Multiple Forms of Learning Yield Temporally Distinct Electrophysiological Repetition Effects

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Prior experience with a stimulus leads to multiple forms of learning that facilitate subsequent behavior (repetition priming) and neural processing (repetition suppression). Learning can occur at the level of stimulus-specific features (stimulus learning), associations between stimuli and selected decisions (stimulus–decision learning), and associations between stimuli and selected responses (stimulus–response learning). Although recent functional magnetic resonance imaging results suggest that these distinct forms of learning are associated with repetition suppression (neural priming) in dissociable regions of frontal and temporal cortex, a critical question is how these different forms of learning influence cortical response dynamics. Here, electroencephalography (EEG) measured the temporal structure of neural responses when participants classified novel and repeated stimuli, using a design that isolated the effects of distinct levels of learning. Event-related potential and spectral EEG analyses revealed electrophysiological effects due to stimulus, stimulus–decision, and stimulus–response learning, demonstrating experience-dependent cortical modulation at multiple levels of representation. Stimulus-level learning modulated cortical dynamics earlier in the temporal-processing stream relative to stimulus–decision and stimulus–response learning. These findings indicate that repeated stimulus processing, including the mapping of stimuli to decisions and actions, is influenced by stimulus-level and associative learning mechanisms that yield multiple forms of experience-dependent cortical plasticity.

Keywords: ERP, plasticity, priming, repetition suppression, response learning

Introduction

Experience-dependent neuroplasticity is evident in multiple forms of learning and memory and provides a powerful means by which prior experience can inform current perceptual processing, conceptual processing, decision making, and action. One robust expression of experience-dependent neuroplasticity is the reduction in neocortical activity that occurs when processing repeated compared with novel stimuli, termed "repetition suppression" (also "neural priming" or "fMRI adaptation"; fMRI, functional MRI). Repetition suppression has been measured by a variety of techniques, including single unit recordings (e.g., Miller et al. 1991; Fahy et al. 1993; Li et al. 1993), magnetoencephalography (e.g., Gonsalves et al. 2005; Ishai et al. 2006), electroencephalography (e.g., Rugg et al. 1992; Otten et al. 1993; Paller and Gross 1998), and fMRI (e.g., Gabrieli et al. 1996; Buckner et al. 1998; Wagner et al. 2000) and has been observed in multiple neocortical regions, including areas of inferior and lateral temporal cortex that represent stimulus-level perceptual and conceptual features

and areas of prefrontal cortex that mediate goal-directed cognition (for reviews see Desimone 1996; Schacter and Buckner 1998; Henson 2003; Grill-Spector et al. 2006). Behavioral facilitation (repetition priming) often accompanies repetition suppression and is implicitly expressed as faster and more accurate judgments to previously encountered stimuli (Tulving and Schacter 1990; Roediger and McDermott 1993; for a review see Schacter et al. 2007). Though repetition suppression has been widely demonstrated, critical questions remain about the cognitive and neural mechanisms supporting this prevalent form of experience-dependent plasticity.

One prominent theory proposes that stimulus repetition strengthens or sharpens cortical representations of stimulus-specific features, leading to long-term changes in cortical activity (Desimone 1996; Wiggs and Martin 1998; Rainer and Miller 2000; Henson 2003; Grill-Spector et al. 2006). These stimulus-specific changes in cortical representations serve to enhance processing efficiency and reduce overall processing demands when a stimulus is subsequently encountered. In cognitive terms, such changes are thought to reflect long-term learning at the stimulus level, such as learning about encountered perceptual or conceptual features (e.g., Schacter and Buckner 1998; Wagner and Koutstaal 2002). Stimulus-level learning can take multiple forms, including implicit perceptual, lexical, and conceptual priming, as well as explicit memory for previously encountered stimuli (e.g., Roediger and McDermott 1993; Wig et al. 2009).

An alternative theory proposes that repetition suppression and priming reflect changes in long-term associative memory, mediated by the medial temporal lobes, in which stimuli are bound to the contextual features with which they co-occur (Logan 1988, 1990; Dobbins et al. 2004; Schacter et al. 2004; Schnyer et al. 2006; Horner and Henson 2008). Because multiple levels of processing occur between stimulus input and action output (e.g., Fuster 2000), these contextual features may include the decisions and the responses made during initial stimulus categorization (e.g., categorizing a visual object as a "living thing" or responding "yes" when asked if an object is a living thing) (Waszak et al. 2003; Hommel 2007; Schnyer et al. 2007). Published data alternately suggest that the nature of the "response" representations associated with a stimulus can be at the level of a particular action mapping (e.g., "left button press") or a response label (e.g., yes) (e.g., Dobbins et al. 2004; Schnyer et al. 2007; Horner and Henson 2009). Though the present manuscript does not distinguish between these 2 levels of response features, such response associations can be directly contrasted with associations formed between stimuli and previously selected "decisions," such as categorization decisions made about a stimulus prior to initial selection of a response.

Critically, according to proposed associative learning theories, a repeated stimulus serves as a cue to reactivate or retrieve these associated decision or response representations, providing an alternate, more efficient, route to responding that may bypass previously engaged stimulus-level neural and cognitive processes. By this view, although repetition suppression and priming are stimulus specific, these phenomena are not consequences of learning at the stimulus level per se but instead reflect the degree to which a specific repeated stimulus elicits retrieval of learned decision and/or response associations that afford the bypassing of stimulus-level processing.

Initial neural evidence for the associative learning theory of repetition suppression came from an fMRI study in which visual objects were repeatedly classified according to decisions that either repeated or switched across repetitions (Dobbins et al. 2004). When objects were repeatedly classified according to the same decision (e.g., "Larger than a shoebox?" → "Larger than a shoebox?"), significant repetition suppression was observed in left fusiform cortex and left ventrolateral prefrontal cortex (VLPFC), and significant behavioral facilitation was evident in faster reaction times (RTs). However, switching the classification decision across repetitions (e.g., "Larger than a shoebox?" → "Smaller than a shoebox?") disrupted behavioral priming and led to reductions in neural repetition suppression in VLPFC and elimination of repetition suppression in fusiform cortex. These results indicate that stimulus repetition alone does not fully account for repetition effects. Instead, neural and behavioral priming at least partially reflect the formation and retrieval of learned associations between stimuli and responses that provide alternate routes to action.

Although learned associations can make significant contributions to repetition priming, accumulating fMRI evidence suggests that a hybrid model incorporating learning at multiple levels of representation may best characterize repetition-related cortical plasticity (e.g., Henson 2003; Schacter et al. 2007). For example, Race et al. (2009) identified 3 dissociable repetition suppression effects during repetition priming, with learning at the stimulus level and 2 distinct associative levels. In that experiment, subjects semantically classified novel and repeated words that differed in the level of repetition between study and test, such that repetition at the stimulus level (e.g., DOG) was crossed with associative repetition at the stimulus–decision level (e.g., DOG—"Larger") and stimulus–response level (e.g., DOG—"yes"). In addition to behavioral expressions of priming, fMRI measures revealed anatomically dissociable repetition suppression effects associated with learning at each of these levels of representation. At the stimulus level, repetition drove neural-activity reductions in left fusiform cortex, left middle temporal cortex, and anterior portions of left VLPFC, regions associated with the storage and controlled retrieval of conceptual knowledge (e.g., Hodges et al. 1992; Thompson-Schill et al. 1999; Koutstaal et al. 2001; Wagner et al. 2001; Petrides 2002; Simons et al. 2003; Badre et al. 2005; Gold et al. 2005, 2006; for reviews see Badre and Wagner 2007; Martin 2007; Binder et al. 2009). Importantly, these stimulus-level effects were independent of stimulus–decision and stimulus–response repetition, arguing against a purely associative account of repetition suppression in which neural-activity reductions reflect bypassed processing. However, associative learning also yielded repetition suppression but in distinct regions of frontal cortex. Specifically, stimulus–decision repetition uniquely drove activity reductions in left middle and posterior VLPFC (~BA 44/45), regions

associated with mnemonic selection and the mapping of stimuli to decisions (Badre et al. 2005; Dobbins and Wagner 2005, Badre and Wagner 2006, 2007; Gold et al. 2006; Danker et al. 2008). These reductions overlapped with the location of the prefrontal repetition suppression effect identified by Dobbins et al. (2004), suggesting that this prior observation of associative learning occurred at the stimulus–decision level. In contrast, stimulus–response repetition resulted in activity reductions in more caudal regions of left VLPFC and premotor cortex, regions closely associated with response selection (Bunge et al. 2002; Koechlin et al. 2003; Badre and D'Esposito 2007; Grafton and Hamilton 2007; Nakayama et al. 2008). Collectively, a functional triple dissociation between these 3 patterns of repetition suppression indicates that at least 3 distinct levels of learning— stimulus learning, stimulus–decision learning, and stimulus–response learning—can contribute to experience-dependent neuroplasticity.

Although repetition-induced neural processing benefits are frequently observed, under some circumstances, learning can result in repetition-related processing costs (Thompson-Schill et al. 1999). For example, in addition to 3 patterns of repetition suppression, Race et al. (2009) observed repetition-related activity increases in dorsal premotor and anterior cingulate cortex (ACC) when learned stimulus–response associations conflicted with subsequent task goals. Such neural markers of proactive interference demonstrate that learned stimulus–response associations can produce either response facilitation or response conflict depending on whether or not the learned associations remain goal relevant. Accordingly, extant fMRI results appear to support a hybrid model of experience-dependent cortical plasticity in which multiple levels of learning confer neural-processing benefits, as well as costs, during repeated stimulus processing.

As extant fMRI data indicate that stimulus, stimulus–decision, and stimulus–response learning affect processing in distinct neocortical regions, a critical question is how these forms of learning influence cortical response dynamics. Convergent evidence from electroencephalography (EEG) and magneto-encephalography (MEG) indicates that long-lag stimulus repetition leads to activity modulations beginning approximately 200-ms poststimulus onset (e.g., Bentin and Peled 1990; Rugg et al. 1992, 1994; Otten et al. 1993; Paller and Gross 1998; Swick 1998; Sekiguchi et al. 2001; Kiefer 2005). In scalp recorded event-related potentials (ERPs), a positive amplitude shift occurs over central and posterior scalp sites and results in a reduction of the negative component occurring ~400 ms poststimulus (N400) as well as enhancement of the subsequent late positive complex (LPC) occurring ~600 ms poststimulus (e.g., Olichney et al. 2000; Henson et al. 2003, 2004). Although these repetition-related amplitude shifts have been widely demonstrated, the potential contributions of learning at the stimulus, stimulus–decision, and stimulus–response levels have yet to be distinguished. One possibility is that these multiple levels of learning yield temporally distinct repetition effects that can be dissociated in EEG measurements of cortical processing.

Indeed, initial ERP support for the hypothesis that multiple forms of learning (at both the stimulus and associative levels) yield temporally distinct repetition effects comes from evidence suggesting that the N400 repetition effect is functionally and anatomically dissociable from the later P600 component. For example, intracranial ERP studies indicate that

different neural populations generate the N400 compared with the P600 (e.g., Guillem et al. 1995), and the magnitude of the P600, but not the N400, is modulated by context-related factors such as tasks and responses (e.g., Karayanidis et al. 1991; Finnigan et al. 2002; but see Rugg et al. 1992). The N400 repetition effect has been hypothesized to index changed demands on postperceptual (i.e., lexical/semantic) processing that can occur in the absence of explicit memory (e.g., Rugg et al. 1998; Schweinberger et al. 2002; Voss and Paller 2006, 2007; see Sekiguchi et al. 2001 for relevant MEG data), whereas the P600 has been associated with explicit recollection of prior episodes (e.g., Wilding and Rugg 1996; Curran 2000; Wolk et al. 2006; for review see Voss and Paller 2008). Accordingly, although the nature of the processes contributing to ERP repetition effects is still a matter of debate, extant results suggest that a single mechanism may not fully explain ERP repetition phenomena. Moreover, conflict-related ERP modulations have also been identified both prior to and following response execution (e.g., Gehring et al. 1990; Botvinick et al. 2001; Van Veen and Carter 2002b; Yeung et al. 2004), raising the possibility that retrieved associations further modulate processing when learned response associations conflict with current goals.

Tentative support for the hypothesis that different forms of long-term learning modulate cortical response dynamics at distinct points of time also comes from observations by Race et al. (2009) that distinct learning mechanisms appeared to contribute to repetition suppression effects at different time points of the fMRI hemodynamic response function (HRF). Specifically, stimulus-specific HRF reductions in left anterior VLPFC and temporal cortex appeared to precede a later emerging repetition suppression effect that reflected decision-level repetition, suggesting that activity in a single cortical region may reflect interactions between different forms of learning and/or feedback between distinct regions of cortex (e.g., Dale et al. 2000). Although the low temporal resolution of fMRI prevented precise temporal specification of these repetition effects, these results suggest that retrieved associations (e.g., at the stimulus-decision and/or stimulus-response levels) may modulate cortical responses later in time compared with priming at the stimulus level.

The current study tested this prediction by investigating how contributions from multiple forms of learning temporally influence cortical activity. Cortical responses were recorded using scalp EEG while subjects semantically classified novel and repeated words that differed in the level of repetition between study and test (a design that paralleled that of Race et al. 2009). Repetition was manipulated at 3 levels: 1) stimulus repetition, 2) stimulus-decision repetition, and 3) stimulus-response repetition. By crossing these 3 levels of repetition in a single paradigm, the distinct contributions of long-term learning at these levels could be investigated concurrently. We had 4 predictions about the temporal dynamics of these repetition effects.

First, given that the N400 component has been associated with semantic processing and neural activity generated in the temporal lobe (Kutas and Hillyard 1980; Holcomb et al. 2005; Matsumoto et al. 2005), we predicted that long-term learning at the stimulus level that sharpened or strengthened conceptual representations would modulate the negative ERP waveform around 400 ms. Second, we predicted that associative learning at the stimulus-decision and stimulus-response levels would yield temporally distinct repetition effects occurring later in time than effects of stimulus-level learning but before the time of response execution (which occurred ~900-ms poststimulus onset, on average). Third, to the extent that learned stimulus-response associations yield both facilitative and competitive effects, we predicted that stimulus-response conflict would be evident in electrophysiological modulations around the time of response execution. Finally, given the prior fMRI findings of Race et al. (2009), to the extent that topographic differences can be detected with our ERP methods, we expected that differences in the effects of stimulus, stimulus-decision, and stimulus-response repetition would be present over frontal scalp sites.

Materials and Methods

Participants
Fifteen right-handed, native English speakers (9 females; mean age = 21 years, range 18-35 years) without a history of neurological or psychiatric illness participated in the study. Participants received $10/h, with the study lasting approximately 3 h. Data from 3 additional participants were collected but excluded from analysis, 2 due to poor behavioral performance (<70% accuracy in a condition of interest) and 1 due to outlier ERP amplitudes (>3 standard deviation, SD from the mean at multiple electrode regions). Participants were recruited from the Stanford University community and surrounding area and gave informed consent prior to participation in accordance with procedures approved by the Stanford University Institutional Review Board.

Materials
The stimulus set consisted of 360 nouns (mean word length = 6.2 letters; mean word frequency = 11.1/million). Half of the words referred to organic objects and half to inorganic objects. For both the organic and the inorganic words, half referred to objects smaller than a 13″ box and half to larger objects. The stimuli were divided into 6 sets of 60 words, matched for mean word length and frequency and containing 15 words from each of the organic/inorganic × smaller/larger crossings. For each participant, 4 of these sets served as repeated items that were studied 3 times during encoding, with the remaining 2 serving as novel items at test. Across participants, sets were counterbalanced across conditions.

Behavioral Procedure and Analysis
Instructions and practice were given prior to the start of the experiment. The experiment proper consisted of 3 study blocks and a final test block. EEG was recorded during all blocks, with the present analyses focusing on data from the critical test block.

The same trial structure was maintained across study and test blocks. On each trial, participants were presented with 1 of 2 task cues and a target word. Task cues appeared in uppercase letters above a central fixation cross and indicated which of 2 semantic decisions was to be made for the target word that would appear below the cross in lowercase letters (Fig. 1A). For the size decision task, the cue "Smaller?" or "Larger?" appeared, whereas the cue "Organic?" or "Inorganic?" appeared for the composition task. Each participant was presented with only 1 of the 2 possible cues for each classification task through the duration of the experiment (i.e., the same participant never encountered both "Smaller?" and "Larger?" trials, nor "Organic?" and "Inorganic?" trials). The cue used for each task and the order of classification decisions were counterbalanced across participants.

Task cues were presented in isolation above the central fixation cross for 500 ms followed by presentation with a target word that appeared below the fixation cross in lowercase letters for 400 ms. The presentation of the task cue and target word was followed by a response period that lasted up to 2000 ms (self-paced). Participants could respond as soon as the target word appeared as well as during the response period, as indicated by the fixation cross turning green during these periods. Participants indicated their responses with "yes" or "no" button presses on a keyboard, using their right middle and index fingers.
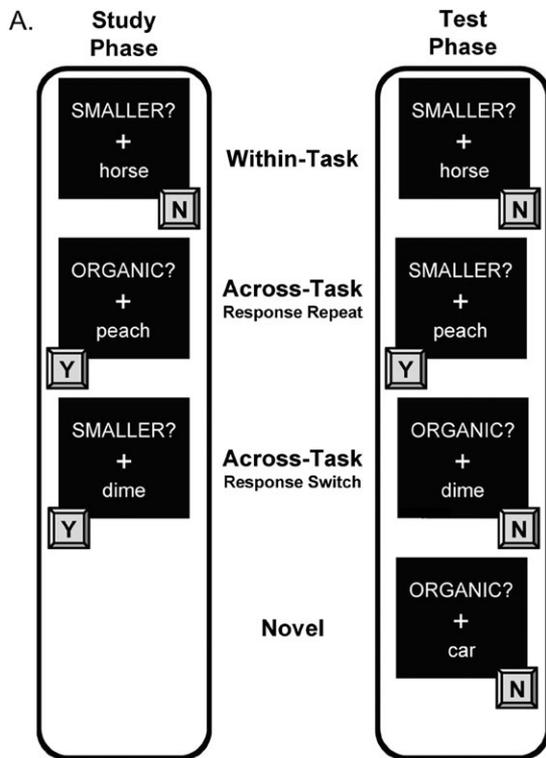
Figure 1. Task schematic and levels of repetition. (*A*) During study, each target word was presented with the same decision cue 3 times, and subjects pressed 1 of 2 buttons to indicate a "yes" (Y) or "no" (N) response. At test, studied target words were presented again either with the same cue (Within-Task) or a different cue (AT), and Novel target words were presented for the first time. Of the AT trials, half required the same response as at study (AT-RR), and half required a different response (AT-RS). (*B*) The 4 test conditions differed according to repetition at the stimulus, stimulus–decision, and stimulus–response levels.

Following each response, a white fixation cross was presented for 250 ms, followed by an explicit cue (blue brackets surrounding the fixation cross) signaling that the participant had 750 ms to blink if necessary. Participants were instructed to minimize blinking and to blink when necessary only during specified postresponse blink periods. The onset of the blink period was timed to prevent eyeblink contamination of the EEG signal for at least 1300 ms after stimulus presentation. If a response was faster than 1300 ms, a filler fixation period was presented before the blink was cued. If a response occurred after 1300 ms, the blink-period onset immediately after the response. Following the blink period, a white fixation cross was displayed for 500 ms before the onset of the next trial.

In the study phase, participants classified 240 words—120 under the size task and 120 under the composition task. The same 240 words appeared 3 times in a pseudorandomized order during study. For a given participant, the task cue associated with each word was held constant across the 3 repetitions.

During the critical final test phase, the 240 words from the study phase were represented along with 120 novel words. Of the 240 repeated words, half required the same classification and response as the study phase (Within-Task), whereas the other half entailed a study-to-test task switch from either size-to-composition or composition-to-size decisions (Across-Task [AT]). Of the 120 AT words, half required the same response as was previously appropriate during study (Across-Task Response-Repeat [AT-RR]), whereas the other half required a different response (Across-Task Response-Switch [AT-RS]). Behavioral and electrophysiological analyses focused on the data from this test phase.

Conditions of interest were defined according to the level of repetition between the study and test phases (Fig. 1*B*). Novel items did not contain any level of repetition. Within-Task items were associated with stimulus, stimulus–decision, and stimulus–response repetition. All AT items were associated with stimulus-level repetition. AT items were further divided according to whether they also included response repetition (AT-RR) or response conflict (AT-RS). Repeated-measures analyses of variance (ANOVAs) were performed on median RTs (restricted to correct trials) using Huynh–Feldt correction where appropriate.

EEG Methods

Electroencephalogram (EEG) was recorded with Neuroscan SCAN version 4.3 acquisition software (Compumedics Inc., El Paso, TX) from 60 electrode sites embedded in an elasticized cap and distributed across the scalp according to the 10–20 system (EasyCap GMbH, Herrsching-Breitbrunn, Germany). The signal was recorded from 0.05 to 40 Hz at a sampling rate of 1000 Hz referenced to the left mastoid, with subsequent offline re-referencing to average mastoids. Interelectrode impedances were kept at 5 kΩ or less. Vertical eye movements were recorded by electrodes placed on the supra and infraorbital ridges of the right eye. Horizontal eye movements were recorded by electrodes placed lateral to the outer canthi of the right and left eyes.

EEG Analysis

Signal processing was performed with EEGLab analysis software (Delorme and Makeig 2004). All analyses were restricted to correct trials from the test phase. For ERP stimulus-locked analyses, epochs spanned 100 ms prior to stimulus onset (baseline) until 900 ms poststimulus onset (all reported effects also hold when a 200-ms baseline period was used). The 100-ms prestimulus baseline was also used for response-locked epochs, which spanned from 500 ms prior to response onset until 500 ms postresponse. The threshold for artifact rejection was set to 100 μV and epochs contaminated with artifacts at any electrode site were rejected before averaging. All continuous EEG data were low-pass filtered at 20 Hz before analysis (all reported effects also hold when a 0.5-Hz high-pass filter was included before analysis). Average ERP waveforms from correct trials were computed for each condition and for each participant and submitted to group analysis. Amplitudes were averaged over 50-ms time windows around peaks of interest and across electrodes in each of 12 topographical regions (4 anterior–posterior regions: fronto-polar, fronto-central, centro-parietal, and parieto-occipital; 3 laterality regions: left, medial, and right; Fig. 2).

For power spectral analysis, data were not low-pass filtered, and event-related spectral perturbation (ERSP) transforms were computed for each channel using Morlet waveforms starting with 3 wavelet cycles and increasing with frequency by a factor of 0.5. ERSPs measured changes in spectral power from baseline across a frequency range of 3–40 Hz. The resulting time–frequency data were averaged across conditions and electrodes as described above. To visualize power changes across the frequency range, the mean baseline log-power spectrum was subtracted to produce baseline-normalized ERSPs. All ERP and spectral data were submitted to repeated-measures ANOVAs with alpha-level adjustment using Huynh–Feldt correction for non-sphericity where appropriate.

Results

Behavioral Performance

Median RT and accuracy were determined for each condition at test (Table 1), and submitted to repeated-measures ANOVA.
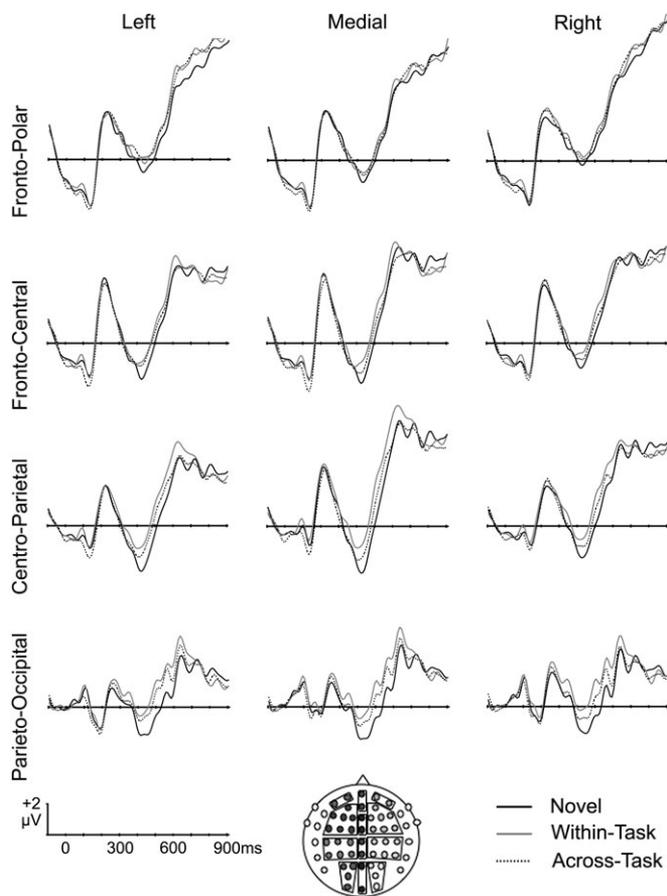
Figure 2. Stimulus-locked ERP repetition effects. Grand average stimulus-locked waveforms averaged into 12 electrode regions as indicated on scalp map. Zero on the time axis (ms) marks target word onset.

Table 1
RTs (ms) and response accuracy varied across conditions (SD in parentheses)

	RT	Accuracy
Novel	898 (202)	0.89 (0.06)
Within-task	832 (196)	0.91 (0.06)
Across-task	894 (219)	0.87 (0.07)
Response-repeat	859 (217)	0.93 (0.07)
Response-switch	942 (227)	0.82 (0.09)

These analyses revealed no effect of task (size/composition; $Fs < 1$), nor an interaction between task and repetition condition (Task × Repetition, $Ps > 0.1$), on either RT or accuracy.

During the test phase, RTs differed across conditions (Novel/Within-Task/AT; $F_{(2,28)} = 14.16$, $P < 0.001$). Specifically, compared with Novel trials, RT was faster for Within-Task trials ($F_{(1,14)} = 24.90$, $P < 0.001$) but not for AT trials ($F < 1$). However, when AT trials were split according to response type, RT on AT-RR trials was faster than that on Novel trials ($F_{(1,14)} = 6.63$, $P < 0.05$) and did not significantly differ from that on Within-Task trials ($F_{(1,14)} = 1.92$, $P > 0.18$). That is, even when the categorization task changed, RT was facilitated for repeated stimuli associated with repeated responses. By contrast, RT on AT-RS trials was significantly slower than during all other conditions (Novel: $F_{(1,14)} = 10.19$, $P < 0.05$; Within-Task: $F_{(1,14)} = 39.04$, $P < 0.001$; AT-RR: $F_{(1,14)} = 17.57$,

$P < 0.001$), revealing an RT cost when the primed response conflicted with the appropriate response at test.[1]
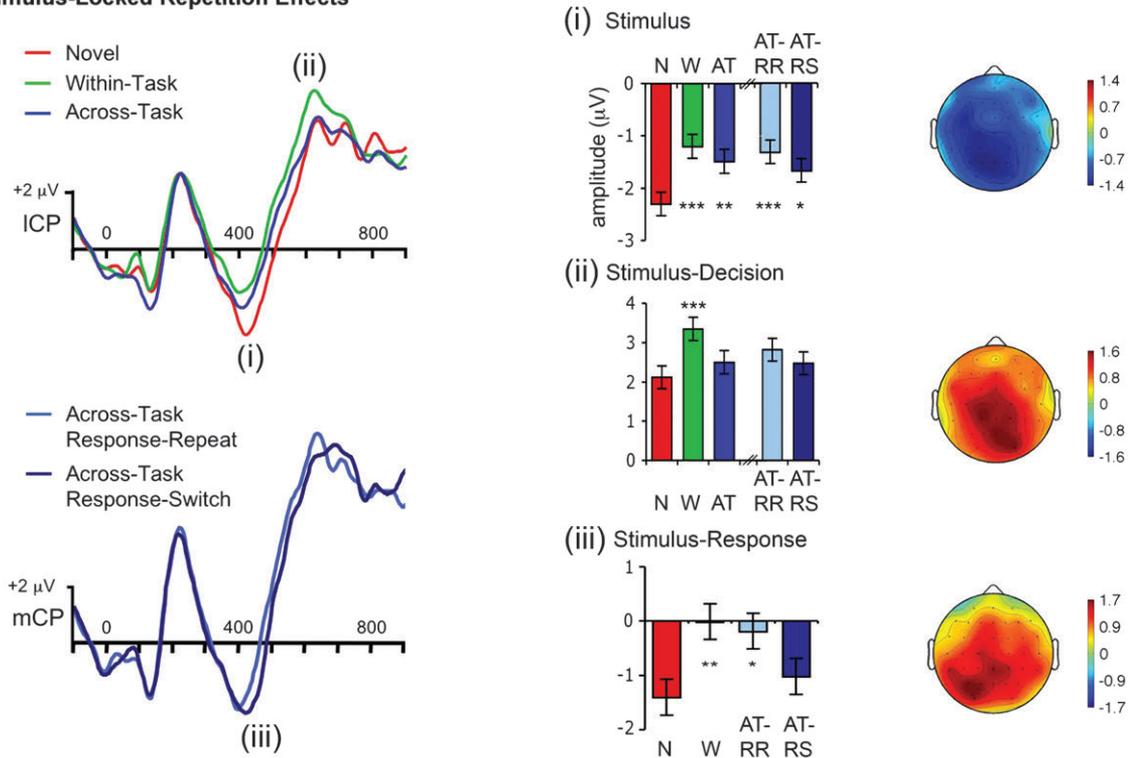
Accuracy differed across conditions, both when the Across-Task conditions were collapsed across response type ($F_{(2,28)} = 5.65$, $P < 0.05$) and when they were separated according to response type ($F_{(3,42)} = 15.54$, $P < 0.001$). The pattern of repetition effects on accuracy paralleled those seen on RT, ruling out a speed–accuracy trade-off. Specifically, there were fewer errors on Within-Task ($F_{(1,14)} = 6.60$, $P < 0.05$) and AT-RR trials ($F_{(1,14)} = 5.24$, $P < 0.05$) relative to Novel trials, and the accuracy on Within-Task and AT-RR trials did not differ from each other ($F < 1$). In contrast, AT-RS trials elicited more errors relative to all other conditions ($Ps < 0.001$).

ERP Results: Stimulus-Locked Analysis

Initial electrophysiological analyses investigated stimulus-locked ERPs on Novel, Within-Task, and AT trials (collapsed over response type). To investigate stimulus- and decision-level repetition effects in an unbiased manner, ERPs for Novel trials (no repetition) were compared with ERPs for Within-Task trials (3 levels of repetition). Amplitude differences between Novel and Within-Task trials emerged at 2 primary latency intervals: the negative peak at approximately 400-ms poststimulus onset and the positive peak at approximately 600-ms poststimulus onset (Fig. 2). We therefore analyzed 50-ms time windows around these peaks of interest (spanning 350–400 and 400–450 ms for the negative peak and spanning 550–600 and 600–650 ms for the positive peak). In the time windows in which Novel and Within-Task amplitudes diverged, we distinguished between effects of stimulus and stimulus–decision learning by comparing Novel and Within-Task amplitudes with AT amplitudes. Critically, ERP signatures of stimulus repetition should be evident in significant amplitude differences from Novel trials for both Within-Task and AT trials, because both conditions contained repetition at the stimulus level. In contrast, decision-level learning should be evident in ERP amplitudes that diverged only for Within-Task trials (the only condition in which stimulus–decision mappings repeated) and should not differ between AT and Novel trials (neither of which contained repetition at the decision level).

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[1]Although we did not have an a priori prediction that practice would differentially influence the observed priming effects (given the hypothesis that the effects are expressions of stimulus-specific, rather than generalized, learning), we conducted an additional analysis to determine whether the magnitude of priming during the first and the second halves of the test block varied by condition. A 3 × 2 ANOVA revealed a significant interaction between priming (RT difference from Novel trials for Within-Task, AT-RR, and AT-RS trials) and time (first half, second half) ($F_{(2,28)} = 4.90$, $P < 0.05$). Follow-up analyses indicated that this interaction was driven by a difference in the magnitude of the response-switch cost (AT-RS slowing compared with Novel trials) that was greater in the first half compared with the second half of the test block ($P < 0.05$). None of the other conditions showed significant priming differences across the first and second halves of the test block ($Ps > 0.09$). Although the reduction in response-switch cost across the first and second halves of the test block could be interpreted as an improved ability to deal with stimulus–response interference as the testing proceeds, this result must be interpreted with caution given the low number of trials in each condition when splitting the test block in half. Future studies specifically designed to test the hypothesis that learning effects (and learning-related interference effects) change with practice or training could shed important light on this issue.
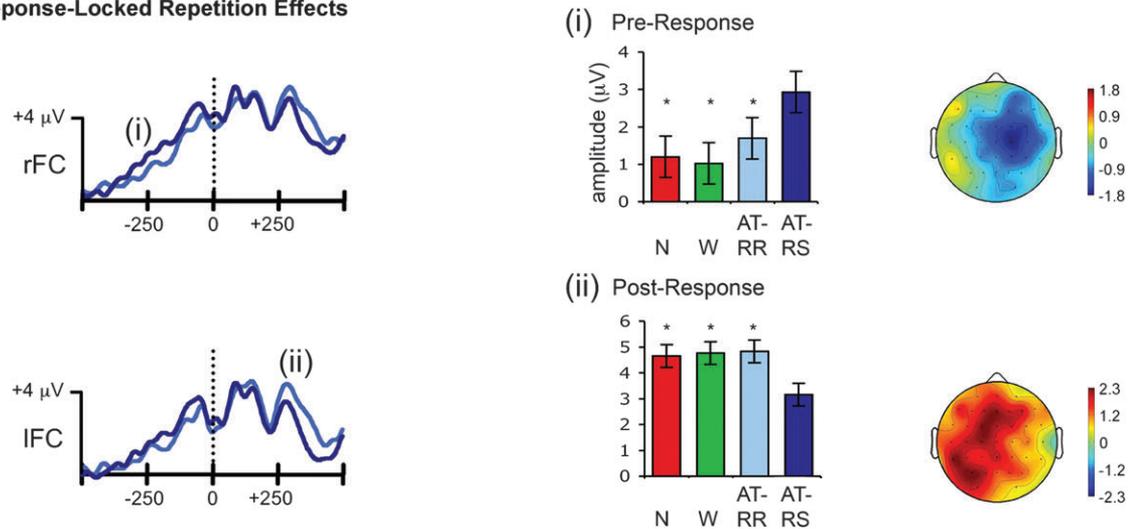
Figure 3. ERP repetition effects. (*A*) Stimulus-locked repetition effects displayed at representative left centro-parietal and medial centro-parietal electrode regions. (*i*) Stimulus repetition effect: stimulus repetition modulated the negative peak from 400 to 450 ms across all electrode regions with amplitude reduction for all repeated trials (W, AT, AT-RR, and AT-RS) compared with Novel trials (*N*). Bar graph represents mean amplitudes from 400 to 450 ms collapsed across all electrode sites. Topographical map represents mean amplitude difference between Novel and all repeated trials from 400 to 450 ms. (*ii*) Stimulus–decision repetition effect: stimulus–decision repetition modulated ERPs from 550 to 600 ms across all electrode regions and reflected more positive amplitudes for Within-Task compared with all other trial types. Bar graph represents mean amplitudes from 550 to 600 ms collapsed across all electrode sites. Topographical map represents mean amplitude difference between Within-Task and all other trial types (Novel and AT trials) from 550 to 600 ms. (*iii*) Stimulus–response repetition effect: stimulus–response repetition modulated ERPs from 450 to 500 ms with reduced negativity for AT-RR compared with AT-RS trials. During this time window, amplitude reductions were present for both of the conditions containing response repetition (Within-Task and AT-RR) compared with both of the conditions without response repetition (Novel and AT-RS) across medial electrodes. Bar graph represents mean amplitudes from 450 to 500 ms collapsed over all medial electrodes. Topographical map represents mean amplitude difference between AT-RS and AT-RR trials from 450 to 500 ms. Zero on the time axis (ms) marks target word onset. ERP amplitude differences relative to Novel trials is denoted ***$P < 0.005$, **$P < 0.01$, and *$P < 0.05$. (*B*) Stimulus–response conflict effects evident in response-locked ERPs displayed at right and left fronto-central electrode regions. (*i*) In the preresponse period (from -300 to -250 ms prior to response onset), amplitudes on AT-RS trials were more positive than all other trial types over right fronto-central electrodes. Bar graph represents mean amplitude during the preresponse period in the right fronto-central electrode region. Topographical map represents mean amplitude difference between AT-RS and AT-RR trials during the preresponse period. (*ii*) In the postresponse period (from 250 to 400 ms postresponse), amplitudes on AT-RS trials were more negative than all other trial types over left fronto-central electrodes. Bar graph represents mean amplitude during the postresponse period in the left fronto-central electrode region. Topographical map represents mean amplitude difference between AT-RS and AT-RR trials during the postresponse period. Zero on the time axis (ms) marks response onset. ERP amplitude differences relative to AT-RS trials is denoted *$P < 0.05$. Novel (N); Within-Task (W); Across-Task (AT); Across-Task Response Repeat (AT-RR); and Across-Task Response Switch (AT-RS). In all figures, error bars reflect within-subject standard error.

Stimulus Repetition Effects

Consistent with prior reports of repetition-related attenuation of the negative ERP deflection occurring at approximately 400-ms post-stimulus onset (N400) (e.g., Nagy and Rugg 1989; Joyce et al. 1999; Ledoux et al. 2006), we observed a repetition-related reduction in the negative ERP deflection from 400 to 450 ms across all electrode regions (Fig. 3*Ai*; main effect of Repetition, $F(2,28) = 6.94$, $P < 0.005$) that did not differ according to task (size/composition) ($F < 1$). N400 amplitude reduction occurred for both Within-Task ($F(1,14) = 11.91$, $P < 0.005$) and AT trials ($F(1,14) = 9.02$, $P < 0.01$) compared with Novel trials. The magnitude of the N400 reduction did not differ between Within- and AT trials ($F < 1$), indicating that reductions of the N400 occur with stimulus repetition independent of stimulus–decision repetition. In addition, the N400 reduction was not dependent on stimulus–response repetition, as indicated by significant amplitude reductions for AT trials both when responses repeated (AT-RR; $F(1,14) = 11.53$, $P < 0.005$) and when responses switched (AT-RS; $F(1,14) = 4.88$, $P < 0.05$), compared with Novel trials. The N400 reductions on AT-RR and AT-RS trials did not differ from the reduction on Within-Task trials ($Ps > 0.21$).

Stimulus–Decision Repetition Effects

Repetition also modulated the positive ERP peak occurring ~600 ms after target presentation and was significant across all electrode regions from 550 to 600 ms (Fig. 3*Aii*; main effect of Repetition ($F(2,28) = 5.92$, $P < 0.01$) and did not differ according to task (size/composition) ($F < 1$). Amplitude differences at this later time window reflected more positive ERP amplitudes for Within-Task compared with both Novel ($F(1,14) = 12.09$, $P < 0.005$) and AT trials ($F(1,14) = 5.38$, $P < 0.05$). Further, ERP magnitudes did not differ between Novel and AT trials ($F < 1$). The specificity of this ERP modulation to Within-Task trials suggests that this effect may be driven by repetition of learned stimulus–decision mappings. Indeed, ERP amplitudes were unaffected by response repetition, as they did not differ between AT-RR and AT-RS trials ($F < 1$). These data suggest a temporal dissociation between earlier stimulus repetition effects (400–450 ms) and later stimulus–decision repetition effects (550–600 ms). This dissociation was supported by a Time × Repetition interaction that, although not significant across all electrode regions ($F(2,28) = 1.84$, $P = 0.19$), reached significance when the ERP data were collapsed over left fronto-polar and left fronto-central electrodes ($F(2,28) = 3.99$, $P < 0.05$, uncorrected for multiple comparisons). Note that this localization is broadly consistent with fMRI data documenting a left frontal dissociation between stimulus and stimulus–decision repetition effects (Race et al. 2009).

Stimulus–Response Repetition Effects

The preceding analyses provide evidence that repetition at the stimulus level and the stimulus–decision level contribute to ERP modulations at earlier (~400 ms) and later (~600 ms) time points, respectively. To investigate the effects of stimulus–response repetition, we directly contrasted the ERPs for the 2 AT conditions, as these conditions differed only with respect to whether responses repeated (AT-RR) or switched (AT-RS) from study to the test.

Visual inspection of the ERP waveforms revealed a small amplitude difference between the 2 AT conditions in the positive peak at ~600 ms, from approximately 600 to 650 ms, and in the later portion of the ~400-ms negative peak, from approximately 450 to 500 ms (Fig.3*Aiii*). No main effect of Repetition (Novel, Within-Task, AT-RR, AT-RS) was present across electrode regions during the positive peak from 600 to 650 ms ($P = 0.24$). However, during the 450–500 ms time window, there was a main effect of Repetition (Novel, Within-Task, AT-RR, AT-RS; $F(3,42) = 4.54$, $P < 0.01$) across all electrode regions, reflecting amplitude reductions for both of the conditions in which responses repeated (AT-RR and Within-Task) compared with Novel trials ($Ps < 0.05$). Although ERP amplitudes for the AT-RR and With-Task trials did not significantly differ from that on AT-RS trials across all electrode regions ($Ps \leqslant 0.2$), an exploratory analysis restricted to medial electrodes revealed a main effect of Repetition ($F(3,42) = 4.25$, $P < 0.05$) during this time window (that did not interact with task, $F < 1$) that reflected a reduction in ERP amplitude for both of the conditions in which responses repeated (AT-RR and Within-Task) compared with both of the conditions without response repetition (Novel and AT-RS trials) ($Ps < 0.05$; Fig. 3*Aiii*). The magnitude of the amplitude reduction for Within-Task and AT-RR trials did not differ from each other ($F < 1$), providing further support that this ERP modulation was driven by the factor of stimulus–response repetition common to both of these conditions.

Although these results provide initial evidence for ERP modulations due to stimulus–response learning, caution must be taken when interpreting this effect as distinct from the earlier N400 stimulus repetition effect given the absence of a Time (400–450, 450–500 ms) × Repetition (Novel, Within-Task, AT-RR, AT-RS) interaction when computed over all electrode regions ($F < 1$). Although exploratory, this interaction did reach significance over the left parieto-occipital electrode region ($F(3,42) = 3.02$, $P < 0.05$, uncorrected for multiple comparisons). Caution must also be taken when interpreting this stimulus–response effect in relation to the later ~600-ms stimulus–decision effect due to the absence of a Time (450–500, 550–600 ms) × Repetition (Novel, Within-Task, AT-RR, AT-RS) interaction when computed across all electrode regions ($P = 0.26$). However, this interaction did reach significance over the left fronto-central electrode region ($F(3,42) = 3.26$, $P < 0.05$, uncorrected for multiple comparisons), a finding that is broadly consistent with the left frontal dissociation between stimulus–decision and stimulus–response learning observed with fMRI (Race et al. 2009).

ERP Results: Response-locked Analysis

Because stimulus-locked analyses do not account for variability in response times within and across participants, we conducted a second analysis of response repetition effects on response-locked ERPs. This analysis focused on time windows in which AT-RR and AT-RS waveforms diverged, including both preresponse and postresponse windows.

During the preresponse window, positive amplitudes for AT-RR trials were reduced compared with those for AT-RS trials starting at approximately 300 ms before response onset (Fig. 3*Bi*). The amplitude difference between the 2 AT conditions was tested in 50-ms bins from –300 to –150 ms and was significant over right fronto-central electrodes from –300 to –250 ms ($F(1,14) = 11.44$, $P < 0.05$). This amplitude difference reflected greater ERP positivity on AT-RS trials compared with all other trial types (including both Novel and

Within-Task trials, *P*s < 0.05), whereas the amplitude of these other trial types did not differ from each other (*F*s < 1). The specificity of this ERP modulation to the response-switch trials likely reflects processing due to response conflict when previously learned stimulus–response mappings are no longer appropriate to current goals.

After response execution, the polarity of amplitude differences between the 2 AT conditions inverted approximately 250 ms after response onset, with reduced positivity on AT-RS than on AT-RR trials (Fig. 3*Bii*). This amplitude difference was tested in 50-ms bins from 250 to 400 ms postresponse and reached significance across the 250- to 400-ms postresponse window at left fronto-central scalp regions ($F(1,14) = 5.80$, $P < 0.05$). Like the response conflict effect that emerged at frontal electrodes before response execution, this postresponse effect was driven by an amplitude divergence on AT-RS trials. Specifically, in addition to reduced positivity compared with AT-RR trials, positivity on AT-RS trials was also reduced compared with Novel and Within-Task trials ($F(1,14) = 5.85$, $P < 0.05$ and $F(1,14) = 6.60$, $P < 0.05$, respectively). Amplitudes on Novel, Within-Task, and AT-RR trials did not differ from each other (*F*s < 1).

The directionality of the response-locked amplitude difference between the AT conditions changed over time, as reflected in a significant Time (–300 to –250, 250–400 ms) × Condition (AT-RR, AT-RS) interaction ($F(1,14) = 6.51$, $P < 0.05$). These pre and postresponse ERP correlates of response conflict also appeared to differ in topography, with a shift from a right-lateralized distribution in the preresponse window to a left-lateralized distribution in the postresponse window (Fig. 3*B*). This topographic shift was confirmed by a significant Time × Repetition × Laterality interaction across fronto-central regions ($F(2,28) = 10.26$, $P < 0.001$) that held when amplitudes were normalized using the vector scaling method ($F(2,28) = 3.43$, $P < 0.05$) (McCarthy and Wood 1985).

Time–Frequency Results

Although ERPs are a powerful index by which to measure learning-related neural activity changes, ERPs do not capture the whole spectrum of relevant electrocortical activity. In addition, ERPs average out induced responses that may reflect important electrophysiological signatures of learning but occur with latency jitters from trial to trial. Accordingly, we next conducted a power spectral analysis to measure learning-related changes in the brain's oscillatory activity.

Motivated by recent magnetoencephalography results indicating that repeated object classification increases beta-band phase locking (neural synchrony) between prefrontal and temporal cortex (Ghuman et al. 2008), we investigated whether repetition also modulates power fluctuations in this frequency range. Specifically, we compared stimulus-induced oscillatory power in each of our conditions of interest at test. Given 1) the association between beta oscillations and learning and 2) demonstrations that although primed stimuli elicit greater cross-regional beta phase synchrony (Ghuman et al. 2008), they also elicit decreased beta power compared with novel stimuli (Duzel et al. 2005), we hypothesized that beta power would be greater for Novel trials than for Repeated trials. A critical further question was whether repetition at a particular level of representation (stimulus, decision, or response) modulates spectral power.
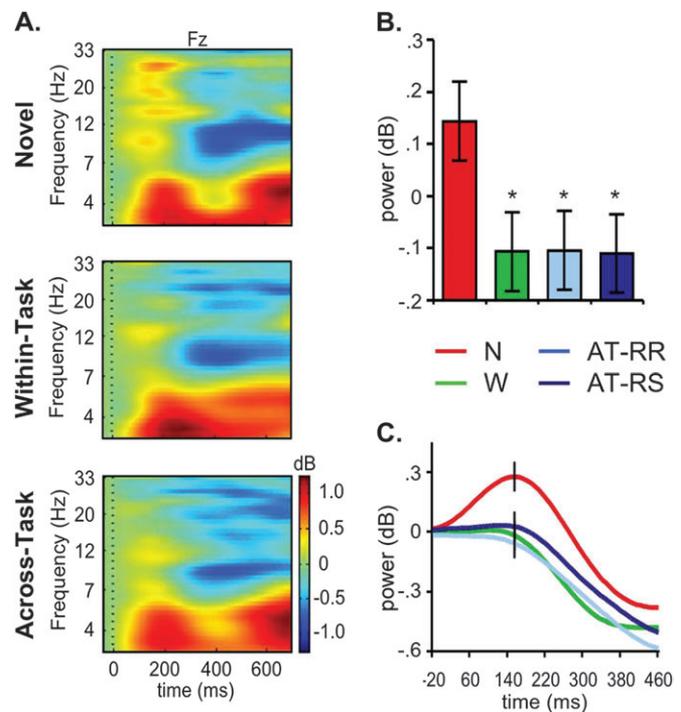

Figure 4. Repetition-related spectral power changes occurred in the beta frequency range (≈12–30 Hz). (*A*) Time–frequency plots demonstrating an early (~100–300 ms) beta power increase following the presentation of Novel trials (displayed at a representative fronto-central electrode). (*B*) Mean beta power from 100 to 300 ms was greater for Novel trials than for all repeated trials (W, AT-RR, and AT-RS). (*C*) Beta power increases for Novel trials compared with all repeated trials peaked at 153 ms.

Prior results suggesting an effect of repetition on neural synchrony identified effects that occurred from approximately 100–300 ms following stimulus onset (Ghuman et al. 2008). Accordingly, our analysis focused on beta power fluctuations during this same time window. As depicted in Figure 4*A*, following the presentation of novel stimuli an early (~100–300 ms) peak in spectral power occurred in the beta band (≈12–30 Hz) over fronto-central electrode regions. Importantly, stimulus repetition modulated this early beta response ($F(2,28) = 5.60$, $P < 0.05$) and power reductions were significant for all repeated stimuli regardless of task repetition or task switching (Within-Task and AT, *P*s < 0.05; Fig. 4*B*). Further, these power reductions were also significant regardless of response repetition (AT-RR and AT-RS, *P*s < 0.05). This beta-band repetition suppression effect peaked relatively early in time (153 ms; Fig. 4*C*). Additional exploratory analysis did not identify repetition effects in other frequency bands. Thus, these results provide novel evidence that stimulus-level learning, independent of stimulus–decision and stimulus–response learning, modulates beta-band repetition effects that onset early upon stimulus repetition.

Brain–Behavior Correlations?

To explore possible brain-behavior correlations, regression analyses were performed on each of the main EEG effects of interest using subjects' behavioral RT and accuracy measurements of priming. No significant correlations were found, suggesting that neural repetition effects may not have linear effects on behavior (e.g., Sayres and Grill-Spector 2006; Xu et al. 2007; Salimpoor et al. 2009; but see Dobbins et al. 2004; Lustig

and Buckner 2004; Maccotta and Buckner 2004). Although a null result, this finding further highlights the complex relationship between neural and behavioral priming (Race et al. 2009).

Discussion

The present findings shed light on the underlying cognitive and neural mechanisms supporting repetition-related cortical plasticity. Complementing recent fMRI results that suggest that stimulus, stimulus–decision, and stimulus–response learning produce functional changes in dissociable regions of frontal and temporal cortex (Race et al. 2009), here we provide novel EEG evidence indicating that learning at each of these levels yields temporally distinct changes in cortical response dynamics. These results support a hybrid model of repetition effects in which multiple forms of learning contribute to long-term changes in cortical function.

Behavioral Evidence for Learning at Multiple Levels of Representation

Behavioral measures of priming revealed the effects of learning at multiple levels of representation. Specifically, RT and accuracy measures of priming demonstrated both repetition-related facilitation as well as repetition-related interference. Three key findings are of note.

First, subjects were faster and more accurate when responding to Repeated compared with Novel items when decisions or responses repeated (Within-Task and AT-RR). Moreover, although behavior during the Within-Task and AT-RR conditions did not significantly differ, RTs were numerically faster during Within-Task trials. This pattern is consistent with Race et al.'s (2009) previous observation, with a larger independent sample (n = 26), of a significant RT advantage when comparing Within-Task with AT-RR trials. Collectively, these data reveal a behavioral benefit of stimulus–decision learning, above and beyond the effects of stimulus–response learning. Second, the presence of behavioral facilitation when responses repeated and the categorization task changed (AT-RR vs. Novel trials) provides strong evidence for learning at the stimulus–response level. Third, the significantly higher error rates and slower RTs when learned stimulus–response associations conflicted with current task goals (AT-RS trials) demonstrate that learning at the stimulus–response level can also result in interference. Thus, stimulus–response learning can lead to either facilitation or interference depending on the current goal.

Early Temporal Signatures of Stimulus-Level Learning

Repeated processing of stimulus-specific features modulated cortical response dynamics earlier in the processing stream compared with repetition of stimulus–decision or stimulus–response mappings. Specifically, reductions in the negative ERP peak occurring ~400 ms after stimulus onset occurred when stimuli were repeated, independent of decision or response repetition. Though the independence of this effect from decision and response repetition indicates the presence of stimulus-level learning (rather than associative learning), our paradigm cannot specify the specific component processes contributing to this stimulus-level effect (e.g., whether this stimulus-level effect reflects modification at the level of perceptual, lexical, or semantic features, or indexes implicit vs. explicit memory). However, the timing of this effect during the N400, widely taken as an electrophysiological index of semantic processing (Kutas and Hillyard 1980; for review see Lau et al. 2008), suggests that long-term learning at the conceptual level may support this repetition-related amplitude reduction.

Lending support to this interpretation of conceptual learning with stimulus repetition, Race et al. (2009) localized similar stimulus-specific repetition effects to left frontotemporal regions that are implicated in the representation (left posterior middle temporal and fusiform cortex) and controlled retrieval (left anterior VLPFC) of semantic information (e.g., Badre and Wagner 2007; Martin 2007; Binder et al. 2009). Repetition-related cortical activity reductions in these regions have also been identified in MEG measurements of word repetition, with a temporal profile that mirrors the timing of the present stimulus-specific ERP effects (~400 ms poststimulus; Dale et al. 2000). Further, ERP signatures of conceptual implicit memory have been attributed to a similar negative deflection occurring at ~400 ms over frontal electrodes (FN400) (Voss and Paller 2006, 2007; for review see Voss and Paller 2008), although this frontal component has also been interpreted as an index of item familiarity (e.g., Woodruff et al. 2006; for review see Rugg and Curran 2007). In the context of these prior results as well as stimulus-level theories of repetition suppression, the present stimulus-specific amplitude reduction for repeated stimuli may reflect the sharpening or strengthening of semantic representations that facilitate "bottom-up" retrieval of relevant conceptual information when a previously processed stimulus is re-encountered (Wagner et al. 2001; Badre et al. 2005). This interpretation fits with prior evidence that multiple features of a stimulus, both task-relevant and task-irrelevant, may be primed with repetition, regardless of the particular task context or selection demands (e.g., Thompson-Schill and Gabrieli 1999; Thompson-Schill et al. 1999).

Spectral analysis of the EEG signal also revealed a stimulus-level repetition effect occurring ~100–300 ms after stimulus presentation. During this earlier time window, EEG power in the beta frequency range was reduced for all repeated stimuli compared with novel stimuli. This oscillatory change occurred even when decisions and responses switched, providing additional evidence for stimulus-level learning independent of stimulus–decision and stimulus–response repetition. Although these early stimulus-specific effects could reflect changes in perceptual representations rather than conceptual representations, the localization of related MEG effects in this frequency band suggest otherwise (e.g., Ghuman et al. 2008).

MEG oscillations in the beta frequency range have been previously associated with stimulus-level conceptual learning (e.g., Duzel et al. 2005; Ghuman et al. 2008). For example, Ghuman et al. (2008) found that repetition-related cross-cortical beta synchrony was enhanced between left VLPFC and left temporal cortex when subjects semantically classified repeated compared with novel objects. Because neural synchrony may reflect enhanced interregional connectivity, the authors concluded that repetition induces enhanced communication between left frontal and temporal cortex that increases processing efficiency. Moreover, mirroring the earlier onset of the present spectral EEG effect compared with the ERP stimulus-specific effect, the timing of the MEG spectral effect in Ghuman et al. (~190–270 ms) preceded the onset of their observed evoked MEG repetition suppression effect. Though speculative, this suggests that spectral signatures of stimulus-specific learning may precede evoked neural

signatures of such learning. Although caution must be taken in directly comparing results across imaging modalities, as well as interpreting the possible anatomical sources of our EEG effects, the current results indicate that stimulus-level learning contributes to cortical response dynamics relatively early in the processing stream. These results also complement prior MEG evidence in which high-level association areas, such as VLPFC, come online at a relatively early stage during conceptual processing and can display repetition effects that precede repetition effects in posterior cortices (Dale et al. 2000; Ghuman et al. 2008). Together, the presence of stimulus-level effects in both spectral and ERP measurements of repetition in the current study argues against the proposal that associative learning bypasses repeated stimulus-level processing. Rather, these results suggest the facilitation of stimulus-level neural processing with repetition (Horner and Henson 2008; Race et al. 2009), an effect that may be masked in behavioral measures of priming when interference occurs at other levels of representation (e.g., stimulus–response conflict).

Temporal Signatures of Stimulus–Decision Associative Learning

Repeated mapping of a stimulus to the same categorization decision modulated electrophysiological responses during the positive peak approximately 600 ms after stimulus onset. This decision-level repetition effect was characterized by greater ERP positivity for the one condition in which decisions repeated across repetitions (Within-Task) and was distinct from the effects of stimulus–response repetition (i.e., the positivity was reduced when responses repeated but decisions switched). This decision-specific ERP modulation provides novel evidence not only for the binding of stimuli to selected decisions in memory (e.g., Logan 1990; Waszak et al. 2003) but also for the influence of stimulus–decision associations on cortical activity during repeated stimulus classification (Race et al. 2009; for related behavioral data see Schnyer et al. 2007).

Increased ERP positivity during the ~600-ms time window (alternately referred to as the LPC or P600) has been widely demonstrated for repeated compared with novel stimuli (e.g., Olichney et al. 2000; Henson et al. 2003, 2004). However, the mechanisms underlying this modulation remain a matter of debate. Although context-related factors (such as tasks and responses) have been shown to influence the magnitude of this component (Karayanidis et al. 1991; Finnigan et al. 2002; but see Rugg et al. 1992), amplitude changes in this time window have also been attributed to explicit memory retrieval (e.g., Wilding and Rugg 1996; Curran 2000; Wolk et al. 2006; for review see Voss and Paller 2008). For example, Wilding and Rugg (1996) demonstrated enhancement in this positivity when subjects made correct source memory decisions (correctly retrieving whether a word had been previously spoken by a male or female voice) compared with when items were remembered without memory for the context in which they were presented. Moreover, neuropsychological data suggest that stimulus–decision effects on behavioral priming are dependent on the medial temporal lobe (Schnyer et al. 2006).

Although the present paradigm cannot distinguish between the contributions of explicit versus implicit memory, the formation and retrieval of stimulus–decision associations may inform both explicit memory decisions as well as the semantic categorization decisions in the present paradigm. As such, modulation of the LPC may reflect an explicit or implicit

retrieval mechanism that activates the features bound to a stimulus in memory. Further, the specificity of the LPC modulation to the Within-Task trials, the only condition in which decisions were repeated from study to test, suggests that this effect reflects the retrieval of the previously learned decision, though we cannot rule out the possibility that retrieval of other, nondecision aspects of the past context is more likely when the study-test cues remain constant (as in the Within-Task condition). Importantly, however, the present data clearly indicate that the LPC modulation was not driven by retrieval (or reinstatement) of response aspects of the study context, as response repetition (i.e., AT-RR trials) did not drive amplitude changes of this component. Accordingly, the retrieval of stimulus–decision associations could serve to reduce decision-level uncertainty and facilitate selection of an appropriate classification. This interpretation is consistent with recent fMRI results (Race et al. 2009) indicating that repeated processing of a stimulus under the same classification decision reduces activity in left mid/post-VLPFC, a region that tracks mnemonic selection demands and the magnitude of decision-level conflict (Thompson-Schill et al. 1997; Badre and Wagner 2006, 2007). This interpretation also complements lesion evidence in which damage to left posterior frontal cortex reduces the amplitude of the LPC and disrupts the LPC repetition effect (Swick 1998).

Temporal Signatures of Stimulus–Response Associative Learning

An ERP signature of associative learning at the stimulus–response level occurred ~450 ms after stimulus onset. The specificity of this amplitude reduction to repetition at the response level was supported by equivalent amplitude reductions for both conditions in which responses repeated from study to test (AT-RR and Within-Task) compared with the conditions in which responses did not repeat (AT-RS and Novel). The presence of this ERP modulation when learned responses remain goal appropriate, regardless of whether stimulus–decision mappings are held constant (Within-Task) or switch (AT-RR), provides novel evidence for the distinct contribution of stimulus–response learning to repetition-related changes in cortical activity (see also Race et al. 2009). These results further suggest that retrieved stimulus–response associations may impact neural processing earlier in time compared with retrieved stimulus–decision associations. Although additional research is needed to clarify the significance of the temporal relationship between decision and response associative learning effects, one possibility is that in the present paradigm the strength of stimulus–response associations is greater than that of stimulus–decision associations, such that the presentation of a repeated stimulus triggers more rapid activation of an associated response compared with an associated decision. This speculative possibility can be tested by varying study factors that independently and parametrically affect the strength of learned decision and response associations.

Regardless of the temporal relationship to stimulus–decision effects, retrieval of learned stimulus–response associations may provide several processing advantages. For example, retrieved stimulus–response associations may provide a more direct route to action that bypasses stimulus-level conceptual processing and/or integration of a stimulus with current task goals (e.g., Logan 1990, 1998; Dobbins et al. 2004; Schacter et al. 2004). However, several observations argue against this

hypothesis. First, as mentioned previously, comparable stimulus-level EEG repetition effects were present when responses repeated and responses switched. Second, the repetition effect occurring ~600 ms poststimulus (LPC) was driven by repetition at the decision level not the response level, indicating that decision-level learning influences processing even when retrieved responses could provide an alternate route to action. Thus, rather than bypassing processing, a more likely interpretation of stimulus–response repetition effects is that retrieved goal-relevant responses provide mnemonic evidence for a particular response that facilitates response selection in parallel with learning effects that affect retrieval and selection at other levels of processing. Such an interpretation fits with the fMRI findings of Race et al. (2009) in which repetition at the response level reduced activity in left premotor/post-VLPFC and left pre-SMA, regions associated with response selection, but did not influence processing in regions associated with stimulus- or decision-level learning (for stimulus-level effects, see also Horner and Henson 2008).

For this interpretation to hold, response retrieval should yield both facilitative as well as competitive effects, depending on whether or not retrieved responses remain goal relevant. In line with this hypothesis, the response-locked analysis revealed that when previously learned responses were no longer relevant to current goals (when responses switched from study to test; AT-RS) ERP amplitudes increased over right fronto-central electrodes ~250 ms before response execution. In addition, following response execution ERP amplitudes for these response-switch trials also diverged from the other conditions as reflected in amplitude reductions over left fronto-central electrodes. In the preresponse and the postresponse periods, amplitude modulations were specific to AT-RS trials and did not differ among the other conditions (Novel, Within-Task, or AT-RR), suggesting an effect specific to situations in which retrieved responses conflict with current goals.

These results complement prior observations of frontal ERP modulations under conditions of high response conflict both prior to and following response execution (e.g., Botvinick et al. 2001; Van Veen and Carter 2002b; Yeung et al. 2004). Prior to response execution, response-switch modulations likely reflect the presence of conflict when retrieved responses are incongruent to current goals and compete for the control of action. After response execution, high conflict trials may incur greater online performance monitoring or response evaluation (Ford 1999; Vidal et al. 2000). Interestingly, both pre and postresponse ERP indices of response conflict have previously been attributed to neural sources in the ACC (e.g., Van Veen and Carter 2002a), a region that was also identified in priming-related fMRI measurements of response conflict (Race et al. 2009).

In sum, the presence of distinct ERP modulations when stimulus–response mappings repeat and when they switch suggests that prior experience can have both facilitative as well as competitive effects on subsequent stimulus-to-action mappings. Further, these 2 response-related repetition effects provide insight into the component processes supporting behavioral measures of priming and suggest a possible explanation for the absence of RT measures of behavioral priming (and instead the presence of negative priming) when stimuli repeat but responses switch (AT-RS). Specifically, behavioral facilitation due to learning at the stimulus level may be offset by behavioral costs due to conflict at the response level.

Conclusion

By demonstrating temporally distinct ERP signatures of learning at the stimulus, stimulus–decision, and stimulus–response levels, the present study supports a hybrid model of repetition suppression in which associative learning occurs in tandem with the strengthening or sharpening of stimulus-specific features in cortex. Future investigations will be needed to test the generalizability of these learning effects to other classes of stimuli (e.g., pictures, sounds, and tastes) as well as to stimuli without prior semantic representations (such as abstract or nonnameable objects). In addition, the repeated association of stimuli with other types of contextual variables, such as reward, may lead to other forms of long-term associative learning that may play an important role in neurocognitive repetition effects. Further characterization of the multiple forms of learning that drive experience-dependent cortical plasticity promises to provide additional insight into the underlying mechanisms by which the brain integrates the past and the present.

Notes

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