Massed and distributed repetition of natural scenes: Brain potentials and oscillatory activity

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Abstract

Neural measures of repetition can result in either repetition suppression or enhancement effects, with enhancement sometimes interpreted as indicating episodic retrieval, rather than stimulus habituation. Here, we manipulated whether repetitions were massed (consecutive) or distributed (intermixed) and measured event-related potentials and oscillatory activity, investigating the question of whether there is evidence of "spontaneous" episodic retrieval for distributed, but not massed, repetition. Results showed that distributed repetition uniquely prompted a significant centroparietal old-new effect as well as enhanced theta, compared to either novel presentations or massed repetitions, consistent with a hypothesis of spontaneous retrieval. Massed repetition, on the other hand, prompted repetition suppression and reduction of the N2/P2. Taken together, the data suggest that distributed repetition may facilitate later memory performance because it spontaneously retrieves prior representations.

Descriptors: Learning, EEG, Emotion

Stimulus repetition can prompt either suppression, in which a late positive potential (LPP) measured over parietal sensors is attenuated (Codispoti, Ferrari, & Bradley, 2006, 2007; Ferrari, Bradley, Codispoti, & Lang, 2011; Henson, Rylands, Ross, Vuilleumeir, & Rugg, 2004), sometimes interpreted as reflecting habituation or neural sharpening, or enhancement, in which "old" items prompt enhanced centroparietal positivity, compared to "new" items, consistent with an interpretation of episodic retrieval (Curran & Doyle, 2011; Ferrari, Bradley, Codispoti, Karlsson, & Lang, 2013; Weymar, Bradley, El-Hinnawi, & Lang, 2013; Voss & Paller, 2008; Wilding, Doyle, & Rugg, 1995; Wilding & Rugg, 1996). Moreover, both repetition suppression (e.g., Codispoti et al., 2007; Ferrari et al., 2011) and enhancement (e.g., Weymar, Löw, & Hamm, 2011) are more pronounced for emotionally arousing pictures (whether pleasant or unpleasant), compared to neutral cues. In the current study, we assessed how differences in the type of repetition impact ERPs when viewing emotional and neutral scenes, varying whether repetitions were massed, in which repetitions are consecutive, temporally contiguous and with no intervening items, or distributed, in which repetitions are intermixed and spaced across the input phase.

In a recent fMRI study (Bradley et al., 2014), we found that, when distributed repetitions were widely spaced across the encoding phase, there was unique activation in regions of the medial posterior parietal cortex, including the precuneus, which has been implicated in studies of episodic retrieval (Schott et al., 2005; Wagner, Shannon, Kahn, & Buckner, 2005). Because enhanced positivity, rather than attenuation, is a classic electrophysiological signature of successful episodic retrieval (i.e., old-new effect), these fMRI data suggest that distributed repetition will prompt centroparietal positivity enhancement, whereas massed repetition will not. Previous ERP studies of repetition that included nominally intermixed repetitions found ERP suppression, however, rather than the enhancement predicted here, when a few pictures (e.g., three) were repeated many times (e.g., 90; Codispoti et al., 2007). With such massive repetition of a few items, all of the stimuli occur in close temporal proximity, which could rule out contributions of spontaneous retrieval. Therefore, in the current study, a large number of scenes (108) were presented in which distributed repetitions were widely spaced across the encoding phase and compared to massed repetitions in which scenes were presented consecutively, without any intervening items, with a hypothesis that distributed, but not massed, repetitions would prompt a significant centroparietal old-new effect.

Stimulus repetition also prompts a reduction in the amplitude of an early negative component measured over centrofrontal sensors (N2: 200–300 ms) and a correspondingly more positive potential (i.e., P2) over occipital sensors, which is often interpreted as an index of stimulus novelty (e.g., Chong et al., 2008; Henson et al., 2004; Folstein, Van Patten, & Rose, 2008; Schendan & Kutas, 2003; Wang, Cui, Wang, Tian, & Zhang, 2004). Indeed, we found

complete attenuation of the frontal N2 and occipital P2 following a single massed repetition (Ferrari, Bradley, Codispoti, & Lang, 2010). We hypothesized that attenuation of the N2 may reflect the availability of a short-lived visual representation that facilitates perceptual processing, indexing perceptual fluency, rather than novelty per se. If so, we expected to replicate this finding for massed repetitions but not when repetitions were distributed at long lags (average 90 items) in which the visual representation is no longer available in a short-term store.

Stimulus repetition also modulates oscillatory brain activity (Herrmann, Munk, & Engel, 2004). For instance, increased theta power (i.e., 4–7 Hz; Bastiaansen & Hagoort, 2003; Busch, Groh-Bordin, Zimmer, & Herrmann, 2008; Klimesch, 1999; Klimesch et al., 2001; Klimesch, Freunberger, Sauseng, & Gruber, 2008; Nyhus & Curran, 2010; Osipova et al., 2006; Sauseng, Griesmayr, Freunberger, & Klimesch, 2010) has been reported for repeated (old), compared to novel (new), items during an episodic recognition task, suggesting that these effects may also reflect episodic retrieval. In addition, although there is also some evidence of increased early (>30 Hz) gamma band activity for old, compared to new, items on a recognition test (Gruber, Tsivilis, Giabbiconi, & Müller, 2008), some studies report gamma band reduction, rather than enhancement, when stimulus repetition is task irrelevant (Busch et al., 2008; Gruber, Malinowski, & Muller, 2004; Gruber & Muller, 2005). To assess whether stimulus relevance is a key factor in modulating oscillatory activity, we presented natural scenes that depicted either neutral, everyday events or emotionally evocative scenes, which prompt a type of "natural selective attention" (Bradley, 2009), as indexed by enhanced cardiac orienting, larger LPPs, heightened pupil dilation, etc. (see Lang & Bradley, 2010, for an overview).

Thus, both ERPs and oscillatory activity were assessed in a free viewing context in which participants viewed emotional and neutral pictures that were novel or repeated four times with massed (contiguous) or distributed (intermixed) repetition to test the hypothesis that distributed, but not massed, repetition prompts spontaneous episodic retrieval. If so, we expected that distributed repetition would be uniquely associated with an enhanced ERP similiar in timing and topography to the classic old-new ERP effect, as well as enhanced activity in either or both of the theta and gamma frequency bands.

Method

Participants

Participants were 47 right-handed students (26 women) with normal or corrected-to-normal visual acuity from a general psychology course at the University of Florida who participated for course credit. Prior to participating, informed consent was obtained in accordance with the UF Institutional Review Board guidelines.

Material

Overall, 108 color pictures were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), consisting of 54 emotional pictures (half pleasant and half unpleasant) of different contents and 54 neutral pictures. Of the 54 pictures, 18 were presented once during the experiment (novel), and the remaining 36 pictures were presented four times each. Of these, half (18) of the pictures were repeated using massed repetition, in which the four presentations were presented consecutively

(i.e., in a row, with no other pictures intervening), while the repetitions of the remaining half (18) were distributed (i.e., intermixed among other pictures) across the encoding phase. The first presentation of each of the 36 pictures that was subsequently repeated (either distributed or massed) was included in the novel condition, resulting in 54 trials in each condition (novel, distributed, and massed). In addition, after each set of four massed repetitions, a buffer picture (neutral content) was presented that was not included in the final analyses, as a previous study indicated that these pictures attract heightened attention (see Ferrari et al., 2010). Finally, five additional buffer trials (neutral images) were added to the beginning and end of the encoding phase. With the 324 critical trials and the buffer trials ($n = 46$), the experimental phase included a total of 370 trials.

Pictures presented in each condition (novel, massed, distributed) were balanced for emotional content, and the specific set of pictures serving as novel, massed, or distributed was counterbalanced across participants such that each picture served in each condition. The presentation order was also counterbalanced such that no more than three series of massed repetitions could occur consecutively.

Each trial consisted of a fixation cross presented at the center of the screen for 500 ms followed by a 2-s picture presentation. Picture offset was followed by a 2-s intertrial interval. All pictures were presented using E-Prime software (Schneider, Eschmann, & Zuccolotto, 2002) that displayed stimuli on a 19" CRT monitor situated approximately 100 cm from the participant. For massed repetitions, the same picture was presented on 4 contiguous trials; for distributed repetitions, the repetition was spaced across trials, with a repetition of the same picture occurring approximately every 90 ± 40 trials.

EEG Recording and Data Analysis

EEG was measured from the scalp using a 128-channel system (Electrical Geodesics, Inc., Eugene, OR) running NetStation software on a Macintosh computer. Scalp impedance for each sensor was kept below 50 kΩ. The EEG was recorded continuously with a sampling rate of 250 Hz, the vertex sensor as reference electrode, and online band-pass filtered from 0.01 to 100 Hz. EEG data were analyzed offline using a MATLAB-based program in which continuous EEG data were low-pass filtered at 40 Hz using digital filtering, and artifact detection was performed by means of a dedicated algorithm that used statistical parameters to determine trials with artifacts (Junghöfer, Elbert, Tucker, & Rockstroh, 2000; Junghöfer & Peyk, 2004). Processed data were then transformed to an average reference and baseline corrected (200 ms before picture onset) prior to subject averaging and analysis.

For time-frequency analysis, data were convolved using complex Morlet's wavelet varying in time and frequency with a Gaussian shape. The time-frequency analysis was performed on single trial data using FieldTrip software (http://fieldtrip.fcdonders.nl/) through EMEGS (Peyk, De Cesarei, & Junghöfer, 2011). The f/ SD(f) ratio was set to 7, and the number of wavelet cycles was set to 3 (Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1997). The range of analysis was from 4 to 80 Hz, and analysis was performed in time windows from 1,000 ms before picture onset to 2,000 ms after picture onset, in steps of 10 ms. As frequency resolution is maximal for low frequencies and minimal for high frequencies (Roach & Mathalon, 2008), the step between successive frequencies varied linearly from 0.5 Hz for the lowest frequencies to 5 Hz for the highest frequencies. The power spectrum was converted in dB (Delorme & Makeig, 2004), and the baseline period (from
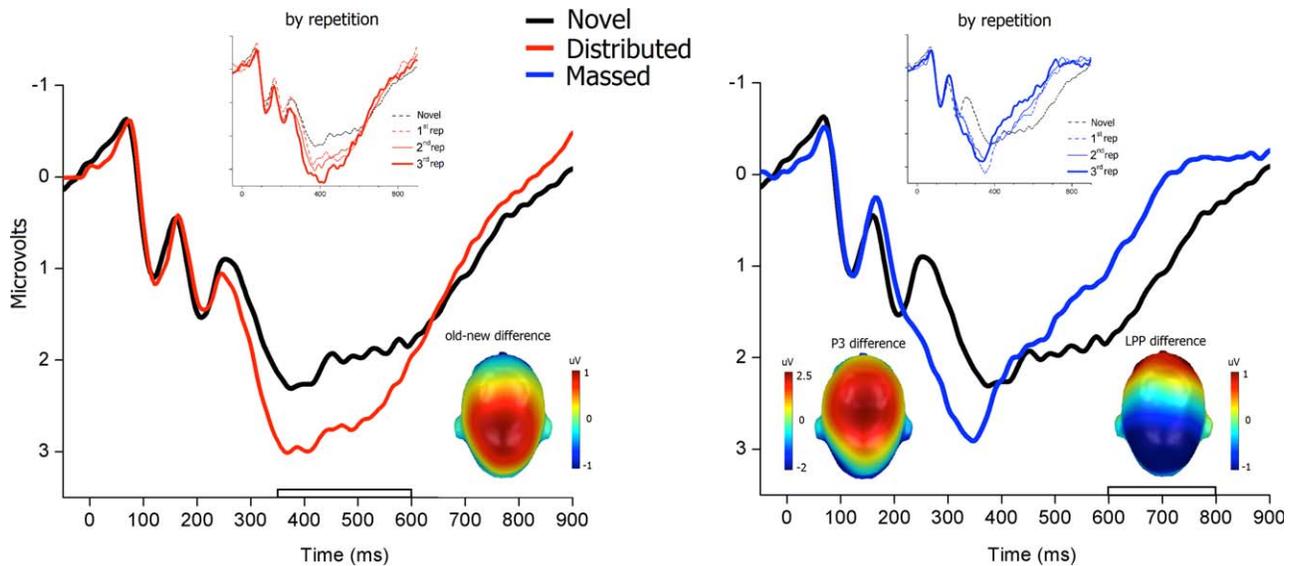
Figure 1. Centroparietal differences. Left: Grand-average ERP waveforms when viewing pictures that were novel (black line) or presented with distributed repetition (red line) show an old-new ERP difference (350–600 ms) that is similar for each repetition (waveform inset) together with the topography (inset) of the old-new difference. Right: Grand-average ERP waveforms when viewing pictures that were novel (black line) or presented with massed repetition (blue line) show an early P3 enhancement (250–350 ms) and suppression of a late positive potential (600–800 ms) that is similar for each repetition (waveform inset) together with the topographies of ERP difference for the early and late windows.

−300 to −50 ms) preceding picture onset was subtracted from the resulting power spectrum.

For both the ERP and the time-frequency data, statistical analyses were performed on the mean value of sensor groups[1] and temporal windows in which the difference between conditions was maximal, based on visual inspection of the grand-average ERP (see Figure 1 and 2) and temporal frequency plot data (see Figure 3). For each picture content (emotional, neutral) and type of repetition (distributed, massed), the 1st, 2nd, and 3rd repetition were averaged together.[2]

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1. Geodesic sensor number for ERP analysis: centroparietal region (32, 38, 53, 54, 55, 61, 62, 68, 79, 80, 81, 87, 88, and 129); centrofrontal region (4, 5, 6, 7, 10, 11, 12, 13, 16, 21, 30, 31, 32, 55, 81, 106, 107, 112, 113, 119, 124, 129); occipitotemporal region (56, 57, 58, 59, 63, 64, 65, 66, 69, 70, 71, 74, 75, 76, 82, 83, 84, 85, 89, 90, 91, 92, 95, 96, 97, 98, 100, 101, 102, 108). Geodesic sensor number for brain oscillation analysis: theta (centrofrontal, 3, 4, 5, 6, 9, 10, 11, 12, 15, 16, 17, 18, 19, 20, 23, 24; posterior, 70, 71, 72, 74, 75, 76, 77, 82, 83, 84, 89, 90); alpha (occipitotemporal, 32, 38, 43, 48, 50, 51, 52, 53, 54, 56, 57, 58, 59, 60, 61, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75); gamma induced (parietooccipital, 54, 55, 61, 62, 68, 79, 80).

2. To evaluate ERPs across consecutive repetitions, ERP waveforms were averaged as a function of the number of the repetition (1st, 2nd, 3rd) separately for massed and distributed repetitions, and analyzed in separated repeated measures ANOVAs with presentation (4: novel, 1st, 2nd, 3rd repetition) and picture content (emotional, neutral) as factors. Enhanced centroparietal positivity for distributed repetition (350–600 ms), compared to novel presentation, was found for each repetition, $Fs(1,46) > 25$, $p < .0001$, $\eta^2 > .35$, and did not vary across the three repetitions. Attenuation for massed repetitions (600–800 ms) compared to novel presentation, was apparent on the 1st repetition, $F(1,46) = 30$, $p < .0001$, $\eta^2 = .4$, with a further decrease for successive repetitions—1st versus 3rd, $Fs(1,46) = 9.3$, $p < .0005$, $\eta2 = .17$. The amplitude of both N2 and the P2 was greatly attenuated after the first massed repetition, $Fs(1,46) > 128$, $ps < .0001$, $\eta^2 > .68$, relative to novel presentation, and did not differ across successive repetitions. For distributed repetition, the amplitude of the centrofrontal N2 and the posterior P2 was somewhat reduced on the first repetition, $Fs(1,46) > 34$, $ps < .0001$, $\eta^2 > 41$, and, again, did not differ across subsequent repetitions—1st, 2nd, 3rd, $F < 1$.

Results

Centroparietal Repetition Effects

Figure 1 illustrates ERPs (averaged over centroparietal sensors) elicited when viewing novel pictures, compared to ERPs elicited during distributed (left) or massed (right) repetition. Differences are apparent in three time windows following picture onset, including 250–350 ms, 350–600 ms, and 600–800 ms. Accordingly, a three-way analysis of variance (ANOVA) was conducted, which included presentation type (3: novel, distributed, massed), time window (3: 250–350, 350–600, 600–800 ms), and picture content (2: emotional, neutral) as repeated measures. An interaction of Presentation × Time, $F(4,184) = 84$, $p < .0001$, $\eta^2 = .6$, was accompanied by three-way interaction Presentation × Time × Content, $F(4,184) = 48$, $p < .0001$, $\eta^2 = .5$. Effects of presentation and picture content were therefore assessed separately for each time window.

250–350 ms window. Mean ERP amplitude in the 250–350 ms window over centroparietal sensors indicated enhanced positivity during massed repetition[3] compared to either distributed repetition, $F(1,46) = 19$, $p < .0001$, $\eta^2 = .29$, or to novel presentations, $F(1,46) = 101$, $p < .0001$, $\eta^2 = .7$. The positivity enhancement for massed repetitions, compared to novel presentation, was significant

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3. The enhanced positivity for massed repetition may be mediated by a latency shift of a P3-like component (see Figure 1). To test this, peak P3 latency was computed as the local positive maximum of this ERP in the 250 to 350 ms using the average waveform for each subject and condition. A main effect of presentation indicated different latencies, $F(2,92) = 15.4$, $p < .0001$, $\eta^2 = .25$, with a shorter latency for massed (333 ms) compared to either distributed repetition, 355 ms; $F(1,46) = 17$, $p < .0001$, $\eta^2 = .28$, or novel presentation, 358 ms; $F(1,46) = 22$, $p < .0001$, $\eta^2 = .33$. This P3 anticipation prompted by massed repetition, compared to novel presentation, was even larger for emotional (−34 ms), compared to neutral (−14 ms), pictures—Presentation × Content, $F(2,92) = 6$, $p < .005$, $\eta^2 = .12$.
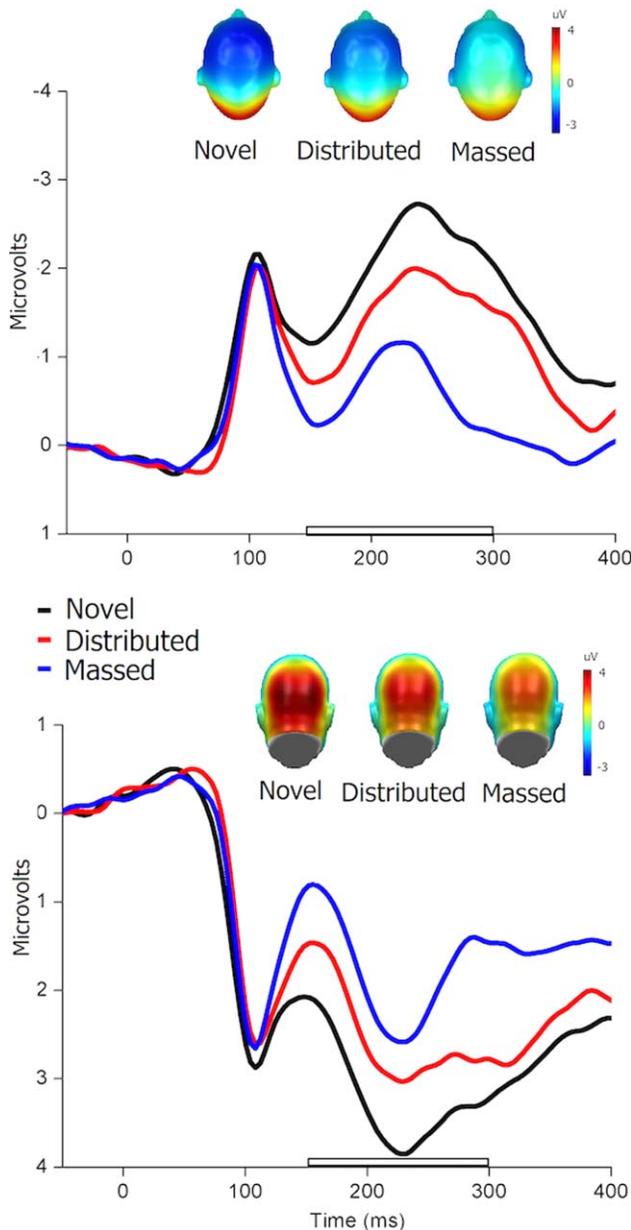
Figure 2. Frontal N2/posterior P2 differences. Grand-average ERP waveforms when viewing novel pictures (black) and pictures presented with massed (blue) or distributed (red) repetitions for frontal (top) and occipital (bottom) sensors in a 150–300 ms window show maximal attenuation for massed repetitions, and the topography of the differences.

for both emotional, $F(1,46) = 108$, $p < .0001$, $\eta^2 = .7$, and neutral pictures, $F(1,46) = 42$, $p < .001$, $\eta^2 = .47$, with a Presentation × Content interaction, $F(2,92) = 24$, $p < .0001$, $\eta^2 = .35$, mainly indicating a larger difference for emotional, compared to neutral, pictures (see Table 1). Although distributed repetition also showed larger positivity compared to novel presentation in this window, $F(1,46) = 32$, $p < .0001$, $\eta^2 = .4$, the difference reflects the onset of positivity that was maximal in the next 350–600 ms window.

350–600 ms window. A main effect of presentation, $F(2,92) = 27$, $p < .0001$, $\eta^2 = .37$, indicated that enhanced positivity was found uniquely for distributed repetitions (see Figure 1,
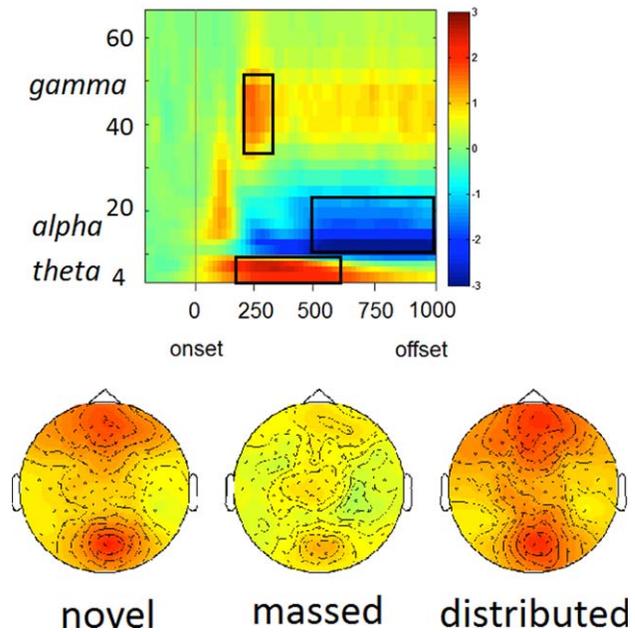
Figure 3. ERD analysis. Top: Time-frequency plot for a representative sensor from the posterior (POZ) scalp region, averaged across experimental conditions. Bottom: Scalp topography of the theta (4–7 Hz) power synchronization (power range −3, 3ΔdB) shows enhanced theta for distributed, compared to massed, repetition during viewing of emotional pictures.

left), compared to when viewing either novel presentations, $F(1,46) = 62$, $p < .0001$, $\eta^2 = .57$, or massed repetitions, $F(1,46) = 32$, $p < .0001$, $\eta^2 = .41$, consistent with the hypothesis that distributed repetition prompts spontaneous retrieval; massed repetition did not significantly differ from novel presentation. Enhanced positivity for distributed repetitions, compared to novel picture viewing, was significant for both emotional, $F(1,46) = 52$, $p < .0001$, and for neutral pictures $F(1,46) = 25$, $p < .0001$, with

Table 1. *Means (Standard Error) of Event-Related Potentials (μV) Show Different Effects as a Function of Sensor Group and Time Window*

Time window	Novel	Distributed	Massed
Centroparietal differences			
250–350 ms			
All pictures	.7 (.23)	1.5 (.27)	2.3 (.20)
Emotional	.9 (.24)	2.0 (.30)	3.1 (.23)
Neutral	.5 (.23)	1.0 (.25)	1.6 (.18)
350–600 ms			
All pictures	1.7 (.17)	2.6 (.23)	1.7 (.15)
Emotional	2.6 (.23)	3.7 (.26)	2.2 (.16)
Neutral	.9 (.18)	1.5 (.19)	1.3 (.14)
600–800 ms			
All pictures	1.2 (.15)	1.2 (.14)	.4 (.10)
Emotional	1.9 (.17)	1.7 (.16)	.6 (.11)
Neutral	.6 (.13)	.8 (.13)	.2 (.10)
Frontal/occipital differences			
Frontal N2			
All pictures	−2.1 (.18)	−1.5 (.19)	−.6 (.14)
Emotional	−1.8 (.18)	−1.1 (.20)	−.3 (.15)
Neutral	−2.3 (.19)	−1.9 (.19)	−.9 (.14)
Occipital P2			
All pictures	3.2 (.28)	2.5 (.27)	1.7 (.24)
Emotional	2.8 (.27)	2.0 (.26)	1.4 (.24)
Neutral	3.6 (.29)	3.0 (.29)	2.1 (.25)

the significant interaction of Presentation $\times$ Content, $F(2,92) = 28$, $p < .0001$, $\eta^2 = .38$, only indicating that enhanced positivity during distributed repetitions (compared to novel scenes) was larger for emotional than for neutral pictures, $F(1,46) = 6.3$, $p < .05$, $\eta^2 = .12$, see Table 1.

600–800 ms window. A main effect of presentation type, $F(2,92) = 42$, $p < .0001$, $\eta^2 = .48$, reflected significant attenuation of late positivity for massed repetitions, compared to either novel presentations, $F(1,46) = 56$, $p < .0001$, $\eta^2 = .55$, or to distributed repetitions, $F(1,46) = 64$, $p < .0001$, $\eta^2 = .58$; ERPs elicited when viewing novel pictures and distributed repetitions did not differ ($F < 1$). Massed repetition attenuated this late potential for both emotional, $F(1,46) = 79$, $p < .0001$, $\eta^2 = .6$, and neutral pictures, $F(1,46) = 8$, $p < .01$, $\eta^2 = .15$, with a significant interaction of Presentation $\times$ Content, $F(2,92) = 11$, $p < .0001$, $\eta^2 = .2$, only indicating that the difference was larger for emotional, compared to neutral, pictures, $F(1,46) = 27.6$, $p < .0001$, $\eta^2 = .37$, see Table 1.

Frontal N2/Posterior P2

Figure 2 illustrates the early (150–300 ms) frontal N2 and posterior P2. Both the N2 and P2 components were significantly modulated by presentation type, $Fs(2,92) > 88$, $ps < .0001$, $\eta^2 > .6$. Compared to novel pictures, massed repetition prompted significantly less ERP negativity in the N2 window over centrofrontal sensors, $F(1,46) = 83$, $p < .0001$, $\eta^2 = .7$, and less positivity over posterior sensors, $F(1,46) = 127$, $p < .0001$, $\eta^2 = .79$, replicating our previous study (Ferrari et al., 2010). Moreover, although distributed repetition also prompted attenuation of the frontal N2, $F(1,46) = 36.7$, $p < .0001$, $\eta^2 = .52$, and posterior P2, $F(1,46) = 50$, $p < .0001$, $\eta^2 = .59$, these effects were significantly larger for massed, compared to distributed, repetition—frontal N2: $F(1,46) = 34.9$, $p < .0001$, $\eta^2 = .5$; posterior P2: $F(1,46) = 19.9$, $p < .0001$, $\eta^2 = .37$.

Emotional pictures were associated with overall less negativity over frontal sensors, $F(1,46) = 108$, $p < .0001$, $\eta^2 = .7$, and less positivity over posterior sensors, $F(1,46) = 94$, $p < .0001$, $\eta^2 = .67$, compared to neutral pictures, but these differences were not affected by repetition (Content $\times$ Presentation, $p > .05$), see Table 1.

Brain Oscillations

Figure 3 illustrates time-frequency plots for a representative sensor from a posterior scalp region (POZ), averaged across experimental condition.

Theta band (4–7 Hz). Theta rhythms[1,4] were overall modulated by presentation type, $F(2,92) = 31$, $p < .0001$, $\eta^2 = .43$, with massed repetition prompting reduction in theta power, compared to either novel presentation, $F(1,46) = 37$, $p < .0001$, $\eta^2 = .45$, or to distributed repetition, $F(1,46) = 46$, $p < .0001$, $\eta^2 = .5$. Moreover, there was a slight, but significant, increase in theta power uniquely during distributed repetitions, compared to novel presentations,

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4. Theta band was initially analyzed including a factor of scalp region (centrofrontal vs. posterior theta, see scalp topography in Figure 3), but no significant differences were found between the two regions in terms of type of presentation. Therefore, the main analysis described in the text was performed on theta power measured over the two regions averaged together.

Table 2. *Means (Standard Error) of Oscillatory Activity (ΔDb) in Different Frequency Bands During the Viewing of Emotional and Neutral Pictures*

Frequency band	Novel	Distributed	Massed
Theta (4-7 Hz)			
All pictures	1.5 (.13)	1.3 (.14)	0.7 (.12)
Emotional	1.4 (.15)	1.7 (.14)	0.9 (.12)
Neutral	0.9 (.12)	0.9 (.14)	0.6 (.13)
Alpha (8-12 Hz)			
All pictures	−2.2 (.21)	−2.5 (.20)	−2.6 (.20)
Emotional	−2.6 (.21)	−2.8 (.20)	−3.0 (.21)
Neutral	−1.9 (.22)	−2.2 (.21)	−2.2 (.19)
Gamma (30-50 Hz)			
All pictures	0.8 (.13)	0.8 (.13)	0.6 (.10)
Emotional	0.8 (.13)	0.9 (.13)	0.7 (.11)
Neutral	0.9 (.13)	0.8 (.13)	0.6 (.10)

$F(1,46) = 4.2$, $p < .05$, $\eta^2 = .08$. A significant interaction of Presentation $\times$ Content, $F(1,46) = 6.8$, $p < .005$, $\eta^2 = .13$, indicated that the theta increase during distributed repetition was significant for emotional, $F(1,46) = 5.27$, $p < .05$, $\eta^2 = .1$, but not for neutral pictures ($F < 1$), see Table 2.

Alpha band (8–12 Hz). Alpha power was significantly modulated by picture content, $F(1,46) = 51.9$, $p < .0001$, $\eta^2 = .52$, with stronger alpha desyncronization for emotional, compared to neutral, pictures, replicating previous research (De Cesarei & Codispoti, 2011), which was not affected by repetition (Repetition $\times$ Emotion, $p > .05$). A main effect of repetition indicated that alpha desynchronization was more pronounced for repeated pictures, $F(2,92) = 6.6$, $p < .005$, $\eta^2 = .12$, regardless of the type of repetition—distributed or massed versus novel presentation: $Fs(1,46) > 10.3$, $ps < .005$, $\eta^2 > .18$.

Gamma band (20–50 Hz). Stimulus repetition suppressed induced gamma-band activity, $F(2,92) = 8.15$, $p < .005$, $\eta^2 = .15$; see Table 2, with massed repetition prompting significantly less gamma activity than novel presentation, $F(1,46) = 14.7$, $p < .0001$, $\eta^2 = .24$, or distributed repetition, $F(1,46) = 4.9$, $p < .05$, $\eta^2 = .1$. Gamma reduction for distributed repetition, compared to novel presentation, was only marginally significant, $F(1,46) = 3.6$, $p = .065$, $\eta^2 = .24$. There were no significant effects of picture content.

Discussion

Whereas previous studies have reported a reduction in the amplitude of a centroparietal positive potential following massive repetition of a few items (Codispoti et al., 2007), in the current study, we found that ERPs differ as a function of the type of repetition: Distributed repetitions prompted a significant centroparietal old-new difference in the ERP, with enhanced positivity for distributed repetitions, compared to novel pictures, whereas massed repetitions prompted suppression of a late (600–800 ms) centroparietal ERP. Moreover, whereas repetition in general decreased frontal N2 and occipital P2 components, these effects were greatly enhanced for massed, compared to distributed, repetition.

Among the numerous mechanisms proposed for whether repetition prompts suppression or enhancement effects (see Grill-Spector, Henson, & Martin, 2006; Segaert, Weber, De Lange, Petersson, & Hagoort, 2013), the most relevant in explaining the differential effects of massed and distributed repetition found here

is the role of episodic memory retrieval. The enhanced positive potential that accompanied processing of distributed repetitions is very similar in timing and topography to the classic old-new ERP difference found during an explicit recognition task for old, compared to new items, (Curran and Doyle, 2011; Ferrari et al., 2013; Weymar et al., 2013; Wilding et al., 1995; Voss & Paller, 2008; Wilding & Rugg, 1996), and is consistent with the evidence of spontaneous episodic retrieval found during distributed repetitions using fMRI (Bradley et al., 2014). In addition, the theta enhancement uniquely found here for distributed, but not massed, repetition provides further support for an interpretation of spontaneous episodic retrieval, as theta enhancement is often reported in studies of memory retrieval (Nyhus and Curran, 2010).

Whereas a hypothesis of episodic retrieval is well founded when repetition enhancement effects occur in the context of an explicit memory task, finding similar effects during free viewing of natural scenes suggests that spontaneous episodic retrieval occurs in many situations that do not explicitly probe memory. Hintzman (2011), for instance, argues that spontaneous retrieval ("reminding") is a common memory process that is the fundamental mechanism mediating judgments of frequency, recency, and occurrence. Both the ERP and theta enhancements found uniquely for distributed repetition in the current study may be neural indices of such spontaneous retrieval, which does not occur for stimuli that are well represented in memory. For instance, when a few scenes are presented a massive number of times (e.g., Codispoti et al., 2007), intermixed presentations do not prompt episodic retrieval, as indexed by repetition suppression of the ERP, probably because these items are already well represented in memory. Evidence that massed repetition is uniquely associated with enhanced activation in dorsolateral prefrontal cortex (Bradley et al., 2014), a region often implicated in working memory, suggests that massed repetition may result in maintenance of the representation.

Both early frontal and occipital potentials were clearly modulated by repetition, with massed repetition strongly attenuating both the frontal N2 and its polarity-reversed posterior P2; effects of distributed repetition on these components were significantly smaller. When the amplitude of the N2/P2 components is interpreted as an index of stimulus novelty (e.g., Chong et al., 2008; Folstein et al., 2008; Wang et al., 2004), these data suggest that, compared to massed repetitions, distributed repetitions are more similar to novel pictures, presumably due to the temporal distance, number of intervening items, or both, between the two repetitions. When attenuation of the N2 is interpreted instead as reflecting heightened perceptual fluency for repeated items, (Ferrari et al., 2010; Jacoby & Dallas, 1981), the weak effects of distributed repetition on N2/P2 attenuation suggest that fluency can also be assisted by the existence of an established memory representation, rather than solely requiring an active (i.e., short-term memory) representation.

In addition to dramatic amplitude reduction of the early N2/P2 complex, massed repetition also prompted a large decrease in induced gamma band activity, consistent with Gruber et al. (2004) who reported reduced gamma in a 200–400 ms window when repetitions were temporally close (fewer than four intervening items). Longer repetition intervals do not seem to prompt gamma suppression (Busch et al., 2008), consistent with the weak effects of distributed repetition on gamma band activity in the current study. Because of the similar effects of repetition on both the modulation of the early N2-P2 component and induced gamma band activity, both of these differences may

reflect increased perceptual fluency prompted by massive stimulus repetition. Moreover, stimulus relevance, manipulated here through hedonic content of the scene, did not affect the amplitude of repetition suppression of either the N2-P2 components or gamma band activity, consistent with previous studies (Codispoti et al., 2007; Schupp et al., 2006).

Massed repetition prompted a centroparietal P3 with a shorter latency than for novel pictures, and for pictures presented using distributed repetition. Indeed, a similar facilitation in latency has been reported even for a single immediate repetition (Henson et al., 2004; Shendan & Kutas, 2003). In these studies, latency shifts are also typically associated with facilitation in task reaction time, suggesting that massed repetition speeds up processing, leading to large and significant priming effects in reaction time. Finding a similar latency shift for massed repetition in the current study, in which there was no requirement to make a speeded decision, suggests that this latency facilitation is not task dependent, but may instead reflect the ease of perceptual processing, perhaps because it exactly recapitulates processing completed on the previous trial. Massed repetition was also associated with suppression of a late (600–800 ms) positive potential, which nonetheless continued to prompt significant difference between emotional and neutral pictures that remains even after 30 massed repetitions (Ferrari et al., 2011). We have interpreted these data as indicating that the LPP reflects, in part, motivational significance, which is not altered by mere repetition (Bradley, 2009).

Effects of emotional content were evident in both the alpha and theta frequency bands. Previous studies (De Cesarei & Codispoti, 2011; Simons, Detenber, Cuthbert, Schwartz, & Reiss, 2003) reported that alpha desynchronization (α-ERD) is positively associated with rated emotional arousal of pictures, and that it covaries with the amplitude of the late positive potential (De Cesarei & Codispoti, 2011). However, in the present study, stimulus repetition was associated with different affective modulation of the LPP and the α-ERD: whereas affective modulation of the LPP (600–800 ms) was reduced by massed repetition, the α-ERD was not affected, suggesting that amplitude of alpha and the LPP are not identically modulated by the same experimental factors. Regarding theta, our findings indicate that synchronization in a window 200–700 ms from picture onset was enhanced when viewing emotional, compared to neutral, pictures. These data agree with the enhanced theta reported by Aftanas, Varlamov, Pavlov, Makhnev, & Reva (2001) for emotional, compared to neutral, pictures in an evaluative rating task and further indicate that modulatory effects of emotion on theta activity do not rely on an explicit task, but are found during free viewing.

In summary, distributed repetition was uniquely associated with repetition enhancement in an ERP similar in timing (i.e., 350–600 ms) and topography (i.e., centroparietal) to the classic old-new ERP as well as in enhanced theta power, both of which are consistent with an interpretation that distributed repetition elicits spontaneous retrieval of episodic information that does not occur for massed repetitions, presumably because contiguous repetition involves memory availability that rules out episodic retrieval. These data mesh well by the recent fMRI findings in which distributed repetitions similarly uniquely prompted BOLD enhancement in a bilateral posterior parietal cluster, including the precuneus and posterior cingulate, which have been implicated in episodic retrieval (Bradley et al., 2014). Taken together, the data suggest that distributed, but not massed, repetition elicits spontaneous episodic retrieval, which may be the mechanism supporting better memory performance in the classic spacing effect.

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