N1 and mismatch-negativity are two spatiotemporally distinct components: Further evidence for the N1 hypothesis of auditory distraction.

Campbell, Thomas

2007

Campbell , T , Winkler , I & Kujala , T M 2007 , ' N1 and mismatch-negativity are two spatiotemporally distinct components: Further evidence for the N1 hypothesis of auditory distraction. ' , Psychophysiology , vol. 44 , pp. 530-540 . https://doi.org/10.1111/j.1469-8986.2007.00529.x

http://hdl.handle.net/10138/136216
https://doi.org/10.1111/j.1469-8986.2007.00529.x

submittedVersion

Psychophysiology, 44 (2007), 530–540. Blackwell Publishing Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2007.00529.x

N1 and the mismatch negativity are spatiotemporally distinct ERP components: Disruption of immediate memory by auditory distraction can be related to N1

TOM CAMPBELL,[a,b] ISTVÁN WINKLER,[a,b,c] AND TEIJA KUJALA[a,b,d]

[a]Helsinki Collegium for Advanced Studies, University of Helsinki, Helsinki, Finland
[b]Cognitive Brain Research Unit, Department of Psychology, University of Helsinki, Helsinki, Finland
[c]Institute of Psychology, Hungarian Academy of Sciences, Budapest, Hungary
[d]Helsinki Brain Research Centre, University of Helsinki, Helsinki, Finland

Abstract

Event-related potentials (ERPs) were recorded for ignored tones presented during the retention interval of a delayed serial recall task. The mismatch negativity (MMN) and N1 ERP components were measured to discern spatiotemporal and functional properties of their generation. A nine-token sequence with nine different tone pitches was more disruptive than an oddball (two-token) sequence, yet this oddball sequence was no more disruptive than a single repeating tone (one-token). Tones of the nine-token sequence elicited augmented N1 amplitudes compared to identical tones delivered in the one-token sequence, yet deviants elicited an additional component (MMN) with distinct temporal properties and topography. These results suggested that MMN and N1 are separate, functionally distinct components. Implications are discussed for the N1 hypothesis and the changing-state hypothesis of the disruption of serial recall performance by auditory distraction.

Descriptors: Auditory mismatch-negativity MMN, Auditory N1, Irrelevant sound effect, Serial recall, Auditory distraction, Selective attention

The mismatch negativity (MMN; Näätänen, Gaillard, & Mäntysalo, 1978) is a frontocentrally distributed, relatively long-lasting component of the auditory event-related potential (ERP) that occurs in response to "deviant" sounds that violate some acoustic regularity. The auditory oddball sequence is the simplest paradigm in which MMN is investigated. In this paradigm, low-probability deviant sounds are interspersed among a repeating sequence of a highly probable "standard" sound, from which the deviant sounds differs in one or more acoustic features. Violation of some regularity in the preceding auditory stimulation, as occurs within an oddball sequence, is necessary for the elicitation of MMN (Näätänen & Winkler, 1999). In contrast, the auditory N1 wave—a frontocentrally negative ERP response occurring approximately 100 ms after stimulus onset (Näätänen & Picton, 1987)—is elicited by the onset of any abruptly commencing sound. The N1 amplitude is augmented by sound change even when acoustic change does not violate any preceding regularity. For example, relative to a sequence containing one repeated sound, ERPs exhibit an N1 amplitude enhancement when recorded from sequences in which each sound differs from the preceding sound (Campbell, Winkler, & Kujala, 2005; Campbell, Winkler, Kujala, & Näätänen, 2003; Jacobsen, Schröger, Horenkamp, & Winkler, 2003).

The auditory N1 and MMN usually overlap in time. The current investigation aimed at testing whether N1 and MMN exhibit distinct spatiotemporal and functional characteristics. This issue has become controversial once more, since a recently proposed explanation of MMN has cast this component as a temporally modulated N1 response that is subject to an adaptation process characterized by differential attenuation of two N1 subcomponents upon repeated stimulation (Jääskeläinen et al., 2004). Thus, the detection of auditory regularities would not be a necessary prerequisite for recording an MMN-like wave; rather an acoustic change would be sufficient for its elicitation. The adaptation process assumed by Jääskeläinen et al. only requires that a given neuronal element has been recently stimulated, such that this element has become less responsive upon subsequent stimulation (cf. "refractoriness"; Alcaini, Giard, Thévenet, & Pernier, 1994; Barry, Cocker, Anderson, Gordon, & Rennie, 1992; Butler, 1968; Woods & Elmasian, 1986). Accordingly, rare "deviant" stimuli in an oddball sequence activate fresh afferent neuronal elements and thus result in an augmented

This work was, in part, supported by a Marie Curie Fellowship of the European Community programme "Improving the Human Research Potential and the Socio-Economic Knowledge Base" under contract number HPMF-CT-2000-00902, the University of Helsinki, the Academy of Finland (200522), and by the Hungarian National Research Fund (OTKA T048383).

Address reprint requests to: Tom Campbell, Helsinki Collegium for Advanced Studies, P.O. Box 4, FIN-00014 University of Helsinki, Finland. E-mail: tom. campbell@helsinki.fi

response compared with the adapted (partially refracted) response elicited by the repeating "standard" sound.

There still remains much evidence that is difficult to reconcile with the N1 adaptation view of MMN (for a summary of the arguments comparing the memory-mismatch and the N1 adaptation explanation of MMN, see Näätänen, Jacobsen, & Winkler, 2005). MMN can be elicited by stimulus omissions whereas N1 is not elicited (Yabe et al., 1998). However, this omission MMN could be the biproduct of oscillatory neuronal populations that are organized into columns, each of which is tuned to a rhythmical stimulation of a specific stimulus onset asynchrony (May & Tiitinen, 2001, 2004). That is, neuronal firing continues to oscillate upon cessation or interruption of that rhythmic stimulation within the column that corresponds to the cycle of the preceding stimulation. The continuation of oscillation could emerge as an omission MMN. Accordingly, there would seem to be no need for recourse to a distinct mechanism for the generation of omission MMN, other than the neuronal population that also generate N1. However, MMN to omissions have been obtained with a variable stimulus onset asynchrony (Oceák, Winkler, Sussman, & Alho, 2006). Furthermore, corroborative evidence for MMN elicitation without a corresponding N1 has been obtained with the event-related optical signal technique. It was shown that an MMN is elicited by tones of 25 ms duration with respect to a 75-ms standard tone, even though the 25-ms tone is too short to elicit N1 of a size comparable to that produced by the 75-ms standard (Rinne et al., 1999).

Another argument against the N1 adaptation view of MMN stems from the assumption that the activation of the neuronal population that generates N1 is time-locked to sound onset. By contrast, MMN can be obtained with latencies that are well beyond that of N1, for example, by using duration deviants (Näätänen, Paavilainen, & Reinikainen, 1989). MMN also peaks later than N1 when the auditory change is harder to discern, for example, by making the difference in frequency between the standard and deviant only just noticeable (Winkler, Tervaniemi, & Näätänen, 1997). However, latency difference does not reliably separate N1 and MMN, because some N1 subcomponents fall into the usual latency range of MMN (Näätänen & Picton, 1987), long sounds evoke offset N1 type of responses, and adaptation can delay some constituents of the N1 response (see below).

Recent in vivo investigations of primary auditory cortical neurons in cats have revealed cells adapting to pitch repetition, responding with an increased spike rate and delayed latency to pitch change (Moore, 2003; Ulanovsky, 2004; Ulanovsky, Las, Farkas, & Nelken, 2004; Ulanovsky, Las, & Nelken, 2003). These neurons exhibit hyperacuity (Ulanovsky et al., 2003), such that these cells are as or possibly more sensitive to small pitch changes as the corresponding just noticeable difference (JND) determined psychophysically in humans (Moore, 2003). Those afferent neuronal populations, which are tuned to the features of the standard sound and undergo the above-described stimulus specific adaptation (SSA), become less responsive upon subsequent presentations of the standard sound. These neuronal populations would then respond more vigorously to a sound that differs from the standard, thus yielding an augmented neuronal response to deviants. The adapted afferent neurons are regarded by some as the memory trace assumed to underlie MMN generation (Ulanovsky, 2004). Thus, unlike the thalamic neurons of the medial geniculate body, which are not subject to SSA, these primary auditory cortex neurons could be involved not only in feature detection but also in "higher level" functions, such as novelty detection, change detection, and sensory memory. If auditory cortical neurons undergoing SSA are involved in the generation of both the N1 and the MMN component, this would substantially strengthen the arguments for the N1 adaptation explanation of MMN.

One argument against the N1 adaptation view of MMN is that MMN can be elicited without stimulus repetitions that would induce N1 refractoriness (Korzyukov, Winkler, Gumenyuk, & Alho, 2003; Paavilainen, Simola, Jaramillo, Näätänen, & Winkler, 2001; Saarinen, Paavilainen, Schröger, Tervaniemi, & Näätänen, 1992). However, Ulanovsky's (2004) findings raise the possibility that afferent auditory cortical neurons serving the coding of higher level interstimulus relations, such as pitch increments between successive sounds, could also be subject to SSA. If this were the case, for which, as yet, there is no direct evidence, an MMN response could be elicited due to adaptation. On the other hand, if such neurons existed, would they also be involved in the generation of the N1 response? No known property of the N1 response matches the operation of adaptable afferent neurons sensitive to abstract interstimulus relationships (Näätänen & Winkler, 1999).

Further, it is difficult to reconcile with the N1 adaptation view that MMN and N1 have different scalp distributions (Alho, 1995) and generator loci (Korzyukov et al., 1999; Opitz, Schröger, & von Cramon, 2005). N1 and MMN are also differentially affected by some clinical states and pharmocological substances (Javitt, 2000; Javitt, Steindschneider, Schroeder, & Areszzo, 1996; Pekkonen, 2000; Pekkonen et al., 2002; Umbricht et al., 2000). Specifically, the observed cholinergic modulation of MMN to pitch change contrasts with the primarily dopanergic and serotonergic modulation found for N1. However, the theoretical approach described in Ulanovsky's (2004, pp. 78–79) thesis may provide an explanation for these effects by distinguishing overall neuronal responsiveness from SSA. For instance, differences in the distribution of MMN and N1 may arise from strong responses in one auditory cortical area that contribute to the N1 response, combined with a weak SSA effect yielding a low amplitude MMN from that area. In contrast, a weak response in a separate auditory cortical area may produce a small contribution to N1 combined with a strong SSA effect resulting in a robust MMN. These brain areas would thus be (1) differentially responsive and, independently, (2) differentially sensitive to SSA, whereas N1 and MMN generation would still be based on the same mechanism and modulated by the same SSA process in both auditory brain areas (for a similar argument, see Jääskeläinen et al., 2004). Such a theoretical viewpoint, in a slightly reconceived form (Ulanovsky, 2004, pp. 84–86), could also account for the observed clinical and pharmacological effects dissociating N1 and MMN. Yet caution is warranted, as it should be considered that much of the evidence needed to support Ulanovsky's theory still requires extensive experimental verification. Indeed, necessary investigations, which would be required to test the validity of Ulanovsky's theory, include the mapping of auditory cortical responsiveness and SSA sensitivity, together with how these areas contribute to N1 and MMN.

Some of the most compelling arguments against the N1 adaptation explanation of MMN stem from investigations that have controlled for the refractoriness effects occurring in oddball sequences. These effects of refractoriness were controlled for by recording ERPs from sequences presenting several different tones with equal probabilities in a randomized order (Jacobsen &

Schröger, 2001; Jacobsen et al., 2003; Schröger & Wolff, 1996; see also Opitz et al., 2005).

The notion here is that presenting the same sound (the oddball deviant) with equal temporal and sequential probability in a many-sound (many-token) sequence (large token set size, equal probability) as in an oddball sequence (two tokens, unequal probabilities) results in an approximately equal refractoriness in the neuronal elements specifically responding to the "deviant" sound. Thus the contribution of the refracted N1 generators to the ERP response would be near identical for the oddball deviant and for the same "control" sound delivered in the multitoken sequence. Therefore, if these two responses differed from each other, the difference could not be attributed to the refracted N1 generators, but must reflect a neuronal process specific to deviation from a repeating sound. Indeed, it has been found that infrequent deviant sounds delivered within an oddball sequence elicit a "genuine" MMN component on top of the augmented N1 amplitude (Jacobsen & Schröger, 2001; Jacobsen et al., 2003; Schröger & Wolff, 1996).

It is important to note that, comparing the deviant-stimulus response with that elicited by the standard sound, a refractoriness-associated N1 enhancement is also to be expected, because the lower the probability of a given sound, the longer the interval between successive presentations of this sound. Thus, there is more time for the afferent neurons that are activated by this sound to recover from the effects of the previous stimulation. In turn, the average N1 amplitude increases with increments in token set size even when the different tokens are delivered with equal probability (Campbell et al., 2003, 2005; Jacobsen et al., 2003).

However, the refractory status of the N1 generators may not be exactly equal in the oddball and the many-token sequences. This is because most afferent neurons preferentially react to a range of the parameters separating the standard and the deviant sound (e.g., most N1-generating neurons respond to sounds containing frequencies within a narrower or wider range). Therefore, the refractory state of those neuronal elements, which are activated both by the frequent standard and the rare deviant stimulus, cannot be fully equated to the refractory state of those neurons that respond both to the "deviant" sound and also to one or more of the various other sounds of the multitoken sequence. Thus the refractoriness control provided by the many-token sequence may either over- or underestimate the contribution of the refracted N1 generators to the deviant-stimulus response in the oddball sequence. An additional weakness of the investigations that have implicated a control for refractoriness is that in these studies, N1 and MMN have been elicited at separable latencies as occurs when the pitch separation between tonal stimuli is small (Jacobsen & Schröger, 2001; Jacobsen et al., 2003). While this latency difference of MMN and N1 could be taken to reflect distinct underlying componentry, it could also, though rather tenuously, be taken to reflect that MMN is a temporal modulation of an N1 process, as would be consistent with the assumptions of the N1 adaptation account of MMN (Jääskeläinen et al., 2004). There is thus the need to demonstrate that even when MMN occurs in the same latency range as N1, there is something additional to the release from refractoriness of N1 seen when a deviant is presented. Therefore, in the current investigation a wider pitch separation between tones was used, resulting in full temporal overlap between MMN and N1.

The current experiment was designed to test three hypotheses regarding the separation of N1 and MMN. (1) If MMN were distinct from N1, the amplitude of the overlapping MMN and N1 response to the deviant should be larger than the enhancement of the N1 produced by an increase in set size alone. This assumption is termed the *MMN-N1 additivity hypothesis*. (2) If MMN were distinct from N1, then a wave summing N1 enhancement and MMN should possess a scalp topography that is different from the pure N1 enhancement obtained with increases in token set size. This assumption is termed the *distribution hypothesis*. (3) If MMN were distinct from N1, then the neural processes underlying N1 and MMN could have different effects on concurrent cognitive performance. This assumption is termed the *functional hypothesis*.

As there are grounds to assume memorial functions both of MMN and the adaptation of N1 (Näätänen et al., 2005; Ulanovsky, 2004; Ulanovsky et al., 2004), it is vindicated to test the functional hypothesis in an investigation of the possible disruptive effects of these components upon the retention of information in memory. With regards to possible functional differences between MMN and N1, previous investigations have revealed a significant increase in memory disruption with increments in the number of different types of sounds (tokens) in an ignored sound sequence (Campbell, Beaman, & Berry, 2002; Tremblay & Jones, 1998). Campbell et al. (2003, 2005) found that an increase in memory disruption coincided with an increase in the amplitude of N1 (the "N1 hypothesis"; see Campbell et al., 2003). Accordingly, the *N1 hypothesis* of memory disruption predicts that factors related to increases in N1 will also be related to increases in the disruption of performance produced by ignored sounds during a delayed serial recall task. Conversely, the current functional hypothesis suggests that factors unrelated to N1, such as those related to the possibly distinct MMN should not influence performance on this serial recall task. Thus, deviant stimuli eliciting MMN would not produce an additional disruption of performance on top of that associated with the N1 enhancement. Alternatively, if the memory implicated in MMN plays a role in memory disruption, possibly by interference, then manipulating parameters of this memory should affect the memory-disrupting potential of the sound sequence. This experiment thus investigated the effects of the accumulation of memory for the standard during an oddball sequence by comparing conditions when a long prelude of standard tones was either present or absent. Such a prelude does under certain circumstances increase the MMN response to subsequent deviants (Cowan, Winkler, Teder, & Näätänen, 1993).

Methods

Volunteers

Fifteen university students and members of the public volunteered in exchange for a small honorarium. The experiment was undertaken with the understanding and written consent of each volunteer according to the Declaration of Helsinki. During the experiment, volunteers were seated in an acoustically and electrically shielded room of the Cognitive Brain Research Unit, Department of Psychology, University of Helsinki. Five volunteers had to be excluded due to technical failures and 1 volunteer was excluded due to excessive electrical artifacts (81.3% of epochs, whereas the rejection of 30% of epochs due to artifacts was otherwise typical for the remaining participants). Data, both behavioral and ERP, from the remaining 9 volunteers are reported.

The ages of the remaining volunteers (2 men) ranged from 19 to 27 years with a mean age of 24 years. All reported intact hearing and normal or corrected-to-normal vision. All but 1 reported being right-handed.

Stimuli and Procedure

The structure of the trials is shown in Figure 1. Rows starting with a "+" sign show the task-relevant (to-be-memorized) stimuli. On each trial, 4.716 s before the onset of the to-be-remembered list, a fixation cross (+) appeared in the center of the computer screen. After 2 s, a tone was presented to warn volunteers that the list was about to be presented. The screen then went blank (black) for 200 ms and a list of nine to-be-recalled items was presented. The list consisted of the numbers 1 to 9 in a random order that contained no easy-to-remember sequences. Each digit was presented for 800 ms with an interitem interval of 200 ms, during which the screen was blank. Digits were presented in the center of the computer screen, at a size of 45–55 mm in white Helvetica font on a black background. Viewing distance was 1.50 m.

Volunteers were required to attend to the digits. A 15.042-s retention interval followed list presentation, during which the word "ODOTA" (meaning "wait") appeared in the center of the screen. During this period, volunteers were required to silently rehearse the list items. At the end of the retention interval, the screen was again blank for 200 ms, and then the word "KIRJOITA" ("write") appeared for 9.8 s, followed by the fixation cross that preceded the next list. During this "write" period, volunteers were required to write down the digits in a strictly left to right fashion, without correction, while attempting to preserve the correct serial order and position of items, leaving a "/" when uncertain about an item. Volunteers initiated the first trial by saying that they were ready; subsequent lists were then presented at a regular interval.

During the presentation of the to-be-remembered items and/or the retention interval, sounds were delivered binaurally via

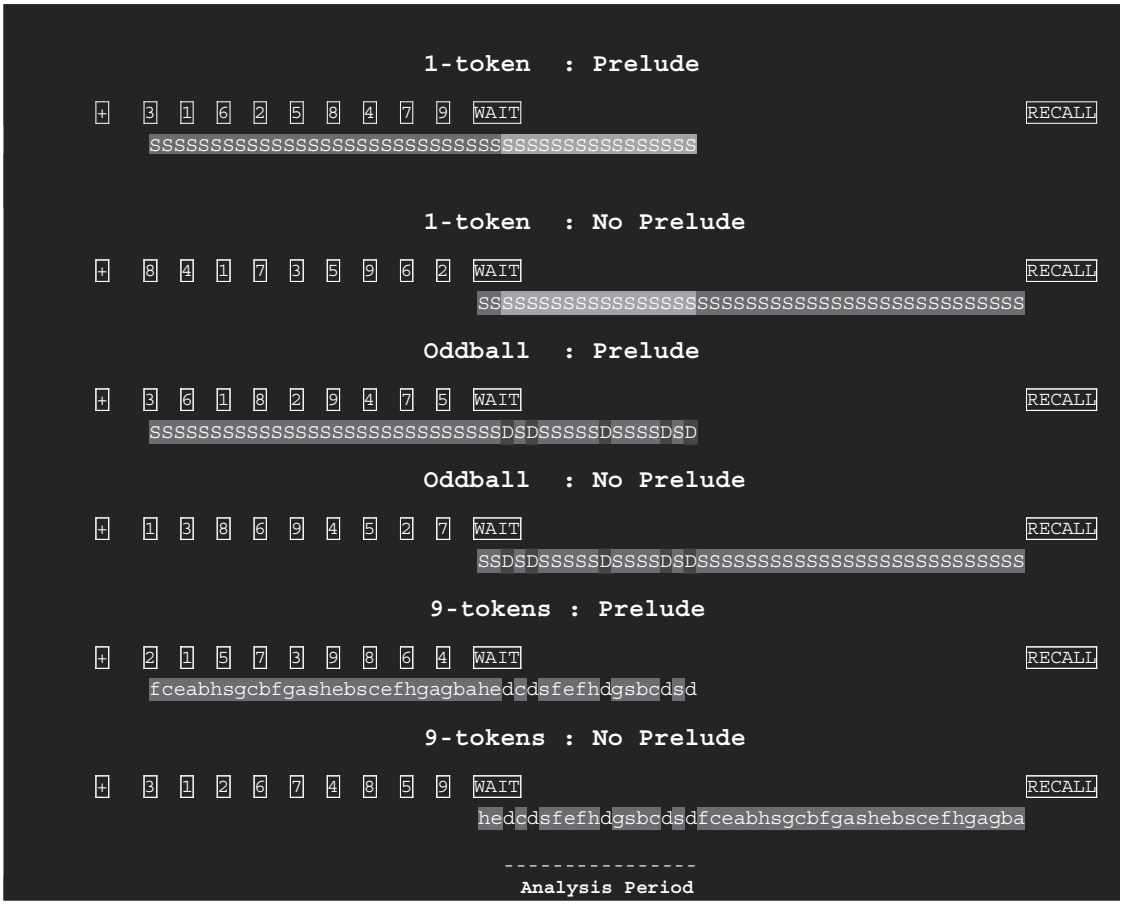

Figure 1. Schematic diagram of one 6-trial cycle. Rows depict examples of trials constituted by a fixation cross followed by a sequence of visually presented digits, delivered one at a time, and followed by the instruction text "WAIT," which was then replaced by the instruction text "WRITE." The row of letters shown below the row of numbers denotes sounds presented alongside the to-be-remembered material. Each of the six different types of trial depicted were presented exactly once during a cycle. One-token sequences repeated a single sound, the standard (marked with S), which was, in separate cycles, either 500 Hz or 1072 Hz in frequency. In the oddball sequences, when the standard was 500 Hz, the "deviant" "D" was 1072 Hz and vice versa. In the nine-tokens condition, the "control" tone "d" was always identical to the deviant sound, and the tone marked "s" to the standard sound. The other seven tones in the nine-token condition, marked a, b, c, e, f, g, h, were 341, 413, 605, 732, 886, 1297, and 1569 Hz in frequency, respectively. Volunteers were instructed to ignore the sounds and to retain the attended visual digits in correct serial order until the recall cue "WRITE," when they tried to write down the digits in the correct order. The analysis period is highlighted by grey background in the letter sequences of the one-token trials and by the dashed line at the bottom of the figure. On prelude sequences, 29 tones preceded the analysis period, whereas on no-prelude sequences 27 of these tones followed the analysis period.

headphones, which the volunteers were required to ignore (Figure 1, letter strings below the task-relevant stimuli). These ignored sounds were presented at 85 dB(A). Precaution was taken that the onsets of tones were not in audiovisual alignment such that the onset of each tone occurred at least 100 ms after the onset of a visual stimulus. Each ignored tone was a fast square wave, with 5 ms rise and fall times, digitized at 11 kHz to 8-bit resolution and lasted 100 ms with an interitem silence of 227 ms.

There were six blocks of trials, each consisting of 4 six-trial cycles (24 trials per stimulus block, 144 trials altogether), during which each of the six auditory sequence type conditions (see below) was presented exactly once, the order varying from cycle to cycle (altogether 24 trials per auditory sequence type condition). Ninety-second breaks intervened between blocks, with the exception of the third block, after which an $\sim$5-min break was taken. A typical cycle is depicted in Figure 1.

In the *one-token* conditions, a single tone (marked "S" in Figure 1) of 500 or 1072 Hz frequency (in separate cycles) was repeated. In accordance with the terminology used in the literature on the cognitive psychology of auditory distraction, the homogeneous tone sequence is termed as one-token (i.e., a single stimulus item, or token, is repeated). The *oddball* conditions differed from the one-token conditions in that five deviants (denoted by D in Figure 1) were presented during the "analysis period" of the retention interval of each oddball trial. These oddball sequences contained two different tokens. However, due to the unequal probabilities with which the two different tones were delivered, "oddball" is a more descriptive name. The analysis period lasted across the 3rd to the 19th sound presented during the retention interval; this period is highlighted with a light grey background in the letter sequences of the one-token trials and by the dashed line at the bottom of Figure 1. The frequencies of the "S" (standard) and "D" (deviant) tones were always exchanged between consecutive cycles. The choice of S and D tones on the first cycle was counterbalanced across volunteers. Thus, to each volunteer, in the oddball condition 500-Hz standard and 1072-Hz deviant tones were delivered on half the trials, vice versa on the other half of trials.

In the *nine-token* conditions, nine tones of different frequencies (341, 413, 500, 605, 732, 886, 1072, 1297, and 1569 Hz) were presented with equal probability in a pseudorandom order, which was constrained to allow the "d" tones (highlighted by black background on nine-token trials depicted in Figure 1) to be presented at the same times as the acoustically identical D (deviant) tones in the corresponding oddball trial (see Figure 1). The tones identical to the S (standard) of the oddball sequence are denoted with the letter "s" in the nine-token sequences on Figure 1. Randomization was also constrained so that no tone could be repeated within the nine-token sound trains.

A prelude of 27 tones was presented alongside the to-be-remembered items on half of the trials (termed "prelude" trials). These prelude tones were followed by two additional tones that always preceded the analysis period. On the corresponding "no-prelude" trials, a sequence of 27 tones, which was identical to the prelude, followed the analysis period, whereas in the prelude trials, the tone sequence stopped at the end of the analysis period. Overall, the same number of tones was presented in corresponding prelude and no-prelude trials.

Analysis of the Behavioral Responses

Behavioral responses were scored with a strict serial position criterion. Error probabilities were then collapsed across serial positions, separately for each condition, thus yielding a mean error probability separately for each of the six auditory sequence type conditions. These mean error-probability data were entered into an Auditory Sequence-type (one-token, nine-token, Oddball) $\times$ Prelude (present, absent) repeated-measures analysis of variance (ANOVA). Planned comparisons were conducted contrasting error probabilities, first, between one-token and oddball conditions and, second, between the oddball and nine-token conditions.

EEG Recording and Analysis

EEG was recorded with a 30-channel array of electrodes that were evenly distributed across the scalp (Virtanen, Rinne, Ilmoniemi, & Näätänen, 1996; for a specific description of the electrodes locations on the 30-channel cap, see Campbell et al., 2005). The common reference electrode was attached to the nose. Horizontal eye movements were monitored with a bipolar setup; the two electrodes were attached laterally to the outer canthi of the eyes. Vertical eye movements were monitored using the frontopolar electrodes (Fp1, Fpz, Fp2) on the cap against the common reference. To record mouth and tongue movements, an additional electrode was placed on the submandibular surface and differentially amplified relative to an electrode located on the right masseter muscle. The bioelectric potentials were amplified within frequency limits (0–30 Hz) and digitized online (500 Hz, NeuroScan SynAmp system). EEG was then filtered (0.1–30 Hz) off-line and epochs of 756 ms starting 100 ms before each sound were extracted. Epochs in which the EEG or EOG signal exceeded $\pm$ 50 μV were rejected from further analysis.

For prelude and no-prelude sequences, separately, auditory ERPs were averaged within the analysis period (across the 3rd to 19th sounds presented during the retention interval; for a similar approach, see Kopp, Schröger, & Lipka, 2004, 2006), separately for standards ("S") in the one-token sequence, the deviants in the oddball sequences ("D"), and the corresponding control tones ("d") in the nine-token sequences (see Figure 1). This averaging was done separately for each of the two frequencies investigated (500 and 1072 Hz). These average ERPs were off-line digitally re-referenced to the average voltage measured over all scalp electrodes (Virtanen, Ahveninen, Ilmoniemi, Näätänen, & Pekkonen, 1998). ERPs were then collapsed across the two frequencies, separately for each of the six auditory sequence type conditions.

ERPs were baseline corrected with the mean voltage during the 100-ms prestimulus period. In the poststimulus range of 80–160 ms, where N1 and MMN were expected to appear with maximal negative amplitude over frontocentral scalp electrodes and maximal positive amplitude at the mastoid electrodes (M1 and M2, the left and right mastoid leads), ERPs were resampled from 500 Hz to 10 kHz by cubic spline interpolation (de Boor, 1978). Latencies could be expressed after this resampling with a resolution of 1/10th of a millisecond. This temporal resolution is identical to that offered by many commercial software packages (e.g., Neuroscan Stats). The purpose of improving the resolution of latency measurements was to maximally utilize the information available in the EEG recording for finding possible differences between N1 and MMN.

For amplitude measurements, sections (see below) of the original (500-Hz digitized) ERPs were resampled using a cubic spline interpolation at 2 kHz with a view to enhancing the accuracy of the amplitude measurement without forsaking computational efficiency. After resampling, the windows could be

centered on the measured peak latencies. To calculate the resampled waveform within the measurement windows, original samples were used between and inclusive of the nearest sample before the onset of the window up until the nearest sample after the whole duration of the window.

Frontocentral N1/MMN amplitudes were averaged from 10-ms-long windows centered condition-wise upon the grand-averaged negative Fz peak found in the 80–160-ms range. N1/MMN amplitudes at the mastoid leads were averaged from 10-ms-long windows centered condition-wise on the mean of the grand-averaged positive peak latencies measured at M1 and M2.

For the N1/MMN wave, amplitudes and latencies were computed for a 3 × 3 array of aligned electrodes (AF3, AFz, AF4, F3, Fz, F4, C3, Cz, and C4) and from M1 and M2. Four repeated-measures ANOVAs were conducted. The average of the frontocentral N1 peak latencies (mean of the peak latencies at all nine frontocentral leads) and, separately, the average of the two mastoid N1/MMN peak latencies were submitted to ANOVAs of the structure Auditory Stimulus-type (standard ["S"], control ["d"], deviant ["D"])] × Prelude (present, absent). Frontocentral N1/MMN amplitudes were submitted to an ANOVA of Auditory Stimulus-type (standard, control, deviant) × Prelude (absent, present) × Frontality (AF, F, C) × Laterality (3, z, 4). The mastoid N1/MMN amplitudes were submitted to a separate Auditory Stimulus-type (standard, control, deviant) × Prelude (absent, present) × Laterality (M1, M2) ANOVA.

Throughout the ANOVA analyses, post hoc Neuman–Keuls tests were conducted as appropriate to further specify significant results. For all analyses, the critical α level was set to .05 and Geisser–Greenhouse correction was used as appropriate. Effect sizes are reported as partial eta squared. All significant results are described in the text.

Results

Behavioral Data

The pattern of mean error probabilities (one-token: 0.401 ≈ oddball: 0.401 < nine-token: 0.443) showed a significant effect of auditory sequence type that revealed a disruptive advantage of the nine-token sequences over the other two conditions, $F(2,16) = 4.93$, $p = .031$, $\varepsilon = .82$, $\eta_p^2 = .38$, (ANOVA structure: Auditory Sequence-type [one-token, nine-token, Oddball] × Prelude [present, absent]). Critical planned comparisons revealed that there was no significant disruptive advantage of oddball over one-token sequences, $F < 1$, whereas there was a significant disruptive advantage of nine-token sequences over oddball sequences, $F(1,8) = 12.75$, $p = .007$, $\eta_p^2 = .62$, which caused the significant main effect of auditory sequence type. The main effect of prelude was not significant, $F(1,8) = 2.39$, n.s., $\varepsilon = 1$, $\eta_p^2 = .23$, nor did prelude significantly interact with the type of the auditory sequence, $F < 1$. Thus nine-token tone sequences disrupted performance in the concurrent memory task significantly more than either one-token or oddball sequences, whereas the oddball sequences produced no significant increase in memory disruption compared with one-token sequences.

ERP Data

Figure 2 shows the anterior-frontal, frontal, central, parietal, and mastoid responses to one-token, oddball-deviant, and nine-token control tones. Auditory sequence type had substantial effects both on the frontocentrally negative and the mastoid positive waves peaking between 100 and 160 ms. In contrast, no significant effect of the presence or absence of prelude can be discerned from the figure. The following sections provide a detailed description of the analyses of latencies and amplitudes.

N1/MMN Peak Latencies

At frontocentral sites, auditory stimulus-type significantly affected the N1/MMN peak latency, $F(2,16) = 7.84$, $p = .01$, $\varepsilon = .75$, $\eta_p^2 = .49$ (ANOVA structure: Auditory Stimulus-type [standard, control, deviant] × Prelude [present, absent]). Post hoc tests indicated that this frontocentral negativity peaked later in response to the standard tones of the one-token sequences than to the corresponding control tones of the nine-token sequences, $p = .003$ (standard: 123.51 > control: 106.80), yet not significantly later than to deviants (deviant: 115.40 ms), $p > .05$. The presence or absence of the prelude did not significantly influence the N1/MMN peak latency, $F(1,8) = 1.32$, n.s., $\varepsilon = 1$, $\eta_p^2 = .14$, nor did the presence of a prelude interact with auditory stimulus-type, $F(2,16) = 0.07$, n.s., $\varepsilon = .95$, $\eta_p^2 = .01$.

At the mastoids, there was a main effect of auditory stimulus-type on the N1/MMN peak latency, $F(2,16) = 13.18$, $p = .003$, $\varepsilon = .66$, $\eta_p^2 = .62$, with post hoc tests revealing that the peak in response to standard tones from the one-token sequence was later than that to the control tone from a nine-token sequence, $p = .002$, and also later than that to the deviant from the oddball sequence, $p < .001$ (standard: 133.40 > control: 117.99 ≈ deviant: 113.23 ms). Again, there was no main effect of prelude, $F(1,8) = 0.48$, n.s., $\varepsilon = 1$, $\eta_p^2 = .06$, nor an interaction between prelude and auditory stimulus-type, $F(2,16) = 1.53$, n.s., $\varepsilon = .73$, $\eta_p^2 = .16$.

N1/MMN Amplitudes

Increments in set size from one to nine tokens augmented the amplitude of the frontocentral N1 response, and deviants elicited a significant additional enhancement in the N1/MMN time range (Figure 3). The ANOVA (structure: Auditory Stimulus-type [standard, control, deviant] × Prelude [absent, present] × Frontality [AF, F, C] × Laterality [3, z, 4]) showed a significant main effect of the auditory stimulus-type, $F(2,16) = 25.61$, $p < .001$, $\varepsilon = .87$, $\eta_p^2 = .76$, with significant differences obtained in the post hoc tests (standard: -1.226 > control: -2.506 > deviant: -4.013 μV; $ps < .005$). Neither laterality, $F(2,16) = 0.84$, n.s., $\varepsilon = .98$, $\eta_p^2 = .1$, nor frontality, $F(2,16) = 3.37$, n.s., $\varepsilon = .66$, $\eta_p^2 = .3$, showed a significant main effect. However, the influence of auditory stimulus-type on the MMN/N1 amplitude varied with frontality, as is apparent in Figure 3. This was confirmed by the ANOVA result showing a significant interaction between auditory stimulus-type and frontality, $F(4,32) = 5.2$, $p = .016$, $\varepsilon = .53$, $\eta_p^2 = .39$. Post hoc comparisons of auditory stimulus type effects revealed that amplitudes in response to the control tones were larger than those to standards, as were deviant responses compared with the control responses at each level of the frontality ANOVA dimension, all $ps < .001$.

To further consider the nature of this Auditory Stimulus-type × Frontality interaction, pairs of levels were analyzed separately, which resulted in four ANOVAs with two levels of frontality and two levels of auditory stimulus-type each. Because laterality and the presence versus absence of a prelude showed neither main effects nor interactions with the other dimensions, for this analysis, amplitudes were averaged over the two prelude conditions and three electrodes of each line of "frontality" (see Figure 3 for a summary of the results). Considering only the anterior-frontal and frontal electrodes, control tones showed an N1 enhancement

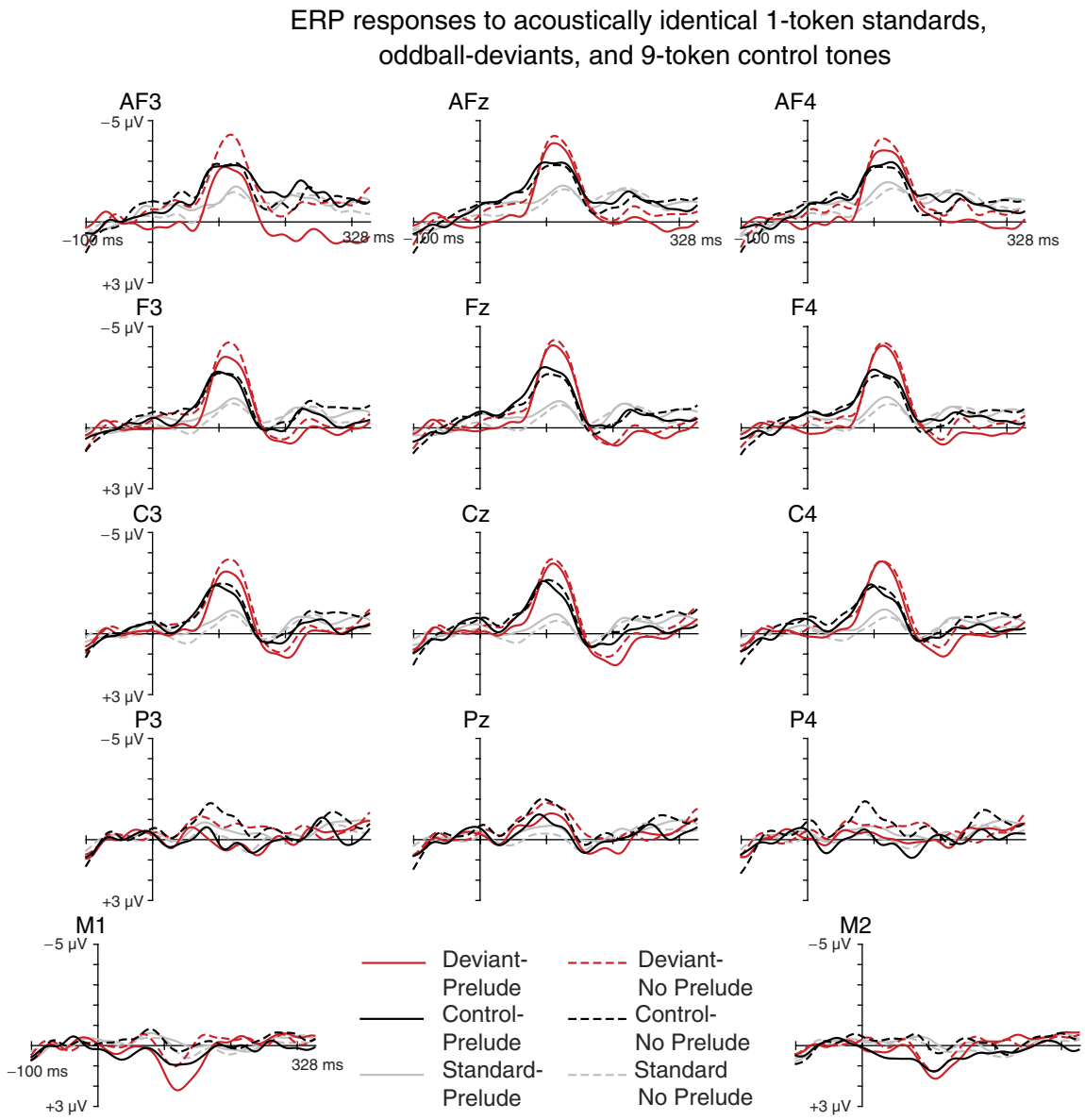

Figure 2. Grand-averaged ERP responses elicited by ignored tones at anterio-frontal, frontal, central, parietal, and mastoid electrode locations (left, center, and right, separately). Responses from the six conditions are superimposed (see line type legend).

over standard tones, $F(1,8) = 17.25$, $p = .003$, $\varepsilon = 1$, $\eta_p^2 = .68$ (ANOVA structure: Auditory Stimulus-type [standard, control] × Frontality [AF, F]), which was, however, larger at frontal than anterior-frontal sites, $F(1,8) = 7.2$, $p = .028$, $\varepsilon = 1$, $\eta_p^2 = .47$. Although the difference between control and deviant tone response amplitudes was also significant at these sites, $F(1,8) = 16.15$, $p = .004$, $\varepsilon = 1$, $\eta_p^2 = .67$ (ANOVA structure: Auditory Stimulus-type [control, deviant] × Frontality [AF, F]), by contrast, this difference was not statistically different at anterior-frontal and frontal sites, $F(1,8) = 2.18$, n.s., $\varepsilon = 1$, $\eta_p^2 = .21$.

The converse pattern of significance was seen when considering only frontal and central electrodes. The main effect of auditory stimulus type, seen in the enhancement with control over standard tones, was again significant, $F(1,8) = 16.44$, $p = .004$, $\varepsilon = 1$, $\eta_p^2 = .67$ (ANOVA structure: Auditory Stimulus type [standard, deviant] × Frontality [F, C] ANOVA), and was not significantly different between the frontal and central sites, $F(1,8) = 0.57$, n.s., $\varepsilon = 1$, $\eta_p^2 = .07$. There was also a significant main effect of frontality, $F(1,8) = 6.76$, $p = .032$, $\varepsilon = 1$, $\eta_p^2 = .46$. Although the difference between the deviant- and control-tone response amplitudes was also significant at both of these sites, $F(1,8) = 9.99$, $p = .013$, $\varepsilon = 1$, $\eta_p^2 = .56$ (ANOVA structure: Auditory Stimulus type [control, deviant] × Frontality [F, C] ANOVA), by contrast, the difference was significantly larger at frontal than central sites, $F(1,8) = 33.21$, $p < .001$, $\varepsilon = 1$, $\eta_p^2 = .81$. There was also a significant main effect of frontality, $F(1,8) = 10.29$, $p = .012$, $\varepsilon = 1$, $\eta_p^2 = .56$. The main effect of auditory stimulus type was also significant at the mastoid leads, $F(2,16) = 18.09$, $p < .001$, $\varepsilon = .79$, $\eta_p^2 = .69$ (ANOVA structure: Auditory Stimulus type [standard, control, deviant] × Prelude [absent, present]), which was caused by a significantly larger response amplitude elicited by the deviant compared with the control tone (Figure 2), $p < .001$. In contrast, the difference between standard and control response amplitudes was not significant, $p = .507$.

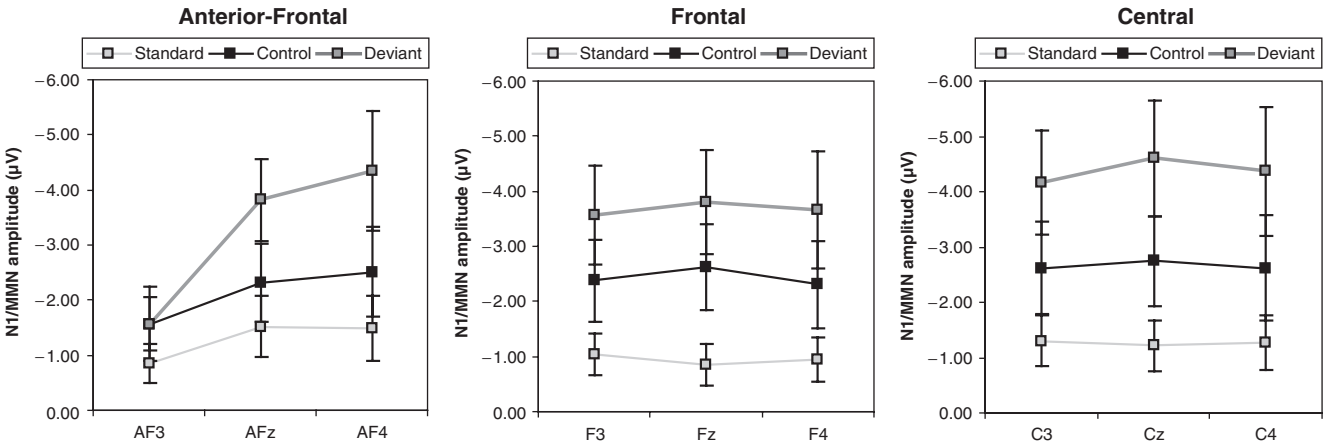

Figure 3. Frontocentral N1/MMN amplitude as a function of auditory stimulus type, averaged, separately for the anterior-frontal (AF3, AFz, and AF4), frontal (F3, Fz, and F4), and central (C3, Cz, and C4) electrodes. Error bars denote the standard error of the mean.

Discussion

The results showed that MMN and N1 were distinct in terms of overall amplitude, latency, and distributional properties and that N1, rather than MMN, could be related to auditory distraction. These results are discussed below in terms of the three hypotheses proposed in the Introduction regarding the separation of the N1 wave from the MMN component.

First, the "MMN-N1 additivity hypothesis" assumed that, if N1 and MMN were distinct ERP responses, then the amplitude of the frontocentral negativity in the N1/MMN latency range, elicited by deviants, would be higher than that elicited by identical tones presented within sequences of several different equiprobable tones. In support of this hypothesis, both the frontocentral and mastoid responses elicited by deviants were higher in amplitude relative to both one-token standards and nine-token controls. This result corroborates those of previous investigations (Jacobsen & Schröger, 2001; Jacobsen et al., 2003; Schröger & Wolff, 1996), which showed that a "genuine MMN" can be obtained by comparing the ERP response elicited by infrequent deviants with those elicited by the same sounds when they are delivered with the same sequential probability within a sequence in which each of several different sounds appears with equal probability.

Although this result is fully compatible with the concept of distinct N1 and MMN generators, the criticism raised in the Introduction against previous similar investigations (Jacobsen & Schröger, 2001; Jacobsen et al., 2003; Schröger & Wolff, 1996) also applies here. That is, it is not possible to determine how well the refractory status of the afferent neurons responding only to the control tones (from the nine-token sequences) matched that of the neurons responding only to the deviant tones (from the oddball sequence). This a priori criticism alone does not militate strongly against the MMN-N1 additivity hypothesis. Indeed, further evidence corroborative of the MMN-N1 additivity hypothesis could reside within the different patterns of the frontocentral and mastoid N1/MMN peak latencies. Whereas frontocentrally, the N1/MMN peak latency monotonously decreased with increasing set sizes, at the mastoids, the peak latency of the deviant-stimulus response was approximately equal to the corresponding measure from the nine-token sequence. This result is, again, compatible with the assumption of a distinct generation processes for N1 and MMN. However, it could be possible to strain the assumptions of the N1 adaptation explanation of MMN (Jääskeläinen et al., 2004) that these deviance-related latency effects might be explained by differential adaptation of some N1 generation process.

According to the "distribution hypothesis," the peak of the MMN response should exhibit scalp topography distinct from those of the N1 enhancements obtained with increases in set size. The results showed exactly that (Figures 2 and 3). The enhancement of N1 with increases in set size exhibited a more frontal and central than anterior frontal distribution, whereas the difference between the oddball deviant and nine-token control tone responses showed a more anterior frontal and frontal than central distribution. These differences in distribution were apparent in the pattern of significance: The set size enhancement of nine-token over one-token responses (N1) was similar over frontal and central sites, yet was attenuated at anterior-frontal sites; the oddball-deviant over nine-token control enhancement (MMN) was stable over frontal and anterior-frontal sites, yet was attenuated at central sites. This significant anterior-frontal/frontally distributed MMN and frontocentrally distributed N1 was also consistent with previous results regarding the scalp-distribution differences between N1 and MMN (Alho, 1995). Thus these results were compatible with the notion of a different configuration of generators for the N1 and MMN components. However, the N1 adaptation explanation of MMN (Jääskeläinen et al., 2004) might also explain this result by differential refractory features of the various N1 subcomponents.

Third, a "functional hypothesis" was proposed. According to this hypothesis, increasing the number of changes within the ignored sequence of sounds—irrespective of whether those changes elicit an MMN or not—will produce increasing memory disruption in the primary task. This hypothesis is based on the view that change is a condition for the disruption of serial recall performance by auditory distraction (Jones, 1993, 1994; Jones, Alford, Bridges, Tremblay, & Macken, 1999; Jones, Alford, Macken, Banbury, & Tremblay, 2000; Jones, Beaman, & Macken, 1996; Jones, Farrand, Stuart, & Morris, 1995; Jones, Macken, & Mosdell, 1997; Jones, Madden, & Miles, 1992; Jones, Saint-Aubin, & Tremblay, 1999; Martín-Loeches &

Sommer, 1998; Tremblay & Jones, 1998). Accordingly, MMN would show no special role in memory disruption. In support of the functional hypothesis, the results showed that increments in the set size of the ignored sequences of sound from one to nine tokens, as well those from two to nine tokens, impaired memory task performance. In contrast, no significant difference in memory disruption was found between the one- and the two-token (oddball) conditions.

Thus, the behavioral findings are consistent with the view that memory disruption is related to auditory change, irrespective of whether the change violates some regularity or not. Indeed, the number of changes increased dramatically between the two- and nine-token sequences. Whereas two-token sequences contained only nine changes (two per deviant, except for the sequence-final one), in the nine-token sequences, each stimulus exhibited a change from the preceding one (see Methods). Because MMN elicitation could only be expected in the oddball (two-token) sequence, the behavioral results suggest that MMN plays no special role in the memory disruption caused by ignored sounds. Rather, the generation of N1 remains more tenably related to the mechanisms via which auditory change produces memory disruption (Campbell et al., 2002, 2003, 2005). N1 would also be elicited under circumstances when a repeated standard still produces a disruption relative to silence despite the absence of change within the ignored sequence of sounds (Tremblay & Jones, 1998, Experiment 1; LeCompte, 1995, Experiments 1–5). Further, increases in memory load have been shown to increase disruption while augmenting N1 (Valtonen, Mäkinen, May, & Tiitinen, 2003). This load-related N1 enhancement occurred alongside an increase in disruption, even when the amount of changes in ignored auditory sequences was identical. The point is that the same changes were more disruptively potent under conditions of higher memory load (see also Gisselgård, Petersson, Baddeley, & Ingvar, 2003; Gisselgård, Petersson, & Ingvar, 2004; Campbell, 2005; Gisselgård, Uddén, Ingvar, & Petersson, 2007), conditions which also augment the N1 amplitude (Valtonen et al., 2003). Accordingly, disruption could be related to the neuronal generation of the response to the ignored sounds, which causes augmented N1 responses, rather than disruption being directly related to auditory change processing per se.

Previous investigations (Campbell et al. 2003, 2005) have shown increased N1 amplitudes to coincide with memory disruption. The current results are compatible with these findings. First, the N1 amplitude was significantly higher in the nine- than in the one-token sequences. Whereas the averages collected from the analysis period provide a good estimate for the average N1 amplitude in the one- and nine-token sequences, estimating the N1 amplitude in the oddball sequence requires a weighted average of the responses elicited by deviant and standard stimuli. Out of the 45 tones presented during the trials, 5 were deviants, 40 standards. Thus the estimate would be $(40 \times A_s + 5 \times A_d)/45$, where A_s and A_d denote the amplitude measured for standards and deviants, respectively. Parenthetically, it is also assumed that the presence of the prelude has no effect on either memory disruption or N1, which was confirmed by the results.

The above formula shows that the average N1 amplitude for the whole oddball sequence would be only slightly higher than the N1 amplitude elicited by standards, which in turn can be expected to be approximately equal to the N1 amplitude in the one-token sequences. In passing, it is worth considering that this estimate of the average N1 amplitude does not take into account the possibility that a part of the response elicited by deviants may be distinct from N1, that is, it is MMN. Taking that into account would bring the estimated average N1 amplitude of the oddball sequences even closer to the one-token N1 amplitude.

Thus, the full-sequence average N1 amplitudes would show the following relationship $A_1 \cong A_2 < A_9$, where A_1, A_2, and A_9 denote the average amplitudes for the one-, two-, and nine-token sequences, respectively. This pattern was exactly that observed for the amount of memory disruption in the experimental conditions. Thus, the current results support the N1 hypothesis of memory disruption (Campbell et al., 2003, 2005).

In terms of the functional hypothesis separating N1 and MMN, the current results provided evidence for a functional distinction of the processes underlying the observable N1 and MMN responses. Whereas the N1 amplitude was found to be closely related to the amount of memory disruption, no evidence was found for an effect of MMN upon memory disruption. Furthermore, the presence or absence of the prelude—a manipulation of the strength of the memory trace of the standard stimulus—showed no discernible effect upon memory disruption. This result is somewhat surprising, because in previous studies it was often found that infrequent deviants eliciting MMN can distract from an ongoing task (for a review, see Escera, Alho, Schröger, & Winkler, 2000). These studies also found that the P3a component, usually interpreted as an ERP index of attention switching (Friedman, Cycowicz, & Gaeta, 2001) was concomitant with the behavioral distraction. However, in the current study, no P3a increase accompanied the increase of memory disruption (see Figure 2). We, therefore, suggest that the memory disruption observed in the current study relies on different mechanisms than those commonly observed for distraction in studies employing the oddball paradigm. The lack of an increase in P3a alongside an increase in memory disruption may be taken as a sign that the current form of memory disruption does not require attentional capture. A distinct form of auditory distraction has been extensively investigated previously.The generation of P3a has been suggested to be a necessary condition for this distinct form of distraction to produce a disruption of performance (Escera et al., 2000). Corroborative evidence of a slightly different sort (Rinne, Särkkä, Degerman, Schröger, & Alho, 2006) has indicated that there is a form of distraction that is associated with the increase of the N1 amplitude, yet dissociated from a distinct form of distraction that is, instead, associated with the MMN. Although the primary task was different from the current one, the differences in character of the distraction associated with MMN and N1 could parallel the functional distinction between N1- and MMN-related processes found in the current study. One may also argue that the advantage of the nine-token sequence over the two-token (oddball) one in memory disruption was due to the fact that relatively few deviants appeared in the oddball sequence. However, using the "optimal MMN" paradigm (Näätänen, Pakarinen, Rinne, & Takegata, 2000), which delivers MMN-eliciting sounds with a high temporal density, we found no increase in memory disruption relative to that occurring in the corresponding one-token sequence (Laitinen & Campbell, 2006). Furthermore, it has been shown that the temporal frequency of changes does not strongly affect the amount of memory disruption (see Tremblay & Jones, 1998, Experiment 4). These results are compatible with the view that the factors influencing N1 also influence memory disruption, whereas the factors specifically influencing MMN elicitation do not (Campbell et al., 2002, 2003, 2005).

In summary, the current results confirmed all three hypotheses set up to distinguish MMN from N1. Deviants in the oddball

condition elicited a higher amplitude response in the N1/MMN latency range than identical tones presented with equal probability within the nine-token sequences (additivity hypothesis). The scalp distribution of the response elicited by deviants (oddball condition) was different from that elicited by identical tones in the one- and nine-token conditions (distribution hypothesis). Finally, there was no special role for MMN in producing memory disruption in a delayed serial recall task (cf. pitch discimination; Rinne et al., 2006). In contrast, memory disruption and the N1 amplitude increased together (functional hypothesis), as was found previously (Campbell et al., 2003, 2005; Valtonen et al., 2003). In addition, differences were found between the oddball deviant and the identical tones of the one- and nine-token conditions in the scalp distribution of the N1/MMN peak latency. Taken together, these results support the existence of MMN generators that are separate from those of the auditory N1 wave.

Some of the other results obtained in the current investigation corroborate previous findings. Frontocentrally, the N1 response to control tones was less refractory than that seen to the one-token sequence. There was also a refractoriness-related prolongation in N1 latency to standards relative to control, both at the mastoids and frontocentrally. These results confirm previous similar observations (e.g., Jacobsen et al., 2003).

One result, however, contrasts with previous findings. The absence of a disruption produced by pitch deviation shown in this experiment, when such a disruption has been seen in a previous investigation (Lange, 2005) is a discrepancy that can, however, be readily reconciled. Deviants were presented during the retention interval in the current experiment, whereas deviants were presented alongside the to-be-remembered list in this previous investigation (Lange, 2005). Together these findings are thus broadly commensurate with those of a recent series of behavioral experiments (Hughes, Vachon, & Jones, 2005): Only deviants presented during the interval when the to-be-remembered items are delivered, and not deviants presented during a retention interval, produce a disruption of memory on a delayed serial recall task. The common cognitive requirement of presentation and retention intervals is that of memory retention, whereas one key difference is that new information is being registered into memory during the presentation interval. That processing of deviant ignored material disrupts performance when deviants are heard during presentation, yet not when deviants are heard during the retention interval, could indicate that deviant processing of the to-be-ignored sound disrupts the registration of new to-be-attended material into memory rather than the retention of that material.

A final discrepancy with the experimental precedent was that a significant influence of prelude was neither seen upon MMN nor upon memory disruption. The implication for MMN is that two repetitions of the standard tone (three identical tones in a row) were sufficient for a distinct MMN to be elicited by subsequent deviants (cf. Cowan et al., 1993). For theoretical accounts of memory disruption (Campbell et al., 2003, 2005; Jones, 1993; Jones et al., 1996), the implication is that deviations from a previously detected regularity may interfere with the registration of new material into memory (Hughes et al., 2005; Lange, 2005). By contrast, all changes, irrespective of whether they represent deviation from a previously detected regularity, interfere with the retention of material that has been already registered into memory.

REFERENCES

Alcaini, M., Giard, M. H., Thévenet, M., & Pernier, J. (1994). Two separate frontal components in the N1 wave of the human auditory-evoked response. *Psychophysiology*, *31*, 611–615.

Alho, K. (1995). Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. *Ear and Hearing*, *16*, 38–51.

Barry, R. A., Cocker, K. L., Anderson, J. W., Gordon, E., & Rennie, C. (1992). Does the N100 evoked potential really habituate? Evidence from a paradigm appropriate to a clinical setting. *International Journal of Psychophysiology*, *13*, 9–12.

Butler, R. A. (1968). Effects of changes in stimulus frequency and intensity on habituation of the human vertex potential. *Journal of the Acoustical Society of America*, *44*, 945–950.

Campbell, T. A. (2005). The cognitive neuroscience of auditory distraction. *Trends in Cognitive Sciences*, *9*, 3–5.

Campbell, T. A., Beaman, C. P., & Berry, D. C. (2002). Auditory memory and the irrelevant sound effect: Further evidence for changing-state disruption. *Memory*, *10*, 199–214.

Campbell, T. A., Winkler, I., & Kujala, T. (2005). Disruption of immediate memory and brain processes: An auditory ERP protocol. *Brain Research Protocols*, *14*, 77–86.

Campbell, T. A., Winkler, I., Kujala, T., & Näätänen, R. (2003). The N1 hypothesis and irrelevant sound: Evidence from token set effects. *Cognitive Brain Research*, *18*, 39–47.

Cowan, N., Winkler, I., Teder, W., & Näätänen, R. (1993). Memory prerequisites of mismatch negativity in the auditory event-related potential (ERP). *Journal of Experimental Psychology: Learning, Memory and Cognition*, *19*, 909–921.

de Boor, C. (1978). *A practical guide to splines*. New York: Springer-Verlag.

Escera, C., Alho, K., Schröger, E., & Winkler, I. (2000). Involuntary attention and distractibility as evaluated with event related brain potentials. *Audiology and Neuro-otology*, *5*, 151–166.

Friedman, D., Cycowicz, Y. M., & Gaeta, H. (2001). The novelty P3: An event-related brain potential (ERP) sign of the brain's evaluation of novelty. *Neuroscience and Biobehavioral Reviews*, *25*, 355–373.

Gisselgård, J., Petersson, K. M., Baddeley, A. D., & Ingvar, M. (2003). The irrelevant speech effect: A PET study. *Neuropsychologia*, *241*, 1899–1911.

Gisselgård, J., Petersson, K. M., & Ingvar, M. (2004). The irrelevant speech effect and working memory load. *NeuroImage*, *41*, 1899–1911.

Gisselgård, J., Uddén, J., Ingvar, M., & Petersson, K. M. (2007). Disruption of order information by irrelevant items: A serial recognition paradigm. *Acta Psychologica*, *124*, 356–369.

Hughes, R. W., Vachon, F., & Jones, D. M. (2005). Auditory attentional capture during serial recall: Violations at encoding of an algorithm-based neural model? *Journal of Experimental Psychology: Learning, Memory and Cognition*, *3*, 736–749.

Jacobsen, T., & Schröger, E. (2001). Is there pre-attentive memory-based comparison of pitch? *Psychophysiology*, *38*, 723–727.

Jacobsen, T., Schröger, E., Horenkamp, T., & Winkler, I. (2003). Mismatch negativity to pitch change: Varied stimulus proportions in controlling effects of neural refractoriness on human auditory event related brain potentials. *Neuroscience Letters*, *344*, 79–82.

Javitt, D. C. (2000). Intracortical mechanisms of mismatch negativity dysfunction in schizophrenia. *Audiology and Neuro-otology*, *5*, 207–215.

Javitt, D. C., Steinschneider, M., Schroeder, C. E., & Arezzo, J. C. (1996). Role of cortical N-methyl-D-aspartate receptors in auditory sensory memory and mismatch negativity generation: implications for schizophrenia. *Proceedings of The National Academy of Sciences, USA*, *93*, 11962–11967.

Jones, D. M. (1993). Objects, streams and threads of auditory attention. In: A. D. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness and control*. Oxford: Clarendon Press.

Jones, D. M. (1994). Disruption of memory for lip-read lists by irrelevant speech: Further support for the changing-state hypothesis. *Quarterly Journal of Experimental Psychology*, *47A*, 143–160.

Jones, D. M., Alford, D. K., Bridges, A., Tremblay, S., & Macken, W. J. (1999). Organizational factors in attention: The interplay of acoustic distinctiveness and auditory streaming in the irrelevant sound effect. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *25*, 464–473.

Jones, D. M., Alford, D., Macken, W. J., Banbury, S., & Tremblay, S. (2000). Interference from auditory degraded stimuli: Linear effects of stimulus mis-match in the irrelevant sequence. *Journal of the Acoustical Society of America*, *108*, 1082–1088.

Jones, D. M., Beaman, C. P., & Macken, W. J. (1996). The object-oriented episodic record model. In S. E. Gathercole (Ed.), *Models of short-term memory*. Hove, UK: Psychology Press.

Jones, D. M., Farrand, P., Stuart, G., & Morris, N. (1995). Functional equivalence of verbal and spatial information in serial short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 1008–1018.

Jones, D. M., Macken, W. J., & Mosdell, N. (1997). The role of habituation in the disruption of recall performance by irrelevant sound. *The British Journal of Psychology*, *88*, 549–564.

Jones, D. M., Madden, C., & Miles, C. (1992). Privileged access by irrelevant speech to short-term memory: The role of changing state. *Quarterly Journal of Experimental Psychology*, *44A*, 645–669.

Jones, D. M., Saint-Aubin, J., & Tremblay, S. (1999). Modulation of the irrelevant sound effect by organizational factors: Further evidence from streaming by location. *Quarterly Journal of Experimental Psychology*, *52A*, 545–554.

Jääskeläinen, I. P., Ahveninen, J., Bonmassar, G., Dale, A. M., Ilmoniemi, R. J., Levanen, S., et al. (2004). Human posterior auditory cortex gates novel sounds to consciousness. *Proceedings of The National Academy of Sciences, USA*, *101*, 6809–6814.

Kopp, F., Schröger, E., & Lipka, S. (2004). Neural networks engaged in short-term memory rehearsal are disrupted by irrelevant speech in human subjects. *Neuroscience Letters*, *354*, 42–45.

Kopp, F., Schröger, E., & Lipka, S. (2006). Synchronized brain activity during rehearsal and short-term memory disruption by irrelevant speech is affected by recall mode. *International Journal of Psychophysiology*, *61*, 188–203.

Korzyukov, O., Alho, K., Kujala, A., Gumenyuk, V., Ilmoniemi, R. J., Virtanen, J., et al. (1999). Electromagnetic responses of the human auditory cortex generated by sensory-memory based processing of tone-frequency changes. *Neuroscience Letters*, *276*, 169–172.

Korzyukov, O., Winkler, I., Gumenyuk, V., & Alho, K. (2003). Processing abstract auditory features in the human auditory cortex. *NeuroImage*, *20*, 2245–2258.

Laitinen, J., & Campbell, T. (2006) Distracting effects of ignored deviants within the optimal paradigm for elicitation of the mismatch negativity? Manuscript in preparation.

Lange, E. B. (2005). Disruption of attention by irrelevant stimuli in serial recall. *Journal of Memory and Language*, *53*, 513–531.

LeCompte, D. C. (1995). An irrelevant speech effect with repeated and continuous background speech. *Psychonomic Bulletin and Review*, *2*, 391–397.

Martín-Loeches, M., & Sommer, W. (1998). Testing models of the irrelevant speech effect on working memory with event-related potentials. *Zeitschrift für Psychologie*, *206*, 1–22.

May, P. J. C., & Tiitinen, H. (2001). Human cortical processing of auditory events over time. *NeuroReport*, *12*, 573–577.

May, P. J. C., & Tiitinen, H. (2004). The MMN is a derivative of the auditory N100 response. *Neurology and Clinical Neurophysiology*, *20*, 1–5.

Moore, D. R. (2003). Cortical neurons signal sound novelty. *Nature Neuroscience*, *6*, 330–332.

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, *42*, 313–329.

Näätänen, R., Jacobsen, T., & Winkler, I. (2005). Memory-based or afferent processes in mismatch negativity (MMN): A review of the evidence. *Psychophysiology*, *42*, 25–32.

Näätänen, R., Paavilainen, P., & Reinikainen, K. (1989). Do event-related potentials to infrequent decrements in duration of auditory stimuli demonstrate a memory trace in man? *Neuroscience Letters*, *107*, 347–352.

Näätänen, R., Pakarinen, S., Rinne, T., & Takegata, R. (2000). The mismatch negativity (MMN) towards the optimal paradigm. *Clinical Neurophysiology*, *115*, 140–144.

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

Näätänen, R., & Winkler, I. (1999). The concept of auditory stimulus representation in cognitive neuroscience. *Psychological Bulletin*, *6*, 826–859.

Oceák, A., Winkler, I., Sussman, E., & Alho, K. (2006). Loudness summation and the mismatch negativity event-related brain potential in humans. *Psychophysiology*, *43*, 13–20.

Opitz, B., Schröger, E., & von Cramon, D. Y. (2005). Sensory and cognitive mechanisms for preattentive change detection in auditory cortex. *European Journal of Neuroscience*, *21*, 531–535.

Paavilainen, P., Simola, J., Jaramillo, M., Näätänen, R., & Winkler, I. (2001). Preattentive extraction of abstract feature conjunctions from auditory stimulation as reflected by the mismatch negativity (MMN). *Psychophysiology*, *38*, 359–365.

Pekkonen, E. (2000). Mismatch negativity in aging and in Alzheimer's and Parkinson's diseases. *Audiology and Neuro-otology*, *5*, 216–224.

Pekkonen, E., Hirvonen, J., Ahveninen, J., Kähkönen, S., Kaakkola, S., Huttunen, J., et al. (2002). Memory-based comparison process not attenuated by haloperidol: A combined MEG and EEG study. *NeuroReport*, *13*, 177–181.

Rinne, T., Gratton, G., Fabiani, M., Cowan, N., Maclin, E., Stinard, A., et al. (1999). Scalp-recorded optical signals make sound processing in the auditory cortex visible. *NeuroImage*, *10*, 620–624.

Rinne, T., Särkkä, A., Degerman, A., Schröger, E., & Alho, K. (2006). Two separate mechanisms underlie auditory change detection and involuntary control of attention. *Brain Research*, *1077*, 135–143.

Saarinen, J., Paavilainen, P., Schröger, E., Tervaniemi, M., & Näätänen, R. (1992). Representation of abstract stimulus attributes in human brain. *NeuroReport*, *3*, 1149–1151.

Schröger, E., & Wolff, C. (1996). Mismatch response to changes in sound location. *NeuroReport*, *7*, 3005–3008.

Tremblay, S., & Jones, D. M. (1998). The role of habituation in the irrelevant sound effect: Evidence from the role of token set size and rate of habituation. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *24*, 659–671.

Ulanovsky, N. (2004) Neuronal adaptation in cat auditory cortex. Doctoral dissertation. Jerusalem, Israel: Hebrew University.

Ulanovsky, N., Las, L., Farkas, D., & Nelken, I. (2004). Multiple time scales of adaptation in auditory cortex neurons. *Journal of Neuroscience*, *24*, 10440–10453.

Ulanovsky, N., Las, L., & Nelken, I. (2003). Processing of low-probability sounds by cortical neurons. *Nature Neuroscience*, *6*, 391–398.

Umbricht, D., Schmid, L., Koller, R., Vollenweider, F. X., Hell, D., & Javitt, D. C. (2000). Ketamine-induced deficits in auditory and visual context-dependent processing in healthy volunteers. *Archives of General Psychiatry*, *57*, 1139–1147.

Valtonen, J., Mäkinen, V., May, P. J. C., & Tiitinen, H. (2003). Visual short-term memory load affects sensory processing of irrelevant sounds in human auditory cortex. *Cognitive Brain Research*, *17*, 358–367.

Virtanen, J., Ahveninen, J., Ilmoniemi, R. J., Näätänen, R., & Pekkonen, E. (1998). Replicability of MEG and EEG measures of the auditory N1/N1m-response. *Electroencephalography and Clinical Neurophysiology*, *108*, 291–298.

Virtanen, J., Rinne, T., Ilmoniemi, R. J., & Näätänen, R. (1996). MEG-compatible multichannel EEG electrode array. *Electroencephalography and Clinical Neurophysiology*, *99*, 568–570.

Winkler, I., Tervaniemi, M., & Näätänen, R. (1997). Two separate codes for missing-fundamental pitch in the human auditory cortex. *Journal of the Acoustical Society of America*, *102*, 1072–1082.

Woods, D. L., & Elmasian, R. (1986). The habituation of event-related potentials to speech sounds and tones. *Electroencephalography and Clinical Neurophysiology*, *65*, 447–459.

Yabe, H., Tervaniemi, M., Sinkkonen, J., Huotilainen, M., Ilmoniemi, R. J., & Näätänen, R. (1998). Temporal window of integration of auditory information in the human brain. *Psychophysiology*, *35*, 615–619.

(Received October 6, 2006; Accepted March 15, 2007)