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The temporal dynamics of visual object priming

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Abstract

Priming reflects an important means of learning that is mediated by implicit memory. Importantly, priming occurs for previously viewed objects (item-specific priming) and their category relatives (category-wide priming). Two distinct neural mechanisms are known to mediate priming, including the sharpening of a neural object representation and the retrieval of stimulus-response mappings. Here, we investigated whether the relationship between these neural mechanisms could help explain why item-specific priming generates faster responses than category-wide priming. Participants studied pictures of everyday objects, and then performed a difficult picture identification task while we recorded event-related potentials (ERP). The identification task gradually revealed random line segments of previously viewed items (Studied), category exemplars of previously viewed items (Exemplar), and items that were not previously viewed (Unstudied). Studied items were identified sooner than Unstudied items, showing evidence of item-specific priming, and importantly Exemplar items were also identified sooner than Unstudied items, showing evidence of category-wide priming. Early activity showed sustained neural suppression of parietal activity for both types of priming. However, these neural suppression effects may have stemmed from distinct processes because while category-wide neural suppression was correlated with priming behavior, item-specific neural suppression was not. Late activity, examined with response-locked ERPs, showed additional processes related to item-specific priming including neural suppression in occipital areas and parietal activity that was correlated with behavior. Together, we conclude that item-specific and category-wide priming are mediated by separate, parallel neural mechanisms in the context of the current paradigm. Temporal differences in behavior are determined by the timecourses of these distinct processes.

Keywords

Priming; neural suppression; event-related potentials; implicit memory

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1. INTRODUCTION

Substantial evidence of learning can be observed after a single encounter with a visual object. Repeated encounters result in facilitated behavior, or *priming*, like faster naming or categorization of the object. Priming occurs without the subjective re-experiencing of the initial encounter, indicating that it is mediated by *implicit memory* rather than explicit memory (Voss & Paller, 2008). Any form of learning must discriminate repeated encounters with objects as “different” or the “same”, but the shared perceptual and conceptual features of objects from the same category, like “dogs”, pose a challenge to this cognitive ability. For example, a retriever and Pomeranian are very “different” in size and appearance, but they are also the “same” since they are both furry and have four legs. Implicit memory is sensitive to the shared perceptual and conceptual features of category members, as demonstrated by results showing priming for the repetition of a previously viewed object as well as a category relative, or *exemplar*, of a previously viewed object (Marsolek, 1999; Marsolek & Burgund, 2008). In other words, implicit memory represents objects on *item-specific* and *category-wide* levels.

Do common or distinct neural processes mediate item-specific and category-wide priming? Research has made headway in addressing this problem, but has not related neural findings to a consistent behavioral result: while both repetitions and exemplars elicit faster responses than novel items, repetitions elicit faster responses than exemplars (Cave, Bost & Cobb, 1992; Chouinard et al., 2008; Francis et al., 2008; Stevens et al., 2012). In other words, item-specific priming is generally faster than category-wide priming. How can this pattern of behavioral priming be explained?

The relationship between item-specific and category-wide priming may be understood by considering the involvement of known neural mechanisms of priming. Early studies using functional magnetic resonance imaging (fMRI) found that behavioral priming to repeated objects was associated with reductions in neural activity, or *neural suppression* (Grill-Spector, Henson & Martin, 2006). These studies showed that while item-specific priming elicited neural suppression in right ventral visual areas (i.e., the fusiform), category-wide priming elicited suppression in left ventral visual areas (Koutstaal et al., 2001; Simons et al., 2003; Vuilleumier et al., 2002). The location of these suppression effects suggested that the neural population representing an object becomes smaller and more selective, or *sharpened*, when re-activated upon viewing a repetition (Grill-Spector, Henson & Martin, 2006). The results of these studies also suggested that distinct item-specific and category-wide representations, residing in different hemispheres, were sharpened depending on whether a previously viewed object or an exemplar was confronted, an account consistent with a previous cognitive theory (Marsolek, 1999).

However, fMRI studies have also shown neural suppression in frontal areas related to priming, suggesting a mechanism distinct from the sharpening of a visual object representation (Maccotta & Buckner, 2004; Dobbins et al., 2004; for a review, see Schacter, Wig & Stevens, 2007). Unlike neural suppression found in the fusiform or early visual areas, the magnitude of neural suppression in frontal areas is correlated with the magnitude of behavioral priming, suggesting that it reflects the retrieval of stimulus-response mappings

that were encoded during the first encounter with an object (Maccotta & Buckner, 2004; Dobbins et al., 2004). The encoding of these mappings could result in priming across stimulus changes, for example viewing one dog and reporting it as “living” could facilitate reporting a different dog as “living”. We refer to this mechanism as the retrieval of stimulus-response mapping, or *S-R retrieval*.

Are these two neural mechanisms, sharpening and S-R retrieval, mutually exclusive routes to priming? Early cognitive studies suggested that these two mechanisms of priming run in parallel to each other. For example, Logan’s (1990) model of priming demonstrated that both of these mechanisms are triggered and “race” to compete for output. Such a *parallel process hypothesis* could help account for the temporal differences between item-specific and category-wide priming. Although it is unlikely that viewing a repeated object or an exemplar necessitates that priming be strictly mediated by sharpening or S-R retrieval, respectively, viewing a repeated object may strongly favor the use of sharpening. Neural suppression in frontal areas that correlates with behavior, indicating the use of S-R retrieval, often require several presentations of a repeated object to be observed (Maccotta & Buckner, 2004; Dobbins et al., 2004), suggesting that S-R retrieval is not the “default” mechanism mediating item-specific priming. Likewise, viewing an exemplar may strongly favor the use of S-R retrieval. The visual discrepancy between two different dogs, for example, may result in bypassing the use of sharpening to generate priming. If item-specific priming favors the use of sharpening while category-wide priming favors the use of S-R retrieval, then it is possible that item-specific priming is faster than category-wide priming effects simply because sharpening is a faster process than S-R retrieval. In support of this account, a recent neuroimaging study recently showed distinct neural networks mediating item-specific and category-wide priming for scenes (Stevens et al., 2011).

Alternatively, both sharpening and S-R retrieval processes may always contribute to priming in discrete, sequential stages. This *serial stage hypothesis* can readily explain why item-specific priming is usually faster than category-wide priming. Both item-specific and category-wide priming involve an early perceptual stage followed by a late response stage of processing. While only item-specific priming involves more efficient processing of low-level perceptual features that were previously viewed, such as the specific orientations of lines in the picture, both item-specific and category-wide priming involve retrieval of previously encoded stimulus-response mappings. In support of this hypothesis, behavioral studies using additive factors logic have suggested that differences between item-specific and category-wide priming can be accounted for by early perceptual and later “post-perceptual” processing occurring in independent serial stages (Francis et al., 2008; Boehm & Sommer, 2012).

In the present study, we tested predictions of the parallel process hypothesis and serial stage hypothesis using ERPs. Our participants incidentally learned pictures of common objects and then performed a fragmented picture identification task while we recorded ERPs (Gollin, 1960). Items appearing in the identification task could be *Studied* pictures from the incidental study task, unstudied *Exemplar* pictures drawn from the same basic-level category as Studied items, or novel *Unstudied* pictures. We defined *item-specific priming* as faster

behavioral responses to Studied items compared to Unstudied items, and *category-wide priming* as faster behavioral responses to Exemplar items compared to Unstudied items.

Based on previous research, we anticipated that Studied and Exemplar items would elicit less activity than Unstudied items, i.e., neural suppression. To help distinguish predictions of the opposing hypotheses, we focused on early- and late-stages of neural activity using stimulus- and response-locked ERPs, respectively. For early-stage activity, likely related to sharpening, both hypotheses can account for earlier neural suppression of Studied versus Unstudied items compared to neural suppression of Exemplar versus Unstudied items. The parallel process hypothesis interprets this pattern as differences in the timecourse of two different processes. The serial stage hypothesis interprets this pattern as facilitation to an early stage of processing in item-specific priming relative to category-wide priming. For late-stage activity, potentially related to S-R retrieval, the parallel process hypothesis predicts that only Exemplars would elicit changes relative to Unstudied items, while the serial stage hypothesis predicts that both Studied items and Exemplars should elicit changes in neural activity relative to Unstudied items relatively late in the time course. We anticipated difficulty in capturing this late stage activity with the traditional method of time-locked the ERP to a stimulus onset, since such processing could be masked by the temporal misalignment of response-based activity related to primed (Studied and Exemplar) and unprimed (Unstudied) items. Therefore, we examined response-locked ERPs to examine late stage activity (Horner & Henson, 2012).

We also conducted correlations between the magnitude of neural suppression and the size of behavioral priming effects. As previous studies have shown, such correlations are important evidence for S-R retrieval (Maccotta & Buckner, 2004; Dobbins et al., 2004). The parallel process hypothesis predicts that only category-wide behavioral priming would be significantly correlated with the degree of neural suppression that it evokes. In contrast, the serial stage hypothesis predicts that both item-specific and category-wide behavioral priming would be correlated with the degree of neural suppression that they each evoke.

2. MATERIALS AND METHODS

2.1 Participants

Participants were 24 right-handed native English speakers (18 female) with a mean education of 16.06 years ($s = 1.61$) and a mean age of 22.70 years ($s = 1.45$). All participants gave written informed consent and were paid \$25/hour. This study was approved by the Behavioral Science Committee of the Vanderbilt University Institutional Review Board.

2.2 Stimuli

The stimuli were black and white line drawings of common objects fitting into an area spanning 9.5 x 9.5 degrees visual angle. The pictures included two sets of categories that we alternated in a counterbalanced manner across participants. Each set consisted of 44 category pairs, each containing two exemplars (e.g., cars, dogs, planes). To ensure that category-wide priming effects were not due to greater perceptual similarity of pictures within a category compared to pictures across categories, we measured the similarities between pictures using the bank of local analyzer responses method (BOLAR; Zelinsky,

2003). This computational method represents a picture as a vector of responses from filters that are sensitive to a range of spatial frequencies and orientations. The similarity between two pictures is calculated as the difference between their vectors. This *difference vector* is summarized into a *similarity* score by calculating the sum of squared responses from the difference vector and then taking the square root of that outcome. Finally, all of the similarities for a set of pictures are normalized to a scale ranging from 0 (very dissimilar) to 1 (identical). The mean similarity between items in the same category was not greater than that between items across categories (see Table 1 for statistics, and Figure 1 of Ko et al., 2013, which illustrates our use of the technique).

For the fragmented pictures identification task, we created fragmented versions of the pictures following a procedure by Snodgrass and Corwin (1988). We divided each picture into 15 x 15 fragments and then identified black pixel-containing fragments. We then created ten levels of completeness for each picture, where the least complete version contained only 10% of the total-pixel containing fragments and the most complete version contained 100% of the fragments, each level differing in 10% fragment increments. The picture fragments were randomly selected as we constructed each level of fragmentation.

The pictures were distributed across three tasks: a size judgment incidental learning task, a size comparison buffer task, and a fragmented picture identification task. Participants viewed 88 pictures during the size judgment task, 44 of which were later used as *Studied* items in the identification task. The size comparison buffer task used 48 pictures, none of which later appeared in the identification task. In addition to the 44 pictures already viewed during the size judgment, the identification task used 44 *Unstudied* items and 44 *Exemplar* items drawn from the same basic level category as items that were viewed during the size judgment task. Importantly, the items in the initial size judgment task that shared categories with Exemplars in the later identification task were not repeated in the identification task. We counterbalanced the use of each category member as a Studied or Exemplar item in the identification task across participants. We also counterbalanced the use of pictures without categorical pairings as Studied items or Unstudied items in the identification task across participants.

2.3 Apparatus

We used E-Prime 2.0 Professional (Psychology Software Tools, Inc.) on a Dell computer in conjunction with a Cedrus button box to present stimuli and collect behavioral responses. For electroencephalography (EEG), we used an ActiveTwo biopotential measurement system (BioSemi, Amsterdam, Netherlands). Participants were fitted with an ActiveTwo electrode cap (Behavioral Brain Sciences Center, Birmingham, UK) containing a full array of 128 Ag-AgCl Biosemi active pin-type electrodes. The electrodes were placed in equidistant concentric circles from 10–20 position Cz. Additionally, we placed flat-type electrodes on the left and right mastoid process, on the left and right outer canthus, and under the left eye to record electrooculogram (EOG) activity. Both EEG and EOG recordings were amplified with a bandwidth of 0.03–35 Hz (3dB points) and digitized at a sampling rate of 256 Hz. Recordings were referenced to the vertex (Cz), but were later re-referenced offline to the common average montage to minimize the effects of reference-site

activity and accurately estimate the scalp topography of the measured electric fields (Ally & Budson, 2007; Curran et al., 2006; Dien, 1998). We replaced poor signals with the weighted average of all other signals, placing greater weight on signals from electrodes that were proximal to the original electrode. We filtered EOG-derived artifacts in the EEG data using the EMSE Ocular Artifact Correction Tool. The tool constructs a spatial filter, based on artifact-containing and artifact-free data identified by the user, which is used to remove EOG contamination from the EEG data. Following the ocular artifact correction, trials were discarded from the analyses if they still contained activity above +90 or below -90 μV .

2.4 Procedure

Participants were told they would perform three separate and unrelated tasks involving black and white pictures. In reality, the size judgment was used as an incidental learning task to prime items that would later appear in the picture identification task. The size comparison task, which participants performed between the size judgment and picture identification, only acted as a buffer and did not share pictures with the other tasks. Each trial of the size judgment incidental learning task began with a central cross appearing for 1000 milliseconds (ms) followed by a picture appearing for 500 ms. The picture offset was followed by the prompt, "Could this item fit in a shoebox?" Participants pressed one of two buttons to indicate either "Yes" or "No". In the size comparison buffer task, participants viewed a pair of pictures appearing on the left and right side of an equal sign ("="). Participants were instructed to make a speeded button press to indicate which of the two objects would be larger in reality. The pictures were visible until the response was made.

Each trial of the final identification task began with a central cross appearing for 500 ms followed by a fragment completion sequence. The sequence began with a picture appearing in its most fragmented version and ending with the complete picture. Each level of fragmentation in the sequence appeared for 500 ms. Participants pressed a button as soon as they could identify the target picture, terminating the sequence. The button press was followed by a 500 ms inter-stimulus interval (ISI), then the prompt, "Does this object fit in a shoebox?" If the participant was unable to identify the picture prior to completion of the sequence, the screen progressed to the response prompt (Figure 1A).

3. RESULTS

3.1 Behavior

We measured the *response threshold*, calculated as the mean number of fragments required before the response (Hirshman et al., 1990). The thresholds were submitted to a one-way analysis of variance (ANOVA) to measure the effect of Condition (Studied, Exemplar, Unstudied), which was significant, $F(2,46) = 97.47$, $p < .001$, η_p^2 (partial eta-squared) = 0.81. Paired t -tests indicated a lower threshold for Studied items (mean = 4.63, standard error of the mean, $SEM = 0.12$) compared to both Unstudied items (mean = 5.38, $SEM = 0.13$), $t(23) = 15.10$, $p < .001$, and Exemplars (mean = 4.85, $SEM = 0.13$), $t(23) = 3.84$, $p = .001$. Thresholds for Exemplar items were also lower than those for Unstudied items, $t(23) = 9.30$, $p < .001$, (see Figure 1B). These results showed evidence of both item-specific priming

and category-wide priming. A complementary analysis on the median reaction times showed the same pattern of behavior (data not shown).

3.2 Stimulus-locked ERPs

To examine early stage activity, we constructed ERPs time-locked to the first stimulus in the picture identification task. The ERPs were baseline corrected with the averaged magnitude of activity occurring 200 ms prior to stimulus onset. Then, we averaged the activity in 10 spatial regions of interest (ROI) corresponding to the following scalp areas (see Figure 2): left anterior inferior (LAI), central anterior inferior (CAI), right anterior inferior (RAI), left anterior superior (LAS), right anterior superior (RAS), left posterior superior (LPS), central posterior superior (CPS), right posterior superior (RPS), left posterior inferior (LPI) and right posterior inferior (RPI). We obtained similar ERP bin sizes across item types: Studied (mean = 42.12, range = 25–44), Exemplar (mean = 38.87, range = 22–44) and Unstudied (mean = 39.12, range = 22–44).

Based on previous research reporting the neural correlates of priming to emerge between 300–500 ms (Kuper et al., 2011) or earlier (Paller et al., 2003), we set our a priori time-of-interest between 100–500 ms and divided it equally across separate analyses examining the 100–300 ms interval and 300–500 ms interval. Also, research has shown that object categorization elicits ERPs with anterior and posterior dipole counterparts (Gruber & Müller, 2006; Schendan & Maher, 2009). Accordingly, we conducted separate ANOVAs for anterior and posterior ROIs. First, we submitted the data from anterior ROIs into separate ANOVAs for the 100–300 ms and 300–500 ms epochs. Each analysis examined the factors of Condition (Studied, Unstudied, Exemplar) and ROI (LAI, CAI, RAI, LAS, RAS), but did not reveal interactions between these factors (all F -values < 1). However, interactions were found when data for posterior ROIs were submitted to the same analysis, reported below. Reports of interactions are followed by confirmatory F -tests conducted on vector-scaled data (McCarthy & Wood, 1985; Dien & Santuzzi, 2005). For brevity, we will not report main effects. The degrees of freedom and p -values are based on Greenhouse-Geisser corrections.

During the 100–300 ms epoch, we observed an interaction between Condition and ROI, $F(4.11, 94.46) = 3.40$, $p = .011$, $\eta_p^2 = .13$, which was confirmed with vector-scaled ERPs, $F(2.53, 58.14) = 14.17$, $p < .001$, $\eta_p^2 = .38$. Follow-up paired comparisons revealed neural suppression effects over parietal regions. In region CPS, the activity elicited by Studied items (mean = 0.07 μ V, $SEM = 0.20$), $t(23) = 3.51$, $p = .002$, and Exemplar items (mean = 0.21 μ V, $SEM = 0.17$), $t(23) = 2.12$, $p = .045$, was less positive than that of Unstudied items (mean = 0.65 μ V, $SEM = 0.24$). There was no difference in activity elicited by Studied and Exemplar items, $t(23) = 0.87$, $p = .42$. In region RPS, Studied items (mean = 0.59 μ V, $SEM = 0.27$) elicited less positive activity than both Unstudied items (mean = 0.98 μ V, $SEM = 0.31$), $t(23) = 2.36$, $p = .027$, and Exemplar items (mean = 0.88 μ V, $SEM = 0.26$), $t(23) = 2.29$, $p = .032$. There was no difference in activity elicited by Exemplar and Unstudied items, $t(23) = 0.517$, $p = .61$. Beyond these parietal effects, activity in region LPI was more positive for Studied items (mean = 3.02 μ V, $SEM = 0.42$) than Exemplar items (mean = 2.49 μ V, $SEM = 0.35$), $t(23) = 2.25$, $p = .035$.

The ERPs during the 300–500 ms epoch also showed an interaction between Condition and ROI, $F(3.93, 90.37) = 2.52$, $p = .048$, $\eta_p^2 = .10$ (vector-scaled: $F(2.59, 59.53) = 29.21$, $p < .001$, $\eta_p^2 = .56$). As in the previous epoch, neural suppression was observed over parietal areas. Activity related to Studied items (mean = 0.67 μV , $SEM = 0.32$) less positive than Unstudied items (mean = 1.16 μV , $SEM = 0.31$) in region CPS, $t(23) = 2.34$, $p = .03$. The activity in CPS elicited by Exemplar items (mean = 0.82 μV , $SEM = 0.25$) also appeared to be more negative compared to that of Unstudied items, but this difference only approached significance, $t(23) = 1.58$, $p = .13$. There was no difference in activity elicited by Studied and Exemplar items, $t(23) = 0.68$, $p = .50$. In region RPS, Studied items (mean = 1.39 μV , $SEM = 0.39$) elicited more negative activity than that of Unstudied items (mean = 1.16 μV , $SEM = 0.31$), $t(23) = 2.51$, $p = .02$. A similar relationship between activity related to Studied and Exemplar items (mean = 1.76 μV , $SEM = 0.37$) was marginally significant, $t(23) = 2.03$, $p = .05$. There was no difference in activity elicited by Exemplar and Unstudied items in region RPS, $t(23) = .67$, $p = .50$. Finally, Studied items (mean = 4.91 μV , $SEM = 0.55$) evoked more positive activity than Exemplars (mean = 4.30 μV , $SEM = 0.52$) in region LPI, $t(23) = 2.25$, $p = .035$.

While item-specific and category-wide neural suppression effects were both observed during the first 100–300 ms epoch, it was possible that different onsets could be found by analyzing the data at a finer temporal resolution. We divided the ERPs from parietal regions CPS and RPS into 100 ms epochs and submitted the data to an ANOVA examining the effects of Epoch (100–200, 200–300), Condition (Studied, Exemplar, Unstudied) and Region (CPS, RPS). Importantly, there was a significant interaction of Epoch and Condition, $F(1.85, 42.67) = 8.95$, $p = .001$, $\eta_p^2 = .28$, but no other interactions were significant (F -values < 1.94). The interaction of Epoch and Condition was further examined by averaging the data across the ROIs and conducting planned comparisons between conditions for each epoch. In the 100–200 ms epoch, Studied items (mean = $-0.19 \mu\text{V}$, $SEM = 0.17$) elicited more negative activity than Unstudied items (mean = 0.26 μV , $SEM = 0.20$), $t(23) = 3.07$, $p = .005$, and Exemplar items (mean = 0.22 μV , $SEM = 0.14$), $t(23) = 3.66$, $p = .001$. There was no difference between activity related to Exemplar and Unstudied items, $t(23) = 0.22$, $p = .82$. However, the pattern differed in the 200–300 ms epoch. Again, Studied items (mean = 0.66 μV , $SEM = 0.28$) elicited less activity than Unstudied items (mean = 1.19 μV , $SEM = 0.32$), $t(23) = 3.51$, $p = .001$. In contrast to the previous epoch, Exemplar items (mean = 0.72 μV , $SEM = 0.25$) also elicited less positive activity compared to Unstudied items, $t(23) = 2.37$, $p = .02$. There was no difference in activity between Studied and Exemplar items, $t(23) = 0.39$, $p = .70$. These results confirmed that item-specific suppression emerged about 100 ms prior to category-wide suppression.

3.3 Correlation with behavior

We investigated the relationship between behavioral priming and the ERP activity in regions that showed neural suppression using Spearman's correlation (r_s), which is more robust to outlier-driven effects than Pearson's correlations and more appropriate for correlating neural and behavioral measures (Rousselet & Pernet, 2012). Specifically, we calculated the correlation between the magnitude of item-specific (Studied-Unstudied) and category-wide (Exemplar-Unstudied) behavioral priming effects with the corresponding ERP suppression

effects in areas CPS and RPS. Category-wide priming was correlated with neural suppression in region RPS during the 100–300 ms epoch, $r_s = .43$, $t(22) = 2.25$, $p = .034$, as well as with neural suppression in region CPS during the 300–500 ms epoch, $r_s = .45$, $t(22) = 2.39$, $p = .025$. There were no correlations of item-specific priming and neural suppression (all t -values < 1.82). Scatterplots of these relationships appear in Figure 3.

3.4 Response-locked ERPs examining late stage activity

We examined our second prediction by time-locking the ERPs to the responses for each item type. All processing steps were identical to those employed in constructing the stimulus-locked ERPs except that baseline correction used activity from –700 to –500 ms prior to the response. We chose to examine the interval between –300 and 0 ms prior to the response, which we believed adequately captured neural processing during the final fragment of the sequence while minimizing the contribution of stimulus onset related activity, based on median reaction times to the last stimulus in the sequence (Studied: mean = 252.04, $SEM = 28.72$; Exemplar: mean = 290.38, $SEM = 26.93$; Unstudied: mean = 244.77, $SEM = 25.63$).

The data were submitted to an ANOVA examining the effects of ROI (LPS, CPS, RPS, LPI, RPI) and Condition (Studied, Exemplar, Unstudied), which revealed a near interaction of these factors, $F(4.2, 96.59) = 2.13$, $p = .08$, $\eta_p^2 = .09$. Although the interaction only approached significance, we were compelled to examine memory-related activity with paired comparisons. Two regions showed separation of activity to Studied items and Unstudied items, indicating activity related to item-specific priming. Region CPS showed more positive activity for Studied (mean = 0.61 μV , $SEM = 0.22$) versus Unstudied items (mean = 0.27 μV , $SEM = 0.26$), $t(23) = 2.12$, $p = .04$, and this effect was correlated with the magnitude of item-specific behavioral priming, $r_s = -.50$, $t(22) = 2.72$, $p = .01$. Region RPI showed more negative activity for Studied (mean = –0.99 μV , $SEM = 0.49$) versus Unstudied items (mean = –0.56 μV , $SEM = 0.40$), $t(23) = 2.16$, $p = .04$, however, this effect was not correlated with behavioral priming, $r_s = .05$, $t(22) = 0.25$, $p = .80$.

4. DISCUSSION

We measured the timing of neural events during the early- and late-stages of priming to determine whether item-specific and category-wide priming were mediated by mutually exclusive neural processes. We sought to find neural evidence to help account for the consistent observation that item-specific priming is typically faster than category-wide priming (Cave et al., 1992; Francis et al., 2008; Boehm & Sommer, 2012). Our behavioral results replicated this previous work. To this end, we focused on early- and late-stage neural activity evoked during a fragmented picture identification task with the goal of testing the parallel processing hypothesis and the serial stage hypothesis. Early-stage activity revealed with stimulus-locked ERPs showed neural repetition suppression over parietal recording sites for both item-specific and category-wide priming. Although these neural suppression effects were topographically similar across both types of priming, they differed in correlation with behavioral priming, supporting the parallel processing hypothesis. Additionally, late-stage activity revealed with response-locked ERPs showed increased parietal activity for item-specific priming that was correlated with the behavioral response. Together, these results motivate us to conclude that distinct, parallel processes mediate item-

specific and category-wide priming. Item-specific priming may generally be faster than category-wide priming because its underlying mechanism has a faster timecourse.

4.1 Early stage neural suppression reveals distinct processes

Early-stage activity measured with stimulus-locked ERPs revealed that item-specific neural suppression emerged about 100 ms prior to category-wide neural suppression. At first glance, the topographic similarity of item-specific suppression, observed over central and right parietal regions, and category-wide suppression, observed over the central parietal region, appears to support the serial stage hypothesis. The topographic overlap of these neural suppression effects suggests that both types of priming shared a common neural process during this early stage, but the earlier temporal onset and broader spatial breadth of item-specific neural suppression may have reflected facilitation to this early neural process for item-specific priming relative to category-wide priming.

However, an important aspect of the stimulus-locked ERPs appears to favor the parallel processing hypothesis over the serial stage hypothesis. Specifically, individuals who showed more neural suppression to Exemplar items compared to Unstudied items also showed lower thresholds to Exemplar items relative to Unstudied items. This brain/behavior correlation was notably absent during item-specific priming in our stimulus-locked ERPs, which suggests that different processes underlie item-specific and category-wide neural suppression despite the topographic overlap. The correlation between the magnitude of category-wide neural suppression and category-wide priming is consistent with the hypothesis that category-wide priming may favor the use of S-R retrieval. Based on this important distinction in correlation with behavior, the stimulus-locked ERP results of our study support the parallel process hypothesis. The difference in temporal onset is not a matter of item-specific priming involving facilitation to an early stage shared by category-wide priming, but by staggered onsets of two different processes.

Our interpretation that these parietal effects reflect parallel processes is consistent with a previous study that revealed distinct neural networks, both involving parietal regions, related to item-specific and category-wide priming. Stevens et al. (2012) showed that while item-specific priming evoked activity in right parahippocampal regions that were functionally connected to right parietal and occipital regions, category-wide priming was related to left parahippocampal activity that was functionally connected to a frontal-parietal network. Based on this study, we suggest that the neural suppression effects that we observed were parietal activations engaged by different networks depending on whether priming was item-specific or category-wide. Item-specific priming elicited activity in right parietal areas as part of a network involved in processing visual features, which includes early visual areas. In contrast, category-wide priming elicited parietal activity related to a network involved in retrieving stimulus-response mappings. The parietal activity elicited during this process may have covaried with frontal regions more directly involved with S-R retrieval (Maccotta & Buckner, 2004), leading to the correlation between neural suppression and behavioral priming that we observed. Therefore, it is very likely that the neural suppression of parietal regions observed in the stimulus-locked ERPs only reveal one component of a more complex network mediating visual object priming.

The stimulus-locked ERPs also revealed more positive activity related to Studied items relative to Exemplar items in the left occipital recording site concurrent with the parietal suppression effects. This effect may have reflected stable activity related to the familiar visual fragments of Studied items compared to reduced activity related to the unfamiliar fragments of the Unstudied items under the degraded viewing conditions of the identification task (Turk-Brown, Yi, Leber & Chun, 2007). However, it is unclear why the enhancement of Studied item features was observed relative to only the Exemplars and not the Unstudied items. In general, it is difficult for us to make a definitive interpretation without detectable differences from the Unstudied items, which was considered our baseline to the effects of memory.

4.2 Early stage category-wide processing

Why was the onset of category-wide neural suppression surprisingly early and temporally distant from the actual response? While we have related these effects to S-R retrieval, based on the correlation between category-wide neural suppression and priming, it is also possible that this activity reflected “conceptual information” activated by the Exemplars, such as the concepts of “four legs” or “fur” shared by two different dogs. The activation of conceptual information may have provided input to the retrieval of S-R mappings and the execution of the response, resulting in the brain/behavior correlation. As we discussed above, Stevens et al. (2012) showed that category-wide priming involved a network between left ventral visual and frontal areas. Earlier research speculated that the neural suppression of ventral visual areas could reflect sharpening of a “prototype” representation common to Studied and Exemplar items (Marsolek, 1999; Koutstaal et al., 2001). This abstract visual representation could interact with frontal regions that are involved in establishing stimulus-response mappings (Maccotta & Buckner, 2004; Dobbins et al., 2004), and together these mechanisms give rise to category-wide priming.

Early activity related to category-wide priming is not consistently found in the literature. For example, Küper and colleagues (2011) did not show activity related to category relatives of studied item within their time window of interest, motivating the authors to interpret category-wide processes being “post-visual”. While Küper et al. (2011) used complete photographic images during study and test phases, our use of fragmented pictures may have placed more demand on the visual discrimination between the item types, eliciting differences large enough to be observed. It is also possible that early category-wide activity is difficult to detect with averaged ERPs. Another study by Fries et al. (2012) investigated priming across modalities by targeting neural suppression of induced gamma-band oscillations, which temporally jitter from trial-to-trial and cancel out in the averaged ERP. They showed that when words primed (i.e., preceded) pictures, neural suppression of induced gamma was observed between 400–700 ms post-picture onset. In contrast, when pictures primed words, neural suppression of induced gamma was observed at an earlier time of 200–400 ms post-word onset. These results demonstrate that early activity related to “conceptual priming” may sometimes require analyses that are robust to wide variability. In line with this notion, while we did show category-wide suppression with averaged ERPs, we also detected it with correlation that was sensitive to variability across individual

participants. Future research should anticipate using sensitive statistical techniques to detect neural activity related to exemplar processing.

4.3 Late stage activity related to item-specific priming

Remarkably, our response-locked analysis of late-stage processing only revealed activity related to item-specific priming. Since the serial stage hypothesis predicts that item-specific and category-wide priming would both evoke common activity during this late stage of the timecourse, this result supports the parallel process hypothesis. The response-locked ERPs revealed two interesting results that bring insight to the neural processing behind item-specific priming. However, we interpret these effects with caution since our analysis only revealed an interaction approaching significance.

First, we observed neural suppression in the right occipital area, a finding consistent with the hypothesis that item-specific priming critically involves sharpening of visual cortex representations (Schacter et al., 2007). Importantly, this occipital neural suppression was observed for fragmented pictures despite our participants studying intact pictures, suggesting that the effect was based on overlaps in visual features between the first and second presentations of the object.

Our second finding was an increase in parietal activity that was correlated with the degree of item-specific priming. What drove this correlation? Based on the paradigm, we presume that participants responded as soon as a critical amount of visual features was available during the sequence. It is possible that item-specific implicit memory retrieval is triggered after this amount of features was available, since previous work has shown increased parietal activity during implicit memory retrieval (Küper et al., 2011). However, the increased parietal activity could also be explained by accounts of explicit memory retrieval. For example, the availability of the visual features could have triggered the retrieval of a Studied item, and bottom-up attention to this memory was drawn to the remaining features (Cabeza, 2008; Li et al., 2013). Alternatively, a participant could have “re-experienced” the original encoding event upon retrieval (Ally, Simons et al., 2008). As we cannot rule out these accounts, a potential weakness of this paradigm is that it does not completely isolate implicit memory from explicit memory. Future research could test this possibility by manipulating non-diagnostic features of studied items, such as color or left/right orientation, since it is known that priming is invariant to such changes but explicit memory is not (Zimmer & Steiner, 2003; Zimmer & Ecker, 2010).

Our interpretations of the effects observed in occipital and parietal areas emphasized the importance of feature matching in the current paradigm. This view contrasts with Schendan and Kutas (2007), who showed neural suppression for fragmented pictures that were studied as fragmented images, not complete images. These results suggested that neural priming relied on consistent use of perceptual closure in identifying study and test pictures (i.e., transfer appropriate processing) rather than the feature overlap between studied and test pictures. It is possible that Schendan and Kutas (2007) used images with small and relatively collinear gaps that strongly engaged a perceptual closure process (Snodgrass & Feenan, 1990). We instead presented a sequence of images beginning with an image composed of

larger gaps in the lines that were non-collinear that may have biased the use of a feature matching process rather than perceptual closure during fragment identification.

Although we have focused on contrasting a parallel processing hypothesis with a serial stage hypothesis, a third *interaction hypothesis* deserves mention in the context of investigating the late-stage activity related to priming (Horner & Henson, 2012; Henson et al., 2014). The neural mechanisms of sharpening and S-R retrieval may proceed in parallel but their outputs may converge at a common decision-making process. Reaction time is fast when the outcomes of the two mechanisms are congruent. However, reaction time is slowed when the outcomes conflict and must be resolved. In the current study, viewing a Studied item would be efficient and generate a fast reaction time because both the stimulus and response are congruent, but viewing an Exemplar item would slow reaction time because while the response is consistent with previously viewed category relative, the stimulus is inconsistent. Similar to the serial stage hypothesis, the interaction hypothesis predicts that both Studied and Exemplar items would evoke differing activity from Unstudied items in the response-locked ERPs. However, since we only observed activity related to item-specific priming in our late-stage analysis, the results of the current study do not support this hypothesis.

CONCLUSION

The current results contribute to the evolving understanding of visual object priming. Item-specific priming is often found to be faster than category-wide priming. This relationship between item-specific and category-wide priming could be understood by considering the known neural mechanisms of priming, including the sharpening of the neural representation and the retrieval of encoded S-R mappings. We examined whether these mechanisms operate in parallel (Logan, 1990) or serially during item-specific and category-wide priming using ERPs. The results showed that while both types of priming evoked early neural suppression in parietal areas, only category-wide suppression was correlated with behavior, suggesting that parallel processes mediate item-specific and category-wide priming. Late-stage activity revealed additional processes related only to item-specific priming, providing further support for the parallel process hypothesis. We conclude that item-specific and category-wide priming are mediated by independent, parallel mechanisms that differ in their timecourse.

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References

- Ally BA, Budson AE. The worth of pictures: using high density event-related potentials to understand the memorial power of pictures and the dynamics of recognition memory. *NeuroImage*. 2007; 35(1):378–395.10.1016/j.neuroimage.2006.11.023 [PubMed: 17207639]
- Ally BA, Simons JS, McKeever JD, Peers PV, Budson AE. Parietal contributions to recollection: electrophysiological evidence from aging and patients with parietal lesions. *Neuropsychologia*. 2008; 46(7):1800–12.10.1016/j.neuropsychologia.2008.02.026 [PubMed: 18402990]

- Boehm SG, Sommer W. Independence of data-driven and conceptually driven priming: the case of person recognition. *Psychological Science*. 2012; 23(9):961–6.10.1177/0956797612440098 [PubMed: 22851442]
- Cabeza R. Role of parietal regions in episodic memory retrieval: The dual attentional processes hypothesis. *Neuropsychologia*. 2008; 46(7):1813–1827.10.1016/j.neuropsychologia.2008.03.019 [PubMed: 18439631]
- Cave CB, Bost PR, Cobb RE. Effects of color and pattern on implicit and explicit picture memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1996; 22(3):639.
- Chouinard PA, Morrissey BF, Köhler S, Goodale MA. Repetition suppression in occipital-temporal visual areas is modulated by physical rather than semantic features of objects. *NeuroImage*. 2008; 41(1):130–144.10.1016/j.neuroimage.2008.02.011 [PubMed: 18375148]
- Curran T, DeBuse C, Woroch B, Hirshman E. Combined pharmacological and electrophysiological dissociation of familiarity and recollection. *Journal of Neuroscience*. 2006; 26(7):1979–1985.10.1523/JNEUROSCI.5370-05.2006 [PubMed: 16481430]
- Dien J. Addressing misallocation of variance in principal components analysis of event-related potentials. *Brain Topography*. 1998; 11:43–55. [PubMed: 9758391]
- Dien, J.; Santuzzi, AM. Application of repeated measures ANOVA to high-density ERP datasets: A review and tutorial. In: Handy, TC., editor. *Event-Related Potentials: A Methods Handbook*. Cambridge, MA: The MIT Press; 2005. p. 57-82.
- Dobbins IG, Schnyer DM, Verfaellie M, Schacter DL. Cortical activity reductions during repetition priming can result from rapid response learning. *Nature*. 2004; 428(6980):316–319.10.1038/nature02400 [PubMed: 14990968]
- Francis WS, Corral NI, Jones ML, Sáenz SP. Decomposition of repetition priming components in picture naming. *Journal of Experimental Psychology: General*. 2008; 137(3):566–590.10.1037/0096-3445.137.3.566 [PubMed: 18729716]
- Friese U, Supp GG, Hipp JF, Engel AK, Gruber T. Oscillatory MEG gamma band activity dissociates perceptual and conceptual aspects of visual object processing: A combined repetition/conceptual priming study. *NeuroImage*. 2012; 59(1):861–871.10.1016/j.neuroimage.2011.07.073 [PubMed: 21835246]
- Gollin ES. Developmental studies of visual recognition of incomplete objects. *Perceptual and Motor Skills*. 1960; 11:289–298.
- Grill-Spector K, Henson R, Martin A. Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences*. 2006; 10(1):14–23.10.1016/j.tics.2005.11.006 [PubMed: 16321563]
- Gruber T, Müller MM. Oscillatory brain activity in the human EEG during indirect and direct memory tasks. *Brain Research*. 2006; 1097(1):194–204.10.1016/j.brainres.2006.04.069 [PubMed: 16729980]
- Henson RN, Eckstein D, Waszak F, Frings C, Horner AJ. Stimulus-response bindings in priming. *Trends in Cognitive Science*. 2014; 18(7):376–384. Epub 2014 Apr 24. 10.1016/j.tics.2014.03.004
- Hirshman, Snodgrass; Mindes; Feenan. Conceptual priming in fragment completion. *Journal of Experimental Psychology: Learning, Memory & Cognition*. 1990; 16(4):634–647.
- Horner AJ, Henson RN. Incongruent Abstract Stimulus–Response Bindings Result in Response Interference: fMRI and EEG Evidence from Visual Object Classification Priming. *Journal of Cognitive Neuroscience*. 2012; 24(3):760–773. [PubMed: 22066586]
- Ko PC, Duda B, Hussey EP, Ally BA. Electrophysiological distinctions between recognition memory with and without awareness. *Neuropsychologia*. 2013; 51(4):642–55.10.1016/j.neuropsychologia.2012.12.012 [PubMed: 23287567]
- Koutstaal W, Wagner AD, Rotte M, Maril A, Buckner RL, Schacter DL. Perceptual specificity in visual object priming: functional magnetic resonance imaging evidence for a laterality difference in fusiform cortex. *Neuropsychologia*. 2001; 39(2):184–199. [PubMed: 11163375]
- Küper K, Groh-Bordin C, Zimmer HD, Ecker UKH. Electrophysiological correlates of exemplar-specific processes in implicit and explicit memory. *Cognitive, Affective, & Behavioral Neuroscience*. 2011; 10.3758/s13415-011-0065-7

- Li L, Gratton C, Fabiani M, Knight RT. Age-related frontoparietal changes during the control of bottom-up and top-down attention: an ERP study. *Neurobiology of Aging*. 2013; 34(2):477–488.10.1016/j.neurobiolaging.2012.02.025 [PubMed: 22459599]
- Logan GD. Repetition priming and automaticity: common underlying mechanisms? *Cognitive Psychology*. 1990; 22:1–35.
- McCarthy G, Wood CC. Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*. 1985; 62(3):203–208.10.1016/0168-5597(85)90015-2
- Maccotta L, Buckner RL. Evidence for neural effects of repetition that directly correlate with behavioral priming. *Journal of Cognitive Neuroscience*. 2004; 16(9):1625–1632.10.1162/0898929042568451 [PubMed: 15601524]
- Marsolek CJ. Dissociable Neural Subsystems Underlie Abstract and Specific Object Recognition. *Psychological Science*. 1999; 10(2):111–118.10.1111/1467-9280.00117
- Marsolek CJ, Burgund ED. Dissociable neural subsystems underlie visual working memory for abstract categories and specific exemplars. *Cognitive, Affective, & Behavioral Neuroscience*. 2008; 8(1):17–24.10.3758/CABN.8.1.17
- Paller KA, Hutson CA, Miller BB, Boehm SG. Neural manifestations of memory with and without awareness. *Neuron*. 2003; 38(3):507–516. [PubMed: 12741996]
- Rousset GA, Pernet CR. Improving standards in brain-behavior correlation analysis. *Frontiers in Human Neuroscience*. 2012; 6(119)10.3389/fnhum.2012.00119
- Schacter DL, Wig GS, Stevens WD. Reductions in cortical activity during priming. *Current Opinion in Neurobiology*. 2007; 17(2):171–176.10.1016/j.conb.2007.02.001 [PubMed: 17303410]
- Schendan HE, Kutas M. Neurophysiological evidence for transfer appropriate processing of memory: processing versus feature similarity. *Psychonomic Bulletin & Review*. 2007; 14(4):612–619. [PubMed: 17972722]
- Schendan HE, Maher SM. Object knowledge during entry-level categorization is activated and modified by implicit memory after 200 ms. *NeuroImage*. 2009; 44(4):1423–1438.10.1016/j.neuroimage.2008.09.061 [PubMed: 19010426]
- Simons J, Koutstaal W, Prince S, Wagner A, Schacter D. Neural mechanisms of visual object priming: Evidence for perceptual and semantic distinctions in fusiform cortex. *NeuroImage*. 2003; 19:613–626. [PubMed: 12880792]
- Snodgrass J, Corwin J. Perceptual identification thresholds for 150 fragmented pictures from the Snodgrass and Vanderwart picture set. *Perceptual and Motor Skills*. 1988; 67:3–36. [PubMed: 3211683]
- Snodgrass JG, Feenan K. Priming effects in picture fragment completion: support for the perceptual closure hypothesis. *Journal of Experimental Psychology: General*. 1990; 119(3):276–296. [PubMed: 2145392]
- Stevens WD, Kahn I, Wig GS, Schacter DL. Hemispheric Asymmetry of Visual Scene Processing in the Human Brain: Evidence from Repetition Priming and Intrinsic Activity. *Cerebral Cortex*. 2012; 22(8):1935–1949.10.1093/cercor/bhr273 [PubMed: 21968568]
- Turk-Browne NB, Yi DJ, Leber AB, Chun MM. Visual quality determines direction of neural repetition effects. *Cerebral Cortex*. 2007; 17(2):425–433. [PubMed: 16565294]
- Voss JL, Paller KA. Brain substrates of implicit and explicit memory: the importance of concurrently acquired neural signals of both memory types. *Neuropsychologia*. 2008; 46(13):3021–3029.10.1016/j.neuropsychologia.2008.07.010 [PubMed: 18691605]
- Vuilleumier P, Henson R, Driver J, Dolan R. Multiple levels of visual object constancy revealed by event-related fMRI of repetition priming. *Nature Neuroscience*. 2002; 5(5):491–499.
- Zelinsky GJ. Detecting changes between real-world objects using spatiochromatic filters. *Psychonomic Bulletin & Review*. 2003; 10(3):533–555. [PubMed: 14620348]
- Zimmer HD, Ecker UKH. Remembering perceptual features unequally bound in object and episodic tokens: Neural mechanisms and their electrophysiological correlates. *Neuroscience & Biobehavioral Reviews*. 2010; 34(7):1066–1079.10.1016/j.neubiorev.2010.01.014 [PubMed: 20138910]

Highlights

We examined priming of objects and their category relatives using ERP

Repeated objects elicited earlier neural suppression than their category relatives

Neural suppression to category relatives emerged early and prior to identification

These two forms of neural suppression reflect distinct neural mechanisms

Figure 1.

(A) A depiction of the behavioral task. First, participants made size judgments while viewing a sequence of pictures (top left) followed by a size comparison task (bottom left). Participants then performed a fragmented picture identification task (on right), viewing a sequence of picture fragments that gradually become a complete picture, and making a speeded response once they could identify the item. Participants then made a size judgment to the identified item. The identification task presented Studied items, Exemplar items, and Unstudied items.

(B) Behavioral results. The mean number of frames required to make a response, or response threshold, is depicted on the horizontal axis with error bars depicting the standard error of the mean. The threshold is plotted in parallel with an example sequence to illustrate its relationship with the stimulus. * $p < .01$, ** $p < .001$

Figure 2.

(A) Waveforms for stimulus-locked ERPs in each spatial region-of-interest (ROI). Regions exhibiting priming-related activity are framed with bold lines.

(B) Difference waves illustrating neural suppression in parietal regions. The black lines depict the mean difference at each time point and the gray regions span the standard deviation around the mean. The top row depicts difference waves for item-specific suppression (Studied – Unstudied) in regions CPS (left) and RPS (right), while the bottom row depicts differences waves for category-wide suppression (Exemplar – Unstudied) in regions CPS and RPS.

(C) Averaged ERP magnitudes for ROIs showing significant differences between conditions. Note that the activity in the parietal regions is plotted on a different scale than the left occipital region. Legend: + = studied different from unstudied ($p < .05$); ^ = exemplar different from unstudied ($p < .05$); * = studied different from exemplar ($p < .05$).

(D) The spatial ROIs located across the scalp.

Figure 3.

(A) Scatterplot depicting the priming/suppression correlation in RPS during the 100–300 ms epoch. The behavioral priming effect (threshold for Exemplar-Unstudied items) is plotted on the y-axis and the neural suppression effect in region RPS (ERP magnitude for Exemplar-Unstudied items) is plotted on the x-axis. The data appear with the linear trend line ($y = 1.28x + 0.571$).

(B) Scatterplot depicting the priming/suppression correlation in CPS during the 300–500 ms epoch. The behavioral priming effect (threshold for Exemplar-Unstudied items) is plotted on the y-axis and the neural suppression effect in region CPS (ERP magnitude for Exemplar-Unstudied items) is plotted on the x-axis. The data appear with the linear trend line ($y = 1.83x + 0.625$).

Figure 4.

(A) Waveforms for response-locked ERPs in each spatial ROI. Regions exhibiting priming related activity are framed with bold lines.

(B) Averaged ERP magnitudes for regions CPS and RPI. $*p < .05$

(C) Scatterplot depicting the priming/enhancement correlation in CPS during the -300 to 0 ms epoch. The memory effect (Studied - Unstudied) is plotted on the y-axis against the ERP effect (Studied - Unstudied) on the x-axis. The data appear with the linear trend line ($y = -1.48x - 0.77$).

TABLE 1

Mean BOLAR scores for stimuli sets 1 and 2. Standard deviations appear in parentheses.

	Set 1	Set 2
Within category BOLAR score	.47 (.14)	.56 (.13)
Across category BOLAR score	.43 (.13)	.53 (.12)
Comparison	$t(1934) = 1.68, p = .09$	$t(1934) = 1.44, p = .15$