, 1993). Steady-state sequences that consist of repetitions of a single distractor disrupt serial recall to a lesser extent than changing-state sequences that consist of several different distractors (Jones et al., 1992). Besides, disruption is enhanced when the to-be-ignored sound sequence contains a single deviant that differs significantly from the other distractors in the sequence (Lange, 2005). Although speech stimuli usually interfere with serial recall more than non-speech stimuli (sine wave tones, environmental sounds; Buchner, Bell, Rothermund, & Wentura, 2008; LeCompte, Neely, & Wilson, 1997), those studies that have controlled the transient characteristics of the stimulation found

equivalent irrelevant sound effects for speech and non-speech distractors (Jones & Macken, 1993; Tremblay, Nicholls, Alford, & Jones, 2000). It is assumed that irrelevant sound interferes with the maintenance of the to-be-remembered items in working memory because the magnitude of interference does not change regardless of whether the to-be-ignored stimuli are played during encoding or retention of the target material (Buchner, Rothermund, Wentura, & Mehl, 2004; Miles, Jones, & Madden, 1991).

Currently, several working-memory models compete for the best explanation of the irrelevant-sound effect (Cowan, 1995; Jones, 1993; Neath, 1999; Salamé & Baddeley, 1982). These theories fall into one of two categories depending on whether they specify a role for attention in the maintenance of information or not (Elliott, 2002). Both the modular working memory model (Baddeley & Hitch, 1974) and the object-oriented episodic record model (Jones, 1993) imply that (a) attention is not needed for the maintenance of information within working memory and (b) attentional distraction does not play a role in the irrelevant sound effect. The embedded processes model (Cowan, 1995), in contrast, implies that the irrelevant sound effect is due to attentional capture. According to this view, unexpected changes in the auditory modality elicit orienting reactions that draw the focus of attention away from the primary task of maintaining the representations of the target items in a highly accessible state. According to this model, steady-state distractors cause less memory disruption than changing-state distractors because the orienting response habituates to repeated stimulation. Only new or changing sounds have to be attended because they may be important to the organism. Thus, the habituation of the orienting response serves as an attentional filter. Another prediction of the model is that auditory distractors that are of relevance for the individual should be more likely to capture attention, thereby increasing the interference effect. Consistent with this hypothesis, the content of the auditory

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distractors enhances interference when it is of relevance to the individual (Bell, Mund, & Buchner, in press; Buchner, Mehl, Rothermund, & Wentura, 2006; Buchner et al., 2004).

A separate line of research has also advanced our understanding of auditory distraction and may provide some insights into the mechanisms underlying the performance decrement in the irrelevant-sound paradigm. There are a number of studies examining event-related brain potentials (ERPs) that occur in response to abrupt changes in the to-be-ignored auditory modality. Typically, the ERPs elicited by rare, novel, or varying stimuli in the ignored auditory modality comprise an N1 component as is typical for auditory stimuli in general and are further characterized by a subsequent positive wave (P3a), and a late negativity. It has been proposed that these components are sensitive to, or might even reflect, different stages of involuntary attention switching (Bendixen, Roeber, & Schröger, 2007; Escera, Alho, Winkler, & Näätänen, 1998; Escera & Corral, 2007).

First, the N1 is elicited even if the auditory modality is to be ignored, and participants focus on a visual primary task such as reading a book or watching a silent movie (Näätänen, 1990; Näätänen & Picton, 1987; Näätänen & Winkler, 1999). It is distributed mostly over frontocentral areas of the scalp. The N1 response is primarily determined by the amount of physical change in the auditory environment. When the amount of “changing states” is controlled, different types of auditory stimuli such as tones, speech, and environmental sounds elicit very similar N1 responses (Näätänen & Picton, 1987). The N1 is modulated by stimulus-nonspecific and stimulus-specific refractoriness effects. Stimulus-nonspecific refractoriness refers to a decrement of the N1 due to any prior acoustic stimulation. A large N1 response is elicited by the first auditory stimulus in a sequence of auditory events after a long period of silence. N1 responses to subsequent stimuli are usually much smaller (Näätänen, 1990; Näätänen & Picton, 1987). Stimulus-specific refractoriness refers to a decrement of the N1 to an auditory stimulus due to the presentation of identical or very similar preceding stimuli (Näätänen & Picton, 1987; Opitz, Schröger, & von Cramon, 2005; Schröger & Wolff, 1998). N1 refractoriness increases and N1 amplitude attenuates with stimulus repetition. Functionally, the N1 is often associated with a “call for attention.” It is assumed that the N1 generator triggers an attention switch to the auditory stimulus when the N1 response exceeds a threshold (e.g., Campbell, Winkler, Kujala, & Näätänen, 2003; Näätänen, 1990; Näätänen & Picton, 1987; Rinne, Särkkä, Degerman, Schröger, & Alho, 2006).

If the to-be-ignored auditory stimulus deviates from a preceding repetitive stimulus sequence, a mismatch negativity (MMN) is elicited (Schröger & Wolff, 1998). The MMN refers to the difference between the ERP to the unexpected deviant and the repetitive standard stimulus. The MMN is a frontocentral component and has a somewhat longer latency than the N1. The MMN has also been associated with a call for attention (e.g., Schröger & Wolff, 1998).

In response to novel, unexpected, or changing task-irrelevant auditory stimuli, the N1/MMN complex is often followed by a subsequent positive wave with a frontocentral scalp distribution. This P3a is associated with an orienting response to the eliciting stimulus (Friedman, Cycowicz, & Gaeta, 2001; Polich, 2007). It is assumed that this orienting response coincides with a conscious evaluation of the auditory stimulus. The P3a is often observed alongside higher error rates and increased reaction times in the primary tasks (Escera et al., 1998; Escera, Yago, & Alho, 2001; Schröger & Wolff, 1998). In some studies, the P3a response was

followed by a late negativity with a frontal maximum (e.g., Escera et al., 2001). This negative deflection has been termed reorienting negativity (RON) based on the assumption that the component may—at least in part—reflect a reorienting of attention back to the primary task (Bendixen et al., 2007; Berti, 2008a; Escera et al., 2001).

There are only a few studies that have examined electrophysiological correlates of the irrelevant sound effect (Campbell, Winkler, & Kujala, 2007; Campbell et al., 2003; Kopp, Schröger, & Lipka, 2004, 2006; Martin-Loeches & Sommer, 1998; Weisz & Schlittmeier, 2006). Most of these studies examined brain responses associated with the processing of the target stimuli, but not the distractor stimuli. Recently, Campbell et al. (2003) observed that the N1 to changing-state distractors was increased in comparison to the N1 elicited by steady-state distractors. The difference between the changing-state and the steady-state condition was explained by a stimulus-specific refractoriness of the supratemporal N1 component. In a subsequent study, Campbell et al. (2007) compared the ERPs elicited by changing-state distractors with those elicited by rare deviants in steady-state sequences. Again, they found an increased N1 elicited by changing-state sounds (as compared to the N1 elicited by steady-state distractors). A MMN was observed only in the deviant condition, consistent with other results suggesting that the MMN is only found if a neural model that is based on the regularities in the auditory environment is violated. In both studies, the auditory distractors elicited no P3a. Based on this finding, the attention-capture account of the irrelevant sound effect was rejected. More specifically, Campbell et al. (2007) suggest that the lack of an increase in P3a alongside with the increase in irrelevant-speech interference means that the memory disruption observed in their study “relies on different mechanisms than those commonly observed for distraction in studies employing the oddball paradigm [and] may be taken as a sign that the current form of memory disruption does not require attentional capture” (p. 538; see Campbell et al., 2003, for a similar claim).

However, the lack of a P3a could also be attributed to the fast presentation rate that was used in these studies. In Campbell et al.’s (2007) study, the auditory distractors were presented for 100 ms with a silent inter-distractor-interval of 227 ms. In other words, the interval between the onsets of two consecutive stimuli was 327 ms. Thus, it is possible that the components of consecutive distractors may have overlapped, which may have decreased the likelihood of finding significant differences in the amplitudes of later components such as a P3a with a to-be-expected latency of about 250 ms (e.g., Escera et al., 2001). The finding of a P3a due to changing-state distractors in the irrelevant-speech paradigm would fit to previous results showing a P3a and a RON in response to varying changing-state distractor stimuli comprising no regularity (Bendixen et al., 2007), which were interpreted in terms of distraction. Thus, it is possible that similar effects can also be obtained in the irrelevant speech paradigm (for evidence that the P3a is not necessarily confined to the oddball paradigm, see, for example, Berti, 2008b).

The purpose of the present study was to replicate the findings of Campbell et al. (2003, 2007) using a somewhat slower presentation rate so as to allow for a better measurement of later ERP components such as the P3a. The experiment was a typical irrelevant-sound experiment. Participants were required to serially recall lists of digits. To-be-ignored sequences of auditory distractors were played during encoding and retention. The distractor sequences consisted either of repetitions of a single

one-syllable distractor word (steady state) or of seven different distractor words (changing state). We expected to find an irrelevant sound effect, that is, a decrement of serial-recall performance due to the presentation of auditory distractors. We also expected to replicate the changing-state effect, that is, worse recall performance in the changing-state condition than in the steady-state condition. With respect to the ERP data, we expected to replicate the finding of Campbell et al. (2003, 2007) that the increase in interference due to changing-state distractors is accompanied by an increase in the N1 amplitude. The most interesting question was whether we would observe a P3a response that would be indicative of an attention switch to the auditory modality.

Method

Participants

EEG recordings and behavioral data were obtained from 40 persons. Six data sets were excluded from the analyses because of muscular artifacts in almost every trial. The remaining 34 participants (24 female, 10 male) were aged between 18 and 40 years ($M = 25$). Participants were German native speakers and had no history of neurological disorders or hearing disabilities.

Stimuli and Procedure. The visually presented, to-be-remembered lists consisted of eight digits sampled randomly without replacement from the set {1, 2, 3, 4, 5, 6, 7, 8, 9}. A total of 50 such lists were generated for each participant, with 15 lists in each of the three different conditions (*silent control*, *steady state*, *changing state*), and five lists for the training trials. The items were presented at the center of a 22-inch CRT screen. The numbers were written in white Arial font on a black background. Viewing distance was approximately 100 cm, although head position was not constrained. At this distance, each target digit subtended about 1.0° horizontally and 1.5° vertically.

Distractor sounds were seven one-syllable German nouns (Bug [bu:k], Eid [a:ɪt], Norm [nɔʁm], Reiz [ra:ɪts], Sieb [zi:p], Tausch [taʊʃ], Term [tɛʁm]; German pronunciation in brackets) with a mean frequency of 8/1,000,000 according to the German language corpus available in the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). Information about the valence and concreteness of the distractor words was obtained in an independent norming study ($N = 34$). Mean valence of the distractor words (on a scale ranging from -10 [extremely unpleasant] to +10 [extremely pleasant]) was 0 ($SD = 1$). Mean concreteness of the distractor words (on a scale ranging from 1 [very abstract] to 20 [very concrete]) was 10 ($SD = 4$). All word recordings were spoken by the same female voice, digitally recorded at 44.1 kHz using 16-bit encoding, edited to last 570 ms, and normalized to minimize amplitude differences among the words. The sounds were delivered binaurally through headphones (Sennheiser OMX 90 VC Style, Wedemark, Germany). The average sound level was about 65 dB(A).

The experiment began with five practice trials, in which eight visually presented digits had to be remembered after a short retention phase. Each of the eight target digits was presented for 800 ms with a 200-ms blank inter-stimulus-interval. The retention phase after each list was 8,000 ms long (i.e., it was as long as the encoding phase during which the targets were presented). Throughout the retention phase, a fixation cross was shown. Following the retention phase, eight question marks appeared on the screen, corresponding to the eight serial positions of the visual targets. This was the signal for the participants to commence

recalling the list items in the order of presentation. The digits were entered via the number keys of the computer keyboard. Typing the first digit replaced the first question mark with that digit, typing the second digit replaced the second question mark, and so on. Participants were required to press a button labeled “don’t know” (the “0” key on the number keypad) for each digit they could not recall. As is usual in many irrelevant-sound experiments, including our own (Bell & Buchner, 2007; Buchner et al., 2008; Buchner & Erdfelder, 2005; Buchner, Irmen, & Erdfelder, 1996; Buchner et al., 2004), participants were allowed to correct their responses. The arrow keys of the computer keyboard could be used to move the current selection to another position at which any prior entry could be replaced. After replacing all of the question marks by numbers or “don’t know” responses, the participants were asked to initiate the next trial by pressing the spacebar. If the spacebar was pressed before all question marks were replaced, a 1,500-ms visual warning was shown.

In the distractor conditions, the first distractor started 170 ms prior to the presentation of the first target stimulus to ensure that the onsets of the target and distractor stimuli were uncorrelated (see Figure 1). The auditory distractors were presented for 570 ms with a silent 230-ms inter-distractor interval. Presentation of the distractors continued throughout the retention phase. Ten distractors were played in the encoding phase, and 10 distractors were played in the retention phase. In the steady-state condition, the to-be-ignored sequences consisted of 20 repetitions of a single distractor word. The distractor word was randomly selected from the set of seven distractor words. In the changing-state condition, the to-be-ignored sequences consisted of all seven words of the distractor set that were randomly ordered and repeated until all 20 distractors were presented.

EEG recordings and data analysis. An elastic cap with predefined electrode positions (Falk-Minow-Services, Munich, Germany) was mounted on the participant’s head. The 30 active silver-silver chloride electrodes were referenced to linked earlobes, with impedance kept below 5 k Ω . Vertical and horizontal electro-oculograms (EOGs) were recorded to control for ocular artifacts. The difference potential between two electrodes placed above and below the right eye provided the vertical EOG. The horizontal EOG was calculated as the difference potential between two electrodes placed at the outer canthi of the right and left eye. Biosignals were recorded continuously (NuAmps 40 channel digital DC EEG amplifier, Neuroscan, Singen, Germany) sampled at 500 Hz, and online band pass filtered (0.1 to 40 Hz). Offline, EEG data were filtered (0.5–30 Hz, –24 dB cut-offs), segmented according to each distractor sound onset (–200 to 570 ms epoch length), and baseline corrected (–200 to 0 ms). Ocular (vEOG, hEOG) artifacts were corrected based on the algorithm proposed by Gratton, Coles, and Donchin (1983). Single electroencephalogram (EEG) sweeps containing muscular artifacts were removed based on visual inspection. The remaining sweeps were averaged according to the distractor condition (*silent control*, *steady state*, *changing state*), presentation phase (*encoding phase*, *retention phase*), and electrode position. ERP analysis of serial position had to be omitted due to insufficient segment numbers.

Three time windows were determined as regions of interest (N1: 80–170 ms, P3a: 200–350 ms, late negativity: 380–490 ms). Mean reference-to-baseline amplitudes within these windows were computed for each participant, distractor condition, presentation phase, and electrode. To examine topographical effects systematically, the electrodes were split according to their

Visual Target Stimuli									
3	5	8	7	1	6	4	9	+	???????
Auditory Distractors									
Silent Control									
-	-	-	-	-	-	-	-	-	-
Steady State									
"Bug"	"Bug"	"Bug"	"Bug"	"Bug"	"Bug"	"Bug"	"Bug"	"Bug"	"Bug"
Changing State									
"Norm"	"Bug"	"Tausch"	"Eid"	"Sieb"	"Term"	"Reiz"	"Norm"	"Bug"	"Tausch"
Encoding Phase				Retention Phase				Recall Phase	

Figure 1. Schematic illustration of a trial. The upper row depicts an example of a sequence of visual target events. The lower rows depict examples for the sequences of auditory distractors in the silent-control condition (second row), steady-state condition (third row), and changing-state condition (fourth row).

caudality (anterior, central, posterior) and laterality (left, medial, right) into nine clusters of electrodes of approximately the same size (left anterior [LA; Af3, F3, F7], medial anterior [MA; Fz, Fc1, Fc2], right anterior [RA; Af4, F4, F8], left central [LC; Fc5, C5, C3, Cp5], medial central [MC; Cz, Cp1, Cp2], right central [RC; Fc6, C4, C6, Cp6], left posterior [LP; P3, P7, O1], medial posterior [MP; Pz, Po3, Po4, Oz], and right posterior [RP; P4, P8, O2]), as is often done in studies examining auditory selective attention (Mayr, Niedeggen, Buchner, & Orgs, 2006; Mayr, Niedeggen, Buchner, & Pietrowsky, 2003). This has been proven to be a good compromise between spatial resolution and reliability of the measures.

Design

The independent variables for the behavioral data were distractor condition (*silent control, steady state, changing state*) and serial position. The dependent variable was serial-recall performance, which was scored according to a strict serial-recall criterion.

For the ERP data, only two levels of the distractor-condition variable—the steady-state condition and the changing-state condition—were of theoretical interest. Given that in most irrelevant-speech experiments the auditory distractors are presented concurrently with the visual, to-be-remembered items (Bell et al., in press; Buchner & Erdfelder, 2005; Buchner et al., 1996, 2006; LeCompte et al., 1997; Salamé & Baddeley, 1982), we were most interested in what happens during the encoding phase, which is why the statistical analysis will focus primarily on the encoding phase. The design included distractor type (*steady state, changing state*), electrode caudality (*anterior, central, posterior*), and electrode laterality (*left, medial, right*) as independent variables. This 2 × 3 × 3 design was considered separately for each of the three different time windows (80–170 ms, 200–350 ms, 380–490 ms).

A multivariate approach was used for all within-subjects comparisons. In our applications, all multivariate test criteria correspond to the same (exact) *F* statistic, which is reported.

Results

Serial-Recall Performance

Figure 2 illustrates the serial-recall performance in the three experimental conditions. A 3 × 8 repeated measures multivariate analysis of variance (MANOVA) with distractor type and serial position as independent variables showed significant main effects of distractor type [$F(2,32) = 38.55, p < .01, \eta^2 = .71$], and of serial position [$F(7,27) = 35.20, p < .01, \eta^2 = .90$]. We used orthogonal contrasts to test more specific hypotheses about the effects of the different distractor types. The first of these orthogonal contrasts showed that the difference between the silent-control condition and the two distractor conditions combined was significant [$F(1,33) = 76.05, p < .01, \eta^2 = .70$], confirming that there was a typical irrelevant sound effect. Performance in the changing-state condition was significantly worse than performance in the steady-state condition, showing that there was also a changing-state effect [$F(1,33) = 19.56, p < .01, \eta^2 = .37$].

ERP Data

First the ERPs evoked by the auditory distractors in the encoding phase were analyzed. The grand-averaged ERPs are depicted in the upper panel of Figure 3. In line with previous findings examining the ERPs to auditory distractors (Escera et al., 1998; Escera & Corral, 2007), the electrophysiological activity generated by the auditory distractors was characterized by a prominent N1 peak, a subsequent positivity, and a late negative component. Mean amplitudes of the ERPs with *t* statistics for significant differences from zero are shown in Table 1. The ERP components differed between the steady-state and the changing-state distractor conditions. The difference waveforms between these two conditions are shown in Figure 4.

Mean amplitudes were submitted to a distractor type (*steady state, changing state*) × caudality (*frontal, central, posterior*) × laterality (*left, medial, right*) MANOVA, separately for each temporal ERP epoch. In order to keep the Results section concise, we report only main effects of the distractor-type variable

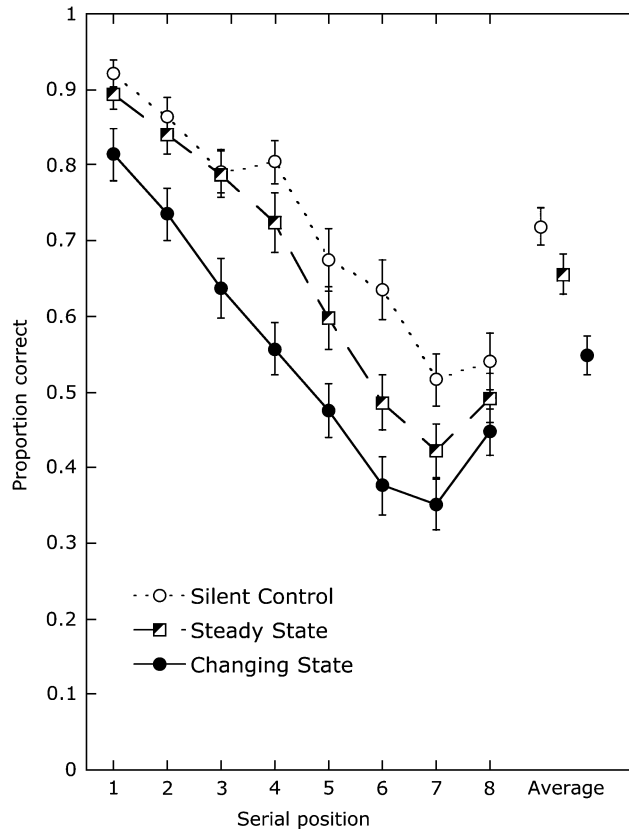


Figure 2. Mean proportion of digits correctly recalled as a function of distractor type and serial position (left panel) and averaged across serial positions (right panel). The error bars represent the standard errors of the means.

and significant interactions involving the distractor-type variable which are theoretically most relevant. First, we examine the N1 negativity. N1 amplitudes were larger for changing-state distractors than for steady-state distractors [$F(1,33) = 5.12, p = .03, \eta^2 = .13$]. There was also a significant interaction between distractor type, caudality, and laterality [$F(4,30) = 4.04, p = .01, \eta^2 = .35$]. This interaction reflects the fact that the effect of distractor type was maximal at medial central and medial anterior electrodes.

The N1 was followed by a subsequent positivity (see Table 1) that was most pronounced at frontal electrodes. Most importantly, there was a much larger positive deflection for changing-state distractors than for steady-state distractors [$F(1,33) = 21.44, p < .01, \eta^2 = .39$]. A significant distractor type \times caudality interaction [$F(2,32) = 33.28, p < .01, \eta^2 = .68$] primarily reflected the fact that the increase in positivity in the changing-state condition was most pronounced at frontal sites.

The positive wave was followed by a late negativity (see Table 1) that was maximal at central and medial electrodes. There was no significant effect of distractor type [$F(1,33) = 0.53, p = .47, \eta^2 = .02$], but a significant interaction between distractor type and caudality [$F(2,32) = 7.12, p < .01, \eta^2 = .31$], and a significant three-way interaction between distractor type, caudality, and laterality [$F(4,30) = 3.06, p = .03, \eta^2 = .29$], indicating a more pronounced negativity at medial, central electrodes in the changing-state than in the steady-state condition.

The lower panel of Figure 3 displays the grand-averaged ERPs evoked by the auditory distractors in the retention phase.

As is evident, N1 amplitudes were much smaller in the retention phase than in the encoding phase. There may be several reasons for this finding. In part, the reduction of the N1 in the retention phase may be due to stimulus-nonspecific refractoriness effects (see Näätänen, 1990; Näätänen & Picton, 1987; Woods & Elm-Asian, 1986) given that the encoding-phase distractor sequence was presented after a period of silence, whereas the retention-phase distractor sequence immediately followed the encoding-phase distractor sequence. Note that even the changing-state distractors had several features in common (e.g., voice, duration, inter-stimulus interval), which might have amplified the refractoriness effect. Furthermore, given that the silent-control baseline was more negative in the encoding phase, the concurrent presentation of the visual target items in the encoding phase as opposed to concurrent target rehearsal during the retention phase may have led to a positive shift of the N1 component. Speculatively, this may also be due to a shift of the focus of attention from an external orientation (encoding phase) to an internal orientation (retention phase). Note that the result fits with the findings of Valtonen and colleagues (Valtonen, May, Mäkinen, & Tiitinen, 2003) who found a decrement of the magnetic counterpart of the N1 (i.e., the N1m wave) in response to the auditory distractors that were played during retention (in comparison to the N1m elicited by the encoding-phase distractors).

However, the most critical aspect of the results is the difference between the changing-state and the steady-state conditions. With respect to this property, encoding phase and retention phase are very similar (see Figure 4 for difference waves between the two distractor conditions) at a descriptive level. This impression was confirmed by the statistical analysis of the results. Mean amplitudes of the difference potentials were submitted to a presentation phase (*encoding phase, retention phase*) \times caudality (*frontal, central, posterior*) \times laterality (*left, medial, right*) MANOVA, separately for each temporal ERP epoch. The mean amplitude of the difference wave in the 80–170 ms time window was different from zero [$F(1,33) = 14.88, p < .01, \eta^2 = .31$]. The analysis of the difference waves in the 80–170 ms time window revealed significant main effects of caudality [$F(2,32) = 4.28, p < .01, \eta^2 = .36$], and laterality [$F(2,32) = 8.76, p < .01, \eta^2 = .35$], and a significant caudality \times laterality interaction [$F(4,30) = 5.07, p = .01, \eta^2 = .24$], confirming that the difference between changing state and steady state was most pronounced at medial anterior and medial central electrodes. Most importantly, there was no main effect of presentation phase [$F(1,33) = 1.28, p = .27, \eta^2 = .04$], suggesting that the difference between changing state and steady state was approximately of the same size in both the encoding phase and the retention phase. Descriptively, the difference between the changing-state and the steady-state condition was even more pronounced in the retention phase than in the encoding phase. This was to be expected given that it can be assumed that stimulus-specific refractoriness increases somewhat with the number of preceding steady-state auditory events. The two-way interactions between presentation phase and caudality [$F(2,32) = 1.48, p = .24, \eta^2 = .08$], and between presentation phase and laterality [$F(2,32) = 1.06, p = .36, \eta^2 = .06$], and the three-way interaction among these variables [$F(4,30) = 0.71, p = .59, \eta^2 = .09$] were not significant, suggesting similar scalp distributions of difference waves in the encoding and in the retention phase.

The mean amplitude of the difference wave in the 200–350 ms window was different from zero [$F(1,33) = 28.02, p < .01, \eta^2 = .46$]. An analysis of the difference waves in the 200–350 ms window revealed significant main effects of caudality

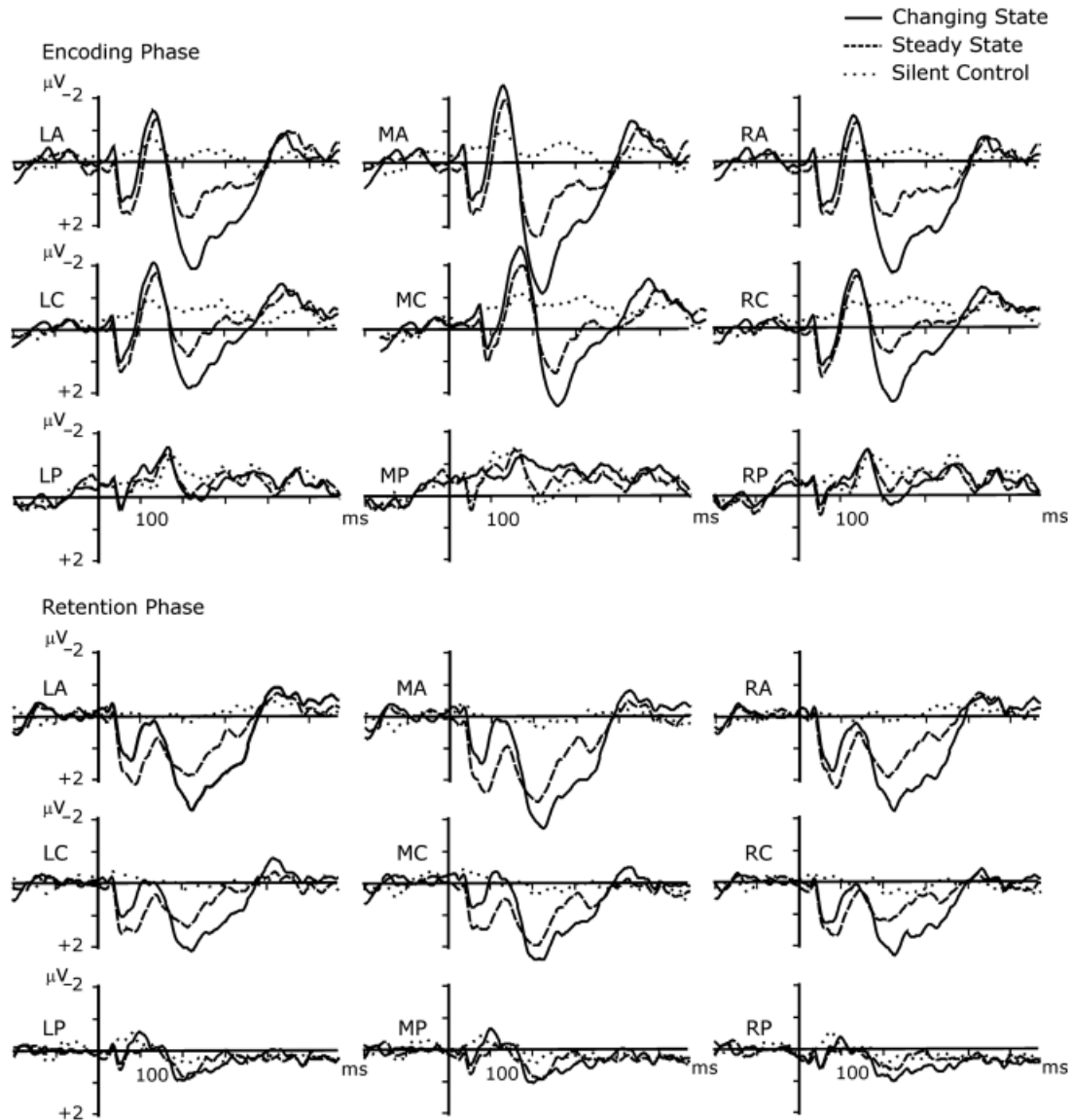


Figure 3. Grand average ERPs for the three distractor conditions (silent-control, steady-state, changing-state), separately for the two presentation phases (upper panel: encoding phase; lower panel: retention phase) as a function of caudality and laterality, that is, for left anterior (LA; Af3, F3, F7), medial anterior (MA; Fz, Fc1, Fc2), right anterior (RA; Af4, F4, F8), left central (LC; Fc5, C5, C3, Cp5), medial central (MC; Cz, Cp1, Cp2), right central (RC; Fc6, C4, C6, Cp6), left posterior (LP; P3, P7, O1), medial posterior (MP; Pz, Po3, Po4, Oz), and right posterior (RP; P4, P8, O2) sites. In the silent-control condition, we averaged across the same time windows as in the other two conditions, although no distractor sounds were played in this condition.

[$F(2,32) = 44.31, p < .01, \eta^2 = .74$], confirming that the difference between the changing-state condition and the steady-state condition was most pronounced at frontal electrodes. Again, there was no main effect of presentation phase [$F(1,33) = 0.71, p = .41, \eta^2 = .02$], suggesting that the mean difference amplitude

was of similar size in the encoding and the retention phase. Furthermore, there were no two-way interactions between presentation phase and caudality [$F(2,32) = 1.15, p = .33, \eta^2 = .07$], and between presentation phase and laterality [$F(2,32) = 0.17, p = .84, \eta^2 = .01$], and the three-way interaction among these variables was also not significant [$F(4,30) = 1.18, p = .34, \eta^2 = .14$], suggesting similar scalp distributions of the difference waves in the encoding phase and the retention phase.

Table 1. Mean Amplitudes of the Event-Related Potentials

Condition	Medial central 80–170 ms			Medial frontal 200–350 ms			Medial central 380–490 ms		
	μV	<i>t</i> (33)	η^2	μV	<i>t</i> (33)	η^2	μV	<i>t</i> (33)	η^2
Steady state	-1.10	5.15**	.46	1.16	3.89**	.31	-0.74	3.64**	.29
Changing state	-1.61	6.81**	.58	2.64	8.69**	.70	-1.18	4.70**	.40

** $p < .01$.

An analysis of the difference waves in the 380–490 ms window revealed significant main effects of caudality [$F(2,32) = 6.88, p < .01, \eta^2 = .30$], and laterality [$F(2,32) = 5.42, p < .01, \eta^2 = .25$], confirming a somewhat more pronounced difference between the steady-state condition and the changing-state condition at medial, central electrodes. Again, there was no main effect of presentation phase [$F(1,33) = 0.01, p = .94, \eta^2 < .01$], and there were no two-way interactions between presentation

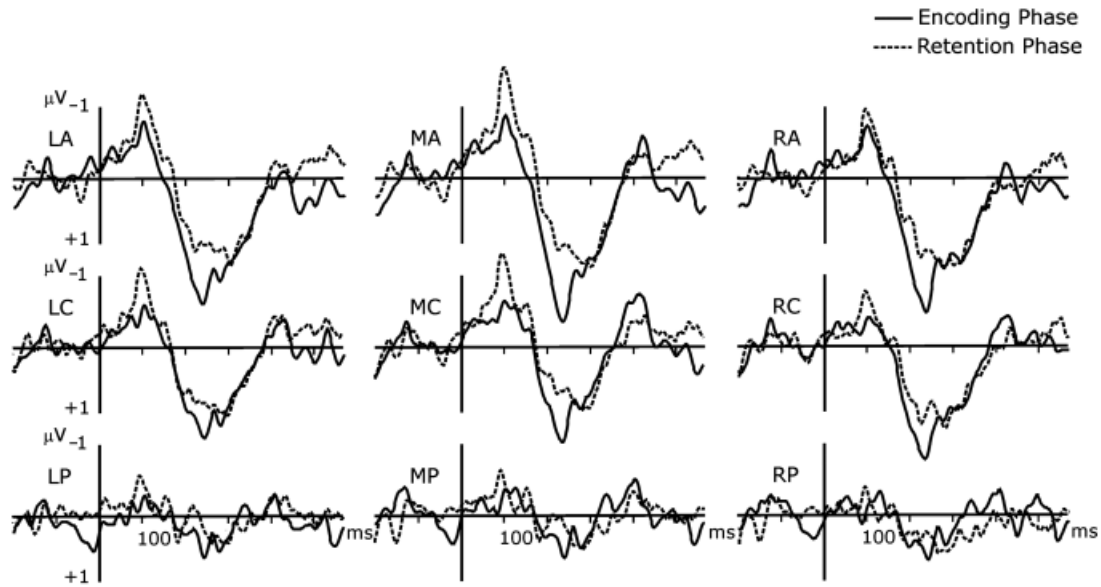


Figure 4. Difference waveforms (changing state–steady-state distractor condition) for the two presentation phases as a function of caudality and laterality, that is, for left anterior (LA; Af3, F3, F7), medial anterior (MA; Fz, Fc1, Fc2), right anterior (RA; Af4, F4, F8), left central (LC; Fc5, C5, C3, Cp5), medial central (MC; Cz, Cp1, Cp2), right central (RC; Fc6, C4, C6, Cp6), left posterior (LP; P3, P7, O1), medial posterior (MP; Pz, Po3, Po4, Oz), and right posterior (RP; P4, P8, O2) sites.

phase and caudality [$F(2,32) = 0.84$, $p = .44$, $\eta^2 = .05$] and between presentation phase and laterality [$F(2,32) = 2.51$, $p = .10$, $\eta^2 = .14$]. The three-way interaction among these variables was also not significant [$F(4,30) = 1.40$, $p = .26$, $\eta^2 = .16$]. Thus, the differences in waveforms between distractor conditions were the same in the encoding and the retention phase.

Discussion

The present results can be summarized as follows: (1) Serial recall was decreased by the auditory distractors, especially by changing-state distractors. In other words, a typical irrelevant sound effect and a typical changing-state effect were observed. (2) Irrespective of whether the distractors were played during encoding or retention, the N1 component was larger in the changing-state condition than in the steady-state condition, indicating that distractor repetition attenuated the auditory N1 component. (3) The N1 was followed by a positive wave. The difference waves between the two distractor conditions showed a positive deflection between 200 and 350 ms. This could be taken as evidence that the changing-state distractors elicited a P3a and that these distractors captured attention. (4) The positivity was followed by a late negative wave. This result fits to findings in auditory distraction paradigms in which a late negativity was associated with a reorienting of attention to the primary task (e.g., Escera et al., 2001). Thus, this late negativity could be associated with an attentional reorienting response. However, previous studies have found a frontal distribution of the RON. Thus, the central scalp distribution of the late negative component observed here should not be counted as clear evidence of the reorienting hypothesis. Furthermore, the RON has been found to be time-locked to the visual target stimuli (Escera et al., 2001), which may be a reason why this component is less well defined in the present experiment. Berti (2008a) has suggested that a late negativity with parieto-central maximum following an unexpected change in the auditory environment may reflect a post-

stimulus evaluation process that is activated by the conflict between the automatically triggered response to the auditory event and the task at hand. Alternatively, the late negativity might reflect further processing of the speech distractors.

The finding that the N1 amplitude in the changing-state condition is enhanced compared to the N1 response to steady-state distractors replicates the findings of Campbell et al. (2003, 2007) that the N1 increases with the number of distinct distractor tokens in the to-be-ignored sequence. This changing-state effect can be explained by stimulus-specific refractoriness of the N1. It has been established that part of the N1 is generated by neuron populations that respond to specific features of the auditory stimuli (frequency, duration, etc.; Näätänen, 1990; Näätänen & Picton, 1987). The responsiveness of these neuronal populations attenuates with stimulus repetition (Opitz et al., 2005; Schröger & Wolff, 1998). Thus, the more changing states (distinct distractors) in a sequence, the less feature-specific refractoriness occurs. As a consequence, the N1 response to changing-state distractors is amplified in comparison to the N1 response to steady-state distractors (Campbell et al., 2003, 2007).

It is often assumed that the N1 response to auditory distractors reflects a call-for-attention mechanism that triggers an attention switch if it exceeds a certain threshold (Näätänen, 1990; Näätänen & Picton, 1987). Consistent with this assumption, a large P3a response followed the early negativity in the changing-state condition. This P3a is typically associated with an orienting response to the eliciting stimulus (Friedman et al., 2001) and thus presumably indicates an attention switch to the auditory modality. The P3a to auditory distractors often occurs alongside a decrement in primary task performance (Escera et al., 1998, 2001; Escera & Corral, 2007). Consistent with these earlier findings, the present experiment shows that changing-state distractors elicited a P3a and also disrupted working-memory performance more than steady-state distractors. Thus, the results suggest that an attention switch to the auditory distractors contributes to the irrelevant sound effect.

This interpretation of the results is consistent with the conclusion of Campbell and colleagues that “supratemporal N1 generators may play a role in memory disruption, but the elicitation of this component is not a sufficient condition for memory disruption” (Campbell et al., 2003, p. 44). Inconsistent with the assumption that the N1 generating processes are sufficient to elicit an irrelevant sound effect, Campbell and colleagues (2003) found a dramatic increase in N1 amplitude when the distractor set size (that is, the number of unique distractor items in a to-be-ignored sequence) was increased from 1 to 2, but no corresponding increase in interference. A significant increase in interference was found when distractor set size was increased from 2 to 5, which also caused a further but much less pronounced increase in N1 amplitude. Campbell and colleagues concluded that the processes underlying the N1 may be a necessary rather than sufficient precondition for irrelevant-sound disruption. The present results suggest that the supratemporal N1 generators represent a call for attention, but the decrement in serial-recall performance may be due to the attention switch that is reflected in the P3a component and that is only elicited when the N1 exceeds a certain threshold (see also Rinne et al., 2006).

In our data, positivity onset was relatively early (200 ms). One concern might thus be that the early part of the P3a may overlap with a P2 component of the event-related potential. The function of the processes reflected in the P2 is less clear. The P2 in response to target stimuli is often interpreted as reflecting a stimulus classification process preceding the P3. In selective attention paradigms, the P2 is frequently thought to reflect inhibition of information processing that serves to protect against interference (see Crowley & Colrain, 2004, for an overview). Thus, one may speculate whether the enhanced positive deflection in the early part of the 200–350 ms time window was caused by an increase in the P2 in response to changing-state distractors. However, this interpretation is not supported by the present data for a number of reasons. First, it has been previously suggested that the P2 can be distinguished from the P3a by their scalp topography. The P2 has a centro-parietal maximum, whereas the P3a is a more fronto-central component (Ceponiene, Lepistö, Soininen, Aronen, Alku, & Näätänen, 2004; Ceponiene, Rinne, & Näätänen, 2002). Figure 5 illustrates the topographical distribution of the ERP response associated with steady-state and changing-state distractors. As can be seen, the ERP response to the steady-state distractors has a fronto-central maximum. The ERP response in the changing-state condition shows a different scalp topography with a more pronounced frontal maximum. Note that the difference between the steady-state condition and the changing-state condition extends over an interval of 150 ms (and is clearly significant in the 275–350 ms window [$F(1,33) = 10.39$, $p < .01$, $\eta^2 = .24$]). Thus, although it cannot be excluded that the positive deflection immediately following the N1 to steady-state distractors may reflect—in part—processes associated to a P2 component, the increase in positivity in the changing-state condition is most plausibly due to a P3a.

This interpretation of the results fits to findings in the oddball paradigm in which the P2 to repetitive standard stimuli and the P3a to deviants or novel stimuli differ in their scalp topographies (Ceponiene et al., 2004, 2002). Using magnetoencephalographic recording, Alho, Winkler, Escera, Huotilainen, Virtanen, et al. (1998) have shown that the early P3a to deviants and the P2 to standard stimuli have different generator source locations. Furthermore, our P3a correlate in the changing-state condition fits to results previously reported in the literature. Parallel to the

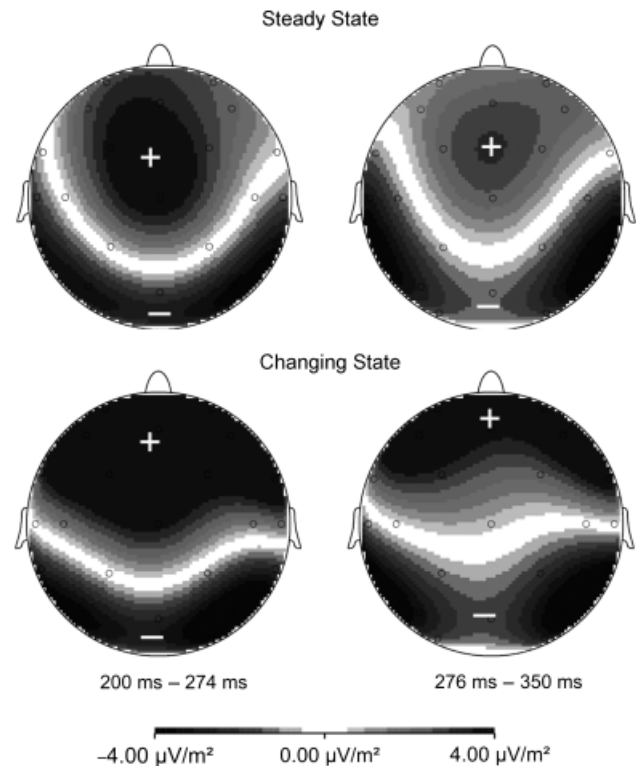


Figure 5. The maps illustrate the topographical distribution of the event-related potentials in response to steady-state and changing-state distractors between 200–350 ms (200–274 ms, and 276–350 ms).

present findings, it has been found that varying (changing-state) tones comprising no regularity can elicit a P3a response and a decrease in behavioral performance in a modified oddball paradigm (Bendixen et al., 2007). Interestingly, in the Bendixen et al. study the P3a to varying (changing-state) tones had also a rather early latency that was in the order of magnitude of the latency observed here. A similarly early latency of the P3a to auditory deviants has been observed under focused attention to the visual channel (Muller-Gass, Macdonald, Schröger, Sculthorpe, & Campbell, 2007). In line with our interpretation of the present results, these results were interpreted as providing support for the hypothesis that varying auditory stimuli can draw attention away from a primary task.

Another interesting question is why Campbell et al. (2003, 2007) failed to observe a P3a response to the auditory distractors, although they obtained (changing-state) irrelevant sound effects. The simplest explanation for this discrepancy seems to be that the fast presentation rate that was used in those studies (the onsets of two consecutive stimuli was 350 ms and 327 ms, respectively) reduced the chance of finding significant differences in the amplitudes of later components. However, alternative explanations should also be considered. Campbell et al. (2007) used non-speech tones as auditory distractors, whereas the present study used speech distractors. It is commonly observed that speech interferes more with serial recall than other distractor material (Buchner et al., 2008; LeCompte et al., 1997). Thus, the speech sounds used in the present study may have been more attention-grabbing than the sine wave sounds used by Campbell et al. (2007). Note, however, that, at least in terms of the standardized effect size, the changing-state effect was of comparable size in the present study ($\eta^2 = .37$) and in Campbell et al. (2007; $\eta^2 = .38$). The decreased presentation rate of the auditory distractors

in our study may also have amplified the N1 amplitudes in comparison to previous studies (by decreasing the refractoriness of the N1 generators) and thereby may have increased the likelihood of eliciting attention switches to these stimuli. It would be interesting to manipulate the features of the irrelevant sound (distractor type, duration, presentation rate) directly to see how these variables relate to the ERP correlates and to the amount of memory disruption. This might help to determine whether attention capture in terms of the P3a effect is the main determinant of irrelevant-sound disruption or whether processes that are associated with the N1 may also contribute to the interference effect.

By showing that an increase in P3a amplitude accompanies the memory disruption, the present results support the attentional-capture account of the irrelevant sound effect that is based on the embedded-processes model (Cowan, 1995). According to this view, changes in the auditory environment capture the focus of attention. Distractors that are of relevance for the individual may be more prone to capture attention than other distractors (Buchner et al., 2004, 2006). Attention capture interferes with serial recall because attentional resources are needed to keep the to-be-remembered items in a highly accessible state. By supporting an attentional interpretation of the irrelevant sound effect, the present results are consistent with other studies examining

electrophysiological correlates of the irrelevant sound effect. For example, Weisz and Schlittmeier (2006) found a decrease in the N1 to the visual targets and a subsequently reduced theta response at right prefrontal electrodes in a changing-state distractor condition. The findings were interpreted as a sign of reduced attentional resources that were available for the processing of the to-be-remembered items during encoding and retention. Based on these findings, Weisz and Schlittmeier suggested that attention may play a key role in explaining the irrelevant sound effect.

In summary, the present results replicate the findings of Campbell et al. (2003, 2007) that an increase in the disruption of serial recall due to a greater variability in the irrelevant auditory stream covaries with an increase in the auditory N1. Extending previous findings (Campbell et al., 2003, 2007), we also found that the amplitude of the subsequent P3a wave increased with increasing amounts of interference, supporting the attention-capture account of the irrelevant sound effect. Given the obvious parallels between the factors influencing the amount of interference in the irrelevant-sound paradigm and the factors determining ERP responses to acoustic sound changes, we think that it is important to integrate these two lines of research. We hope that the present study may provide a step forward in this direction.

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