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Changes in brain electrical activity during extended continuous word recognition

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Twenty healthy subjects (10 men, 10 women) participated in an EEG study with an extended continuous recognition memory task, in which each of 30 words was randomly shown 10 times and subjects were required to make old vs. new decisions. Both event-related brain potentials (ERPs) and induced band power (IBP) were investigated. We hypothesized that repeated presentations affect recollection rather than familiarity.

For the 300- to 500-ms time window, an 'old/new' ERP effect was found for the first vs. second word presentations. The correct recognition of an 'old' word was associated with a more positive waveform than the correct identification of a new word. The old/new effect was most pronounced at and around the midline parietal electrode position. For the 500- to 800-ms time window, a linear repetition effect was found for multiple word repetitions. Correct recognition after an increasing number of repetitions was associated with increasing positivity. The multiple repetitions effect was most pronounced at the midline central (Cz) and fronto-central (FCz) electrode positions and reflects a graded recollection process: the stronger the memory trace grows, the more positive the ERP in the 500- to 800-ms time window. The ERP results support a dual-processing model, with familiarity being discernable from a more graded recollection state that depends on memory strengths.

For IBP, we found 'old/new' effects for the lower-2 alpha, theta, and delta bands, with higher bandpower during 'old' words. The lower-2 alpha 'old/new' effect most probably reflects attentional processes, whereas the theta and delta effects reflect encoding and retrieval processes. Upon repeated word presentations, the magnitude of induced delta power in the 375- to 750-ms time window diminished linearly. Correlation analysis suggests that decreased delta power is moderately associated with faster decision speed and higher accuracy.

Keywords: Event-related brain potentials; Induced band power; Alpha; Theta; Delta; Old/new effect; Recognition; Familiarity; Recollection

Introduction

In event-related electrical potential (ERP) studies of recognition memory, the word-repetition (old/new) effect has been well established. If words are presented twice in a single series, the correct identification of words that are shown for the second time (i.e., as 'old' stimuli) is associated with an increased positivity of the ERP waveform in the time range of 300–800 ms after stimulus onset (for reviews, see Mecklinger, 2000; Rugg, 1995). This 'old/new' effect has been explained by Rugg (1995) as a reduction of the word-elicited N400 by a positive component that reflects the awareness that a word has recently been experienced. According to dual-process models of recognition, recognition may be the result of either the conscious recollection of having previously seen the word or a more implicit familiarity. There is evidence that the ERP old/new effect comprises an early component (<500 ms) related to familiarity and a later component (>500 ms) related to recollection. The early component is often labeled with "N400" (time window 300–500 ms), the later component with "late positive complex" (LPC, time window 500–800 ms). The ERP familiarity component usually has a frontal–central distribution and is thought to reflect a relatively fast and automatic global matching process, whereas the ERP recollection component has a left greater than right parietal distribution and is thought to reflect a memory retrieval process that supports novel learning (Rugg and Yonelinas, 2003; Yonelinas, 2002).

The 'old/new' effect is not only found with ERPs but also with induced band power (IBP). The IBP procedure measures changes in the EEG frequency domain. During the test phase of their study, Klimesch et al. (2000) had participants to recognize words that had been shown during the study phase. Correctly recognized targets resulted in larger increases in delta (approximately 2–4 Hz) and theta (approximately 4–6 Hz) power, when compared to correctly rejected words.

The IBP 'old/new' effect is functionally related to the ERP 'old/new' effect, but because IBP is devoid of phase-locked ERP

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activity, they are independent and complementary measures (Klimesch et al., 2000). The ERP indexes phase-locked evoked activity, which reflects the summation of transient post-synaptic potentials in large groups of cortical pyramidal neurons triggered by an event. IBP indexes non-phase locked induced activity, which is thought to reflect changes in the parameters controlling dynamic interactions within and between brain structures (Bastiaansen and Hagoort, 2003; Pfurtscheller and Lopes da Silva, 1999).

'Old/new' studies employ either a study phase followed by a test phase in which the studied items have to be recognized from a list of targets and distractors or a continuous recognition paradigm in which 'new' (=first presentation) and 'old' (=second presentation) items are intermixed. In both paradigms, a word is typically repeated just once. It is unknown what the repetition effects will look like, if the same word is repeated over and over again in the same series. With verbal learning tests such as the Rey Auditory Verbal Learning Test or the California Verbal Learning Test, words have to be recalled after each of the five successive presentations of a 15- or 16-item word list (see Lezak, 1995). Healthy individuals show an asymptotic learning curve upon repeated presentations, with the largest memory performance enhancements at the first trials of the series (e.g., Van Strien, 1999). Because these tests require an active recall of the list words, the learning curve obviously reflects a strengthening of memory traces, which aids memory retrieval.

The present EEG-study examined the word-repetition effect for up to nine repetitions of 30 different words in a continuous word recognition paradigm. Both ERPs and IBP were analyzed. We expected to find 'old/new' effects with both techniques. Because additional repetitions of the words (up to nine times) will result in better memory retrieval, we hypothesized that multiple repetitions affect the later ERP recollection component rather than the earlier ERP familiarity component. Furthermore, because there is evidence that the delta, theta, and alpha frequency bands are sensitive to task difficulty and decision making (e.g., Basar et al., 2001; Gevins et al., 1997; Harmony et al., 1996), it was anticipated that the delta and theta bands will show a decrease and the alpha bands will show an increase in activity across the nine word repetitions.

Methods

Participants

Twenty healthy Dutch-speaking students (10 men, 10 women) volunteered for the experiment and were paid for their participation. They ranged in age from 19 to 29 years, with a mean age of 23.1 years. All participants had normal or corrected-to-normal vision and were right-handers by self-report.

Stimuli

The continuous recognition memory task contained 330 trials. In each trial, one of a set of 30 Dutch mono- and bisyllabic words (length: 3–7 letters) was presented on a 17-in. VGA monitor screen. Words were displayed in the 36-points uppercase Swiss roman font. Each word was presented ten times in random order: each trial therefore was either a new word, or a first, second to ninth repetition. In addition, 30 filler words (i.e. new words that were not repeated, but that were necessary to generate "new" responses) were presented, semi-randomly mixed with new words and word repetitions. New words were presented within the first 45% of trials, while the presentation of filler words started after the first 17% of trails. The filler items were not included in the data analysis. All stimuli were frequent and imaginable nouns, such as the Dutch words for "chair", "shoe", "bread", and "flower".

Procedure

The sequence for each trial was: (1) the presentation of a fixation cross in the center of the screen with a variable duration of 400 to 600 ms, (2) the 300 ms presentation of the word in the center of the screen, and (3) the 1200 ms presentation of the fixation cross. The interval between the end of one trial and the beginning of the next trial lasted 1500 ms. Participants were seated in an electrically-shielded, sound attenuated, and dimly-lit chamber at a distance of approximately 150 cm in front of a window. The monitor was placed outside the chamber, directly behind the window. Participants were told that words would be repeatedly presented and that for each trial, they had to indicate whether the word was new or familiar by pressing response buttons with the right index or middle finger, respectively. To minimize eye movements, which may lead to ERP-artifacts, the participants were instructed to avoid eye blinks during stimulus presentations (words and fixation cross). Preceding the experimental run, the participants received 21 practice trials with words that were not used in the experimental run.

EEG recording

EEG activity was recorded from 30 Ag/AgCl electrodes positioned according to the International 10–20 System at Fz, FCz, Cz, CPz, Pz, Oz, FP1/2, F3/4, F7/8, FC3/4, FT7/8, C3/4, T7/8, CP3/4, TP7/8, P3/4, P7/8, and O1/2. The electrodes were embedded in an elastic cap (Quick-Cap, NeuroMedical Supplies). The EEG was referenced to the linked mastoids. Impedances of the EEG electrodes were kept below 5 kΩ. Electro-oculogram (EOG) activity was recorded from electrodes placed above and beneath the left eye, and from electrodes at the outer canthus of each eye. The EEG and EOG signals were amplified with a band pass of 0.15 to 70 Hz and digitized with a 500 Hz sampling rate (SynAmps amplifier, Neurosoft Inc.). Response latencies were recorded online along with the EEG data.

The off-line processing of the EEG signals consisted of the correction for vertical ocular artifacts employing the regression approach of Semlitsch et al. (1986) and the offline low pass filtering at 30 Hz (48 dB roll-off).

Data analyses

Event-related potentials

ERP epochs with a 1100-ms duration were extracted, beginning 100 ms prior to stimulus onset. The ERP signals were defined relative to the mean of the 100 ms prestimulus baseline period. Average ERPs were computed for each participant and each task condition. Epochs with incorrect responses and epochs with a baseline-to-peak amplitude larger than 75 μV on any channel (e.g., muscle artifacts) were excluded from averaging. The mean numbers of valid epochs per condition ranged from 20.35 (first repetition) to 28.7 (seventh repetition), with a mean across conditions of 26.71.

ERP waveforms were quantified by mean amplitude measures for three time windows: 140–220 ms, 300–500 ms, and 500–800 ms. The 140- to 220-ms window was utilized to represent the posterior-N180/anterior-P180 peak. This peak represents the early automatic stage of word-processing, that is, the processing of well-learned stimuli such as letter strings (Hillyard et al., 1998). Consistent with previous ERP studies (e.g., Finnigan et al., 2002; Rugg et al., 1998), the 300–500 ms window was utilized to represent the N400 and the 500- to 800-ms window to represent the LPC.

Induced band power

To analyze induced band power changes during continuous word recognition, the EEG was filtered for the delta, theta, lower-1 alpha, lower-2 alpha, and upper alpha bands, respectively. The frequency bands were based on the individual alpha peak frequency (IAF, see Klimesch, 1999). For each participant, the maximum power in the 7- to 13-Hz frequency range was determined by averaging the power spectra over epochs and electrodes. Across participants, the mean IAF equaled 10.38 Hz (SD = 1.07). The frequency bands were: delta (IAF-8 Hz to IAF-6 Hz), theta (IAF-6 Hz to IAF-4 Hz), lower-1 alpha (IAF-4 Hz to IAF-2 Hz), lower-2 alpha (IAF-2 Hz to IAF), and upper alpha (IAF to IAF + 2 Hz). For each frequency band, a zero phase band pass filter was employed with 2 Hz band width and 96 dB/oct roll-off. Epochs with a 1375 ms duration were extracted, beginning 375 ms prior to stimulus onset. Epochs with incorrect responses and epochs with a baseline-to-peak amplitude larger than 100 μV on any channel were excluded from analysis.

For each frequency band, condition, and electrode, IBP measures were obtained by computing the intertrial variance for each sample point across epochs. This procedure removes the average evoked activity from the data (Kalcher and Pfurtscheller, 1995). The sample point variances were then averaged within consecutive time windows of 125 ms starting at stimulus onset and expressed as percentage change relative to the 375-ms prestimulus baseline, with positive percentages denoting power increases and negative percentages denoting power decreases.

Statistical analyses

The behavioral data were analyzed by means of a repeated-measures analysis of variance (rmANOVA), in which all 10 repetition levels (new words, repetitions 1–9) were included.

The ERP data were analyzed using rmANOVAs with *repetition* (10 levels) and *location* as factors within subjects. F ratios were tested with Greenhouse–Geisser corrected degrees of freedom. In case of a significant interaction of repetition and location, contrasts were computed for (a) the old/new effect (i.e., first repetitions versus new words) and (b) the word repetition effect across the nine repetitions. Note that in this paper, 'word repetition' refers to the nine repeated presentations and not to the second vs. first presentations. When a contrast was significant, topographic voltage maps were constructed, and the most salient electrode sites were further analyzed statistically.

Because the IBP procedure yields large data sets, with 2400 (30 electrodes, 8 time windows, 10 conditions) cells for each frequency band, the 'old/new' effect and the repetition effect across the nine repetitions were tested directly with the data collapsed across electrodes. When there was a significant effect for a certain frequency band in a certain time window, the topographical distribution was further inspected and the most striking electrode sites were further analyzed statistically.

Results

Behavioral data

Mean percentages correct responses and latencies to new (first) word presentations and word repeatings (r1 to r9) are displayed in Fig. 1. The overall repetition effect was significant for both accuracy, $F(9,171) = 45.45$, $\varepsilon = 0.20$, $P < 0.001$, and latency, $F(9, 171) = 37.41$, $\varepsilon = 0.30$, $P < 0.001$. The difference between new words and first repetitions was significant, for both accuracy, $F(1,19) = 38.34$, $P < 0.001$, and latency, $F(1,19) = 14.65$, $P < 0.001$. As Fig. 1 shows, responses to words that were repeated for the first time were less accurate and less quick. Upon repeated presentations, accuracy improved and response latency diminished in a curvilinear fashion. The linear and quadratic trends across the nine repeatings were significant for both the accuracy measure [linear: $F(1,19) = 63.07$, $P < 0.001$; quadratic $F(1,19) = 73.18$, $P < 0.001$] and the latency measure [linear: $F(1,19) = 92.95$, $P < 0.001$; quadratic: $F(1,19) = 20.43$, $P < 0.001$].

Event-related potentials

For the 140- to 220-ms area measure, no significant interaction of repetition and location was found, $F(261, 4959) = 1.56$, $\varepsilon = 0.051$, $P = 0.092$. Exploratory analyses on the data of this time window revealed no significant interaction effects of location and either the 'old/new' effect, $F(29,551) = 1.59$, $\varepsilon = 0.171$, $P = 0.171$ or the first through ninth repetition effect, $F(232,4408) = 1.37$, $\varepsilon = 0.055$, $P = 0.178$. Therefore the 140–220 area measure was not further examined. There were significant interactions of repetition and location for the 300–500 ms area measure, $F(261, 4959) = 2.76$, $\varepsilon = 0.053$, $P = 0.001$, and the 500- to 800-ms area measure, $F(261, 4959) = 2.71$, $\varepsilon = 0.049$, $P = 0.001$. The 300- to 500-ms and 500- to 800-ms area measures were further analyzed employing contrasts for the 'old/new' effect and the first through ninth repetition effect.

'*Old/new*' *effect*

The grand average ERPs for the new words and the first repetitions are shown in Fig. 2. Compared to the first presentation

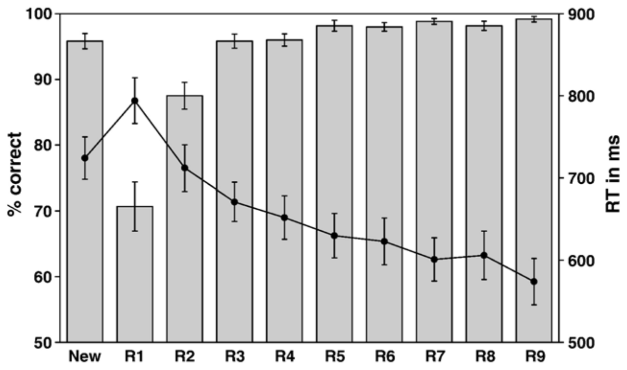

Fig. 1. Mean percentages correct responses (bar chart) and mean reaction times (RT) in milliseconds (line chart) on new words and nine repeatings (r1 to r9). Error bars depict the standard error of the means.

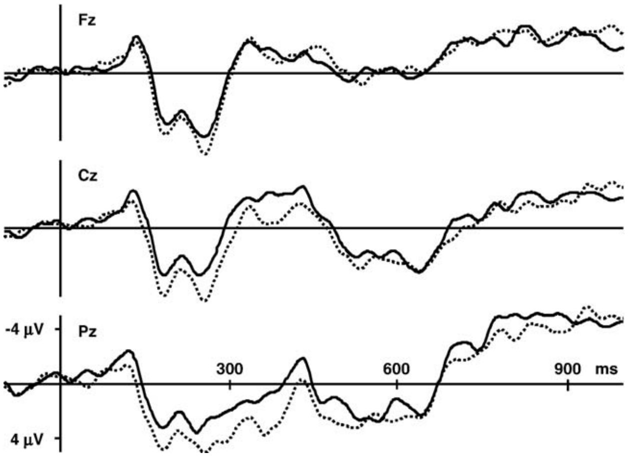

Fig. 2. Grand-average ERPs (n = 20) from Fz, Cz, and Pz of the first (=new word; solid lines) and second (=first repetition; dotted lines) presentations of the words.

(new words), the second presentation (first repetition) was associated with a more positive waveform at central and parietal electrode regions in the interval of about 140 to 500 ms. For the 300–500 ms area measure, there was a significant interaction of the 'old/new' effect and location, $F(29,551) = 2.94$, $\varepsilon = 0.193$, $P = 0.013$. The topographical distribution of this 'old/new' effect is depicted in Fig. 3. In the 300- to 500-ms time window, the largest old vs. new diffences were found at and around Pz. The average of the 300–500 ms area measure across the four parietal electrodes (P3, Pz, P4, and CPz) was significantly higher during the first repetition of the words (M = 1.69 µV) than during presentation of new words (M = 0.32 µV), $F(1,19) = 5.51$, $P < 0.03$.

For the 500- to 800-ms area measure, the interaction of the old/new effect and location was not significant, $F(29, 551) = 1.01$, $\varepsilon = 0.216$, $P = 0.422$.

First through ninth repetition

The grand-average ERPs at the Cz electrode site are displayed in Fig. 4 for new words, and the first, third, fifth, seventh, and ninth repetition. From this figure, it can be seen that, beginning at about 500 ms, the ERPs to the later presentations are associated with increasing positivity.

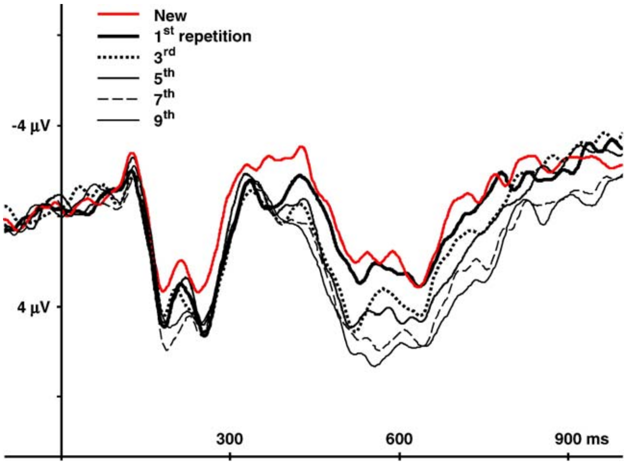

Fig. 4. Grand-average ERPs (n = 20) from Cz of new words (red line) and the first, third, fifth, seventh, and ninth repetition (for clarity, the even repetitions have been omitted from this graph).

For the 300- to 500-ms area measure, the rmANOVA revealed no significant interaction of location and the first through ninth repetition effect, $F(232,4408) = 1.60$, $\varepsilon = 0.057$, $P = 0.084$. Exploratory analyses of the linear and quadratic trends at individual electrode sites yielded no readable statistical results.

For the 500- to 800-ms area measure, the interaction of location and the first through ninth repetition effect was significant, $F(232,4408) = 2.44$, $\varepsilon = 0.053$, $P = 0.005$. In Fig. 5, the topographical distribution of the linear trends across all nine repetitions is depicted for the 500- to 800-ms area measures. The highest linear trends for the 500- to 800-ms interval were found at Cz, $F(1,19) = 11.42$, $P = 0.003$, and FCz, $F(1,19) = 11.52$, $P = 0.003$. No quadratic trends were found at these sites (both F's < 0.52).

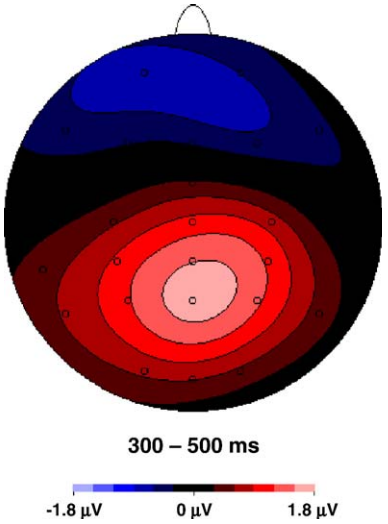

Fig. 3. Scalp distribution of the difference between ERPs to first repetitions (old words) and new words for the 300- to 500-ms area measure.

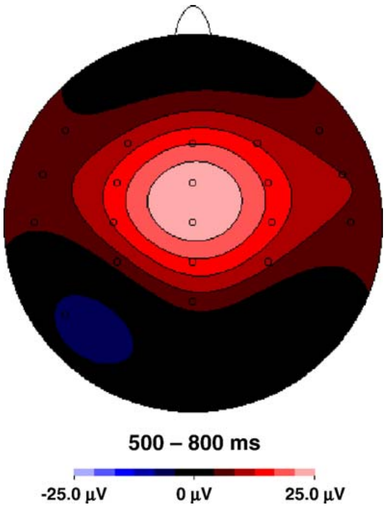

Fig. 5. Scalp distribution of the linear ERP trend for the 500–800 ms for the 500- to 800-ms area measures across the nine word repetitions.

Induced band power

Old/new effect

The mean IBP changes in delta, theta, lower-1 alpha, lower-2 alpha, and upper alpha collapsed across electrodes for new words and first repetitions are shown in Fig. 6. Compared to new words, the second presentation was associated with greater delta power, $F(1,19) = 17.30$, $P = 0.001$, and theta power, $F(1,19) = 6.18$, $P = 0.022$, in the 375- to 750-ms time window. In the 250–625 ms time window, new words elicited a lower-2 alpha power decrease, whereas first repetitions did not, $F(1,19) = 6.53$, $P = 0.019$. For the lower-1 alpha and upper alpha frequency bands, the ‘old/new’ effect was less marked.

The topographical distributions of the ‘old/new’ effect for the delta, theta, and lower-2 alpha bands are depicted in Fig. 7. As can be seen from this figure, the most robust delta increase during the 375- to 750-ms interval took place at left frontal and left fronto-temporal sites. Across FT7, F7, F3, and Fz, the ‘old/new’ effect was significant, $F(1,19) = 8.78$, $P = 0.008$. The most salient theta increase during the 375- to 750-ms interval was found at midline frontal and left fronto-polar sites. Across Fz and FP1, the ‘old/new’ effect was significant, $F(1,19) = 6.26$, $P = 0.022$. The lower-2 alpha decrease for new words was most pronounced at midline central and frontal sites. Across these electrodes (Fz, FCz, Cz), the ‘old/new’ effect was significant, $F(1,19) = 10.24$, $P = 0.005$.

First through ninth repetition

Across electrodes, a significant negative linear trend was found for the delta band in the 375- to 750-ms time window [overall repetition effect: $F(8,152) = 2.72$, $\varepsilon = 0.734$, $P = 0.018$; linear trend: $F(1,19) = 4.68$, $P = 0.044$; quadratic trend: $F(1,19) = 4.00$, $P = 0.060$]. The negative linear trend indicates that the later presentations are associated with decreasing delta activity. From Fig. 8, it can be seen that in the 375- to 750-ms time window, the most robust linear trends were found at midline frontal and fronto-central sites (Fz, FCz), at parasagittal frontal sites (F3, F4), and at the left fronto-lateral site (F7). The average repetition effect across these electrodes is shown in Fig. 9. The figure illustrates that delta power increases during the first repetition, but gradually decreases after the second repetition (with a steep decrement during the third repetition). For this electrode cluster, the linear trend was significant [overall repetition effect: $F(8,152) = 3.83$, $\varepsilon = 0.616$, $P = 0.004$; linear trend: $F(1,19) = 9.49$, $P = 0.006$; quadratic trend: $F(1,19) = 2.18$, $P = 0.156$].

To explore a possible relation between delta IBP and the behavioral measures, the correlations between latency, accuracy, and 375–750 ms frontal IBP change were computed for each participant across the 10 conditions (new words, repetition 1–9). To compute mean correlations, the correlations of the 20 participants were averaged using Fisher’s Z transformation. The mean correlation between IBP change and latency equalled 0.32

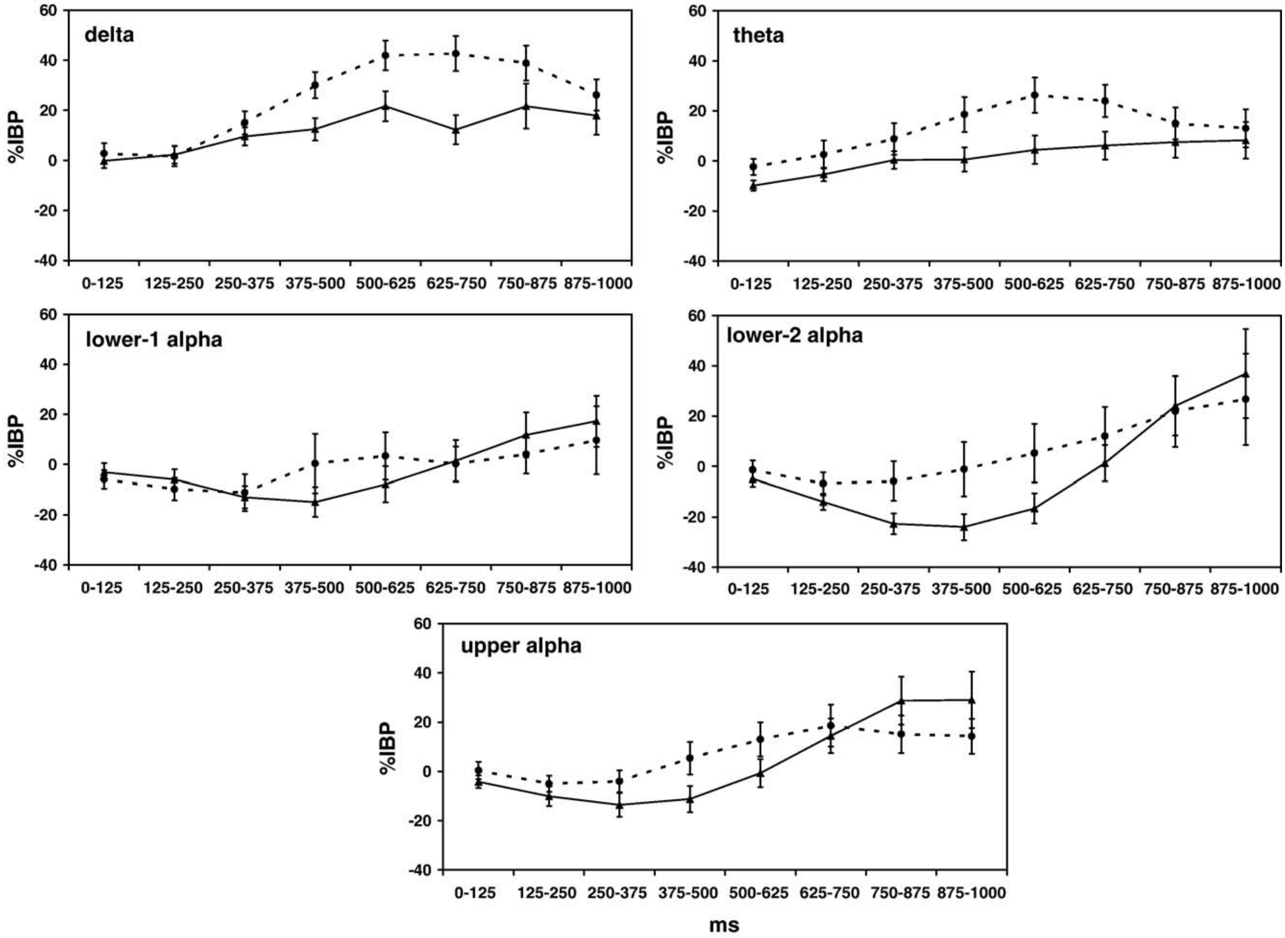

Fig. 6. Changes in induced band power (IBP) for first (=new; solid lines) and second (=first repetition; dotted lines) presentations in the delta, theta, lower-1 alpha, lower-2 alpha, and upper alpha bands.

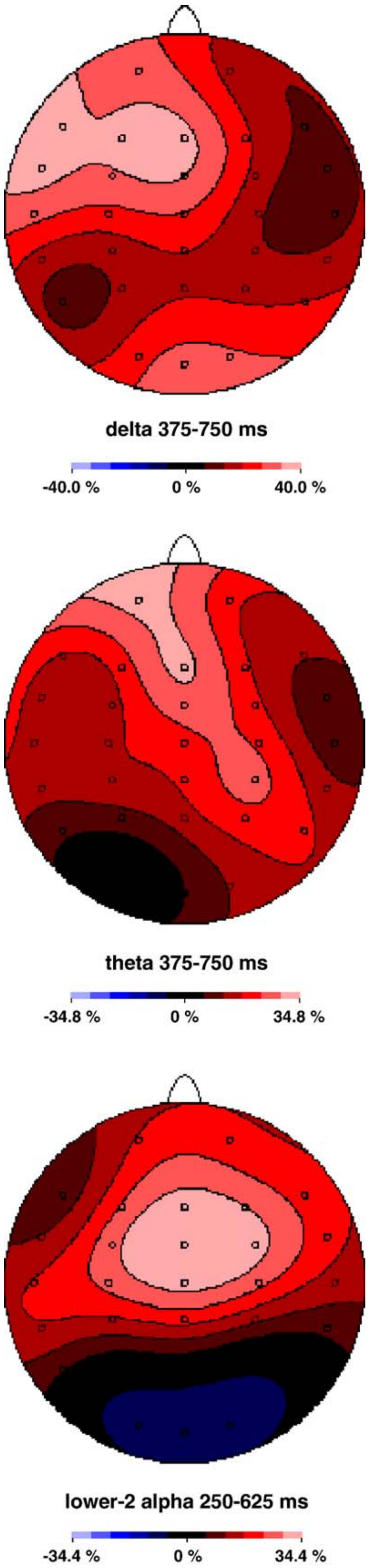

Fig. 7. Scalp distributions of the ‘old/new’ effect (first repetition minus new presentation) for the delta frequency range (375–750 ms time window), theta frequency range (375–750 ms time window), and lower-2 alpha frequency range (250–625 ms time window).

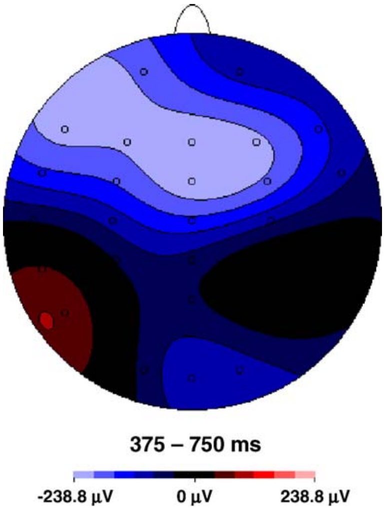

Fig. 8. Scalp distribution of the linear delta frequency repetition effect across the nine word repetitions for the 375–750 ms time window.

($P = 0.013$, two sided one-sample t test after applying Fisher’s Z transformation) and the mean correlation between IBP change and accuracy equalled -0.38 ($P = 0.002$). Both correlations constitute medium effect sizes (Cohen, 1988).

In the other frequency bands, no consistent repetition effects were found (all F’s < 1.34, $P > 0.25$).

Discussion

Behavioral data

We found less accurate and slower responses to the first word repetitions as compared to the presentations of new words. This outcome is in accordance with the behavioral data of other studies that employed a continuous recognition paradigm (e.g., Kayser et al., 2003). Across repetitions, both accuracy and decision speed increased, which indicates better encoding and retrieval (i.e., a strengthening of the memory traces).

ERP data

From the ERP literature on recognition performance, it is well known that correct recognition of verbal stimuli is associated with increased positivity in the time range of 300–800 ms after stimulus onset, with an early component (in the 300- to 500-ms time

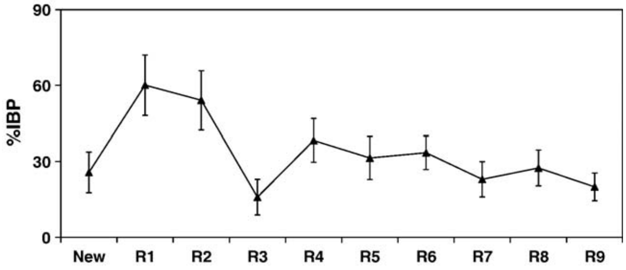

Fig. 9. Induced band power (IBP) change for the delta frequency range on new words and nine repetitions across F7, F3, Fz, F4, and FCz in the 375- to 750-ms time window (linear trend across the nine repetitions: $P = 0.006$).

window) related to familiarity and a later component (in the 500- to 800-ms time window) related to recollection (Rugg and Yonelinas, 2003; Yonelinas, 2002). In the present study, we found a clear 'old/new' effect for the early component. The correct recognition of an 'old' word was associated with a more positive waveform than the correct identification of a new word. The old/new effect was most pronounced at and around the midline parietal electrode position. Rugg et al. (1998) found in the same 300–500 ms time window that 'old' words produced more positive ERPs than did 'new' words, regardless of the accuracy of the recognition judgement. They proposed that this parietal effect is a neural correlate of implicit memory processes.

In our study, the early component did not exhibit a repetition effect across the nine word repetitions, whereas the later (LPC) component did. The more accurate and faster responses to later repetitions most probably are the result of stronger memory traces for a particular word. Hence, the increasing ERP positivity in response to an increasing number of repetitions may reflect a graded process: the stronger the memory trace, the more positive is the ERP in the 500- to 800-ms time window. Finnigan et al. (2002) manipulated memory strength by having their participants memorize words that were presented either once (weak words) or three times (strong words) during a study phase. At test, ERPs to correct old decisions after the presentation of strong words were more positive-going than ERPs to correct old decisions after the presentation of weak words. This strength effect was observed in both the 300–500 ms interval (N400) and the 500–800 ms interval (LPC). Finigan et al. offer an alternative interpretation of the early and late old/new components. Instead of a dual process-model, they suggest a single-process model, with the N400 effect being modulated by memory strength and the LPC effect being sensitive to decisional factors. In the present research, however, the new vs. first repetition comparison was only significant in the 300- to 500-ms intervals, whereas a memory strength effect was only demonstrated for the 500- to 800-ms interval. Our results rather support a dual-processing model, with an early familiarity component being discernable from a more graded recollection component that depends on memory strengths.

Induced band power

In the 375- to 750-ms time window, the first repetitions (i.e., 'old' words) provoked more delta power than new words. This is in agreement with the Klimesch et al. (2000) study, in which larger delta activity for 'old' (hits to previously learned words) compared to 'new' words was found in the same 375–750 ms interval. In the Klimesch et al. study, however, the delta 'old/new' effect was larger at posterior (midline parietal and left occipital) sites, whereas in the present study, the effect was larger at left anterior sites.

While the first repetition words resulted in higher IBP changes than did new words, the repeated presentations resulted in a more or less linear decline of the delta IBP changes in the 375- to 750-ms time window. For the behavioral data, there was a more or less similar but inverse pattern. Words that were repeated for the first time resulted in lower accuracy scores and slower responses than new words. Upon repeated presentations, however, there was an improvement in task performance measures, with accuracy and decision speed rising again. In the 375- to 750-ms time window, we found significant mean correlations between delta IBP change on the one hand, and decision speed and accuracy on the other hand. The correlations had a medium effect size and showed that a decrease in delta power was related to higher accuracy and shorter latencies. It has been suggested that delta activity is associated with task difficulty (Harmony et al., 1996) and decision making (Basar et al., 2001). This notion might be in agreement with the relation that we found between delta IBP and the behavioral measures, with later word repetitions requiring less decision making effort.

In the 375- to 750-ms interval, new words elicited less theta power than words that were repeated for the first time. This is also in accordance with the Klimesch et al. (2000) study, in which larger theta activity for 'old' compared to 'new' words was found in the 375- to 750-ms interval. Again, Klimesch et al. found the largest theta 'old/new' effects at posterior sites, whereas we found the largest effect at left and midline anterior sites.

In animal studies, there is ample evidence that hippocampal theta activity is related to the encoding of new information (see, for review, Kahana et al., 2001). In humans, it has been observed that theta power increases with memory load during both verbal and spatial working memory tasks (e.g., Gevins et al., 1997). The exact relationship between human scalp-recorded theta and hippocampal theta is still unclear, but it is highly likely that the hippocampal system is involved (Bastiaansen and Hagoort, 2003). However, theta activity is found throughout the human brain. Stam et al. (2002) characterized synchronization in terms of couplings between EEG channels and found increased theta band coupling across most electrodes during a working memory task. Theta oscillations may function as a general synchronizing mechanism, binding together the activity of several cortical regions (see Kahana et al., 2001).

In humans, theta power increases are larger during retrieval than during encoding (Bastiaansen and Hagoort, 2003). In the present study, a larger theta power increase in response to 'old' words compared to new words was found for the 375- to 750-ms time window. According to Bastiaansen and Hagoort (2003), a theta power increase during both encoding and retrieval is in accordance with their hypothesis that theta activity plays a functional role in cell assembly formation. The present study, however, found no theta repetition effect across the nine repeated word presentations. In other words, theta activity appeared not to be affected by the strengthening of the memory trace.

In the 250- to 625-ms interval, new words resulted in less lower-2 alpha power (mainly at frontal and central sites) than words that were repeated for the fist time. Lower-2 alpha desynchronization most probably reflects attentional processes, in particular expectancy effects (see Klimesch, 1999). The lower-2 alpha expectancy effect was limited to new words, since there were no word repetition effects for this frequency band. Expectancy effects will be found in the prestimulus period of both new and repeated words. Therefore, lower-2 alpha desynchronization may already have started before a word appeared. During new words, the desynchronization probably further increased, whereas during repeated words, the desynchronization attenuated. In our research, new words were much less frequent than repeated words, which may have similar effects as infrequent targets in a visual oddball task. With such an oddball task, Klimesch (1999) demonstrated a lower-2 alpha desynchronization which continued during the poststimulus period of (infrequent) targets but not during the poststimulus period of nontargets.

Although we found a clear improvement in task performance measures across the nine word repetitions, no linear or quadratic repetition effects were found in the alpha bands. It could be that the continuous recognition paradigm, despite the fact that the task gets easier after several repetitions, has attentional demands that last throughout its complete execution.

An inherent problem of the present continuous word-recognition paradigm is that, as the task proceeds, the participants may develop a tendency to give an 'old' response regardless of the actual word stimulus. Such a bias might affect the 'old/new' decisions, but is less likely to play a role in the linear repetition effect across the nine repetitions. The clear dissociation between the early (N400) and late (LPC) ERP measures regarding the repetition effect, and the absence of a repetition effect across the nine repetitions in the theta and alpha bands may indicate that the behavioral task did not become trivial.

In an accompanying fMRI study (to be reported), employing the same extended continuous word recognition paradigm, a systematic decrease in brain activation was found across the nine word repetitions at frontal, thalamic, anterior cingulate, and parietal regions. Although fMRI and EEG are quite different technologies, the ERP and IBP word repetition effects that were found in the present EEG research may be functionally related to these brain structures.

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