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Object identification leads to a conceptual broadening of object representations in lateral prefrontal cortex

Stephen J. Gotts^{1,*}, Shawn C. Milleville¹, and Alex Martin¹

¹Section on Cognitive Neuropsychology, Laboratory of Brain and Cognition, National Institute of Mental Health (NIMH), National Institutes of Health, Bethesda, MD 20892, USA

Abstract

Recent experience identifying objects leads to later improvements in both speed and accuracy (“repetition priming”), along with simultaneous reductions of neural activity (“repetition suppression”). A popular interpretation of these joint behavioral and neural phenomena is that object representations become perceptually “sharper” with stimulus repetition, eliminating cells that are poorly stimulus-selective and responsive and reducing support for competing representations downstream. Here, we test this hypothesis in an fMRI-adaptation experiment using pictures of objects. Prior to fMRI, participants repeatedly named a set of object pictures. During fMRI, participants viewed adaptation sequences composed of rapidly repeated objects (3–6 repetitions over several seconds) that were either named previously or that were new for the fMRI session, followed by single “deviant” object pictures used to measure recovery from adaptation and that shared a relationship to the adapted picture (a different exemplar of the same object, a conceptual associate, or an unrelated picture). Effects of adaptation and recovery were found throughout visually responsive brain regions. Occipitotemporal cortical regions displayed repetition suppression to previously named relative to new adaptors but failed to exhibit pronounced changes in neural tuning. In contrast, changes in the slope of the recovery curves were found in the left lateral prefrontal cortex: Greater residual adaptation was observed to exemplar stimuli and conceptual associates following previously named adapting stimuli, consistent with greater rather than reduced neural overlap among representations of conceptually related objects. Furthermore, this change in neural tuning was directly related to the proportion of conceptual errors made by participants in the naming sessions pre- and post-fMRI, establishing that the experience-dependent conceptual broadening of object representations seen in fMRI is also manifest in behavior. In a follow-up behavioral experiment, we further show that recent naming experience leads to greater semantic priming when using the previously named pictures as briefly presented primes. Taken together, our results fail to support perceptual sharpening as the primary mediator between repetition suppression and behavioral priming at durations typically used to study priming and instead highlight an experience-dependent broadening of conceptual

*To whom correspondence should be addressed: Bldg 10, Rm 4C-104 Bethesda, MD 20892-1366 (301) 435-4948 (office) gotts@mail.nih.gov.

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representations. We suggest that alternative mechanisms, such as increases in neural synchronization, are more promising in explaining priming in the face of repetition suppression.

Keywords

sharpening; priming; repetition suppression; synchrony; semantic memory; tuning curve

1. INTRODUCTION

A fundamental challenge for cognitive neuroscience is to understand how neural representations are altered by experience and how these alterations mediate changes in behavior. Experience with visual objects commonly leads to improved behavioral identification in terms of speed and accuracy, referred to as “repetition priming”, while neural activity measured in BOLD fMRI in humans or in single-cell recording experiments in monkeys commonly decreases, referred to as “repetition suppression” (see Gotts et al., 2012a; Henson et al., 2014, for recent reviews). These joint behavioral and neural phenomena are relatively automatic, long-lasting, and occur generally across a wide range of task contexts and sensory and motor modalities, although the matching of study and test contexts leads to the largest and most robust effects (for discussion, see Dobbins et al., 2004; Horner & Henson, 2008, 2012; Wig et al., 2009; Race et al., 2009, 2010). The simultaneous observation of improved identification with decreased neural activity clearly indicates some form of improved neural information processing efficiency, yet the precise form of this efficiency remains unclear.

One popular theoretical model of this relationship, referred to as perceptual “sharpening” (Desimone, 1996; Wiggs & Martin, 1998), holds that while average neural activity decreases following stimulus repetition, it is becoming more selectively tuned to particular stimuli - with the decreases mainly due to the dropping out of poorly tuned and poorly responsive cells via synaptic plasticity. This, in turn, could lead to improved identification by removing support for competing objects/responses in downstream brain regions. Indeed, following extended experience with visual objects over several months, single-cell recording studies in monkeys in inferior temporal and lateral prefrontal cortex have provided direct empirical support for increased sharpening of neural representations (e.g. Baker et al., 2002; Freedman et al., 2006; Rainer & Miller, 2000). Further support has come from fMRI-adaptation studies in humans that have trained participants to classify objects into novel categories (e.g. Jiang et al., 2007). After training with numerous exposures to visually similar objects that were assigned to distinct categories (morphed pictures of cars), Jiang et al. (2007) observed greater recovery from adaptation in lateral occipital cortex to similar objects, consistent with reduced neural overlap of the corresponding visual object representations. While initially conceived as occurring in more perceptual brain regions (e.g. extrastriate and occipitotemporal regions for vision; e.g. Desimone, 1996), the basic notion of “sharpening” has since been extended more generally throughout the brain to other levels of representation, including frontal regions involved in higher level cognitive decisions (see Grill-Spector et al., 2006, for review).

However, several challenges have been raised for the sharpening model in explaining the relationship between repetition priming and repetition suppression when using typical practice durations (i.e. a small number of repetitions within one experimental session of 1–2 hours). Short-term repetitions over a few seconds (e.g. De Baene & Vogels, 2010; McMahon & Olson, 2007; Miller et al., 1993) and longer-term repetitions within a single experimental session (e.g. Li et al., 1993) have often failed to provide support for sharpening, yielding instead evidence for proportional scaling of responses with the largest decreases observed for the most responsive cells. Proportional scaling of responses has also been observed in fMRI-adaptation experiments over similar practice durations (e.g. Weiner et al., 2010). In the experimental circumstances in which sharpening has been observed (more extended practice), it is also unclear why more selective firing-rate responses in a sending region are not reflected as enhanced, earlier firing rates in cells in receiving regions that prefer the repeated object. The typical pattern observed in higher-level temporal and prefrontal cortical regions in monkeys is for firing rates to be reduced throughout the evoked firing rate response (e.g. Rainer & Miller, 2000; Freedman et al., 2006; although see Woloszyn & Sheinberg, 2012). Furthermore, repetition “enhancement” is not typically observed in whole-brain neuroimaging studies in humans unless there is a working memory aspect to the task or some large change in task context (e.g. Henson, 2003; Jiang et al., 2000). Perhaps an even more fundamental limitation of the sharpening model, though, is that the sole task of object identification is not simply to discriminate or distinguish amongst possible stimuli. The perceptual and conceptual systems of the brain critically have to be able to generalize knowledge to novel instances of objects that have never been encountered. Particularly within the domain of concepts, representational similarity, property sharing and inheritance, and generalization are key mechanistic ideas (e.g. Martin, 1992; Rogers & McClelland, 2004; Warrington & Shallice, 1984) that sharpening could potentially conflict with or counteract.

Nevertheless, the direct link between repetition priming and sharpened neural representations at delays typical of most repetition priming studies has yet to be explicitly examined in either humans or monkeys. The Jiang et al. (2007) study mentioned above did not evaluate repetition priming behaviorally, and the sole study in monkeys that measured both single-cell responses and behavioral priming did not use repetitions over a duration longer than a few seconds (McMahon & Olson, 2007). In the current study, we present both an fMRI-Adaptation experiment (Experiment 1) in which we manipulate experience with a set of objects and assess changes in neural tuning preferences throughout the brain along with changes in identification ability, as well as a follow-up behavioral experiment (Experiment 2) that tests a central prediction of the first experiment using a semantic priming paradigm.

2. EXPERIMENT 1: FMRI-ADAPTATION EXPERIMENT

In the first experiment, we use fMRI-adaptation (e.g. Grill-Spector & Malach, 2001; Naccache & Dehaene, 2001) with pictures of common objects (animals) to assess changes in neural tuning with stimulus repetition throughout the brain. The paradigm that we employ is a modification of one first employed by Piazza, Dehaene and colleagues to study graded tuning curves to numerosity in the parietal cortex (Piazza et al., 2004), and subsequently

extended by us to measure graded perceptual and conceptual tuning curves to object pictures (Gotts et al., 2011) (see Figure 1A and B). During fMRI, we repeat single animal pictures (referred to as “anchor” pictures) several times in a row over a few seconds. This is expected to lead to large, temporary decreases in neural activity (i.e. “adaptation”) throughout visually responsive brain regions in cells that are active to the anchor pictures (Figure 1A). Recovery from adaptation can then be measured within each fMRI voxel to a single “deviant” picture that occurs immediately after the anchor picture and shares a certain relationship with it (e.g. perceptual, conceptual). If the neural representations of the anchor and deviant stimuli share many of the same cells within a voxel, as one might expect for highly related objects that share component parts or features, the recovered response should be relatively weak due to the persistent effects of adaptation (Figure 1B). In contrast, if the neural representations share few cells, as one might expect for unrelated objects, the response should be recovered to non-adapted levels.

We manipulated experience by pre-exposing half of the anchor pictures in a picture naming task approximately 30 minutes prior to the fMRI session. During fMRI, adaptation sequences of “old” (previously named) and “new” anchors were randomly intermixed with baseline images (phase-scrambled versions of the animal pictures) and pictures of man-made objects to which participants were instructed to make a button press response. Changes in neural tuning as a function of experience were then assessed by the responses to the deviant pictures, all of which were new for the fMRI session and which shared one of three possible relationships to the anchor pictures: 1) a different exemplar of the same type of object, 2) a semantically related picture (e.g. cow -> donkey), or 3) an unrelated picture (e.g. cow -> lobster). Additionally, the last anchor picture in the adaptation sequence served as an estimate of an “identical” deviant picture, completing the tuning curve over four levels of relatedness (identical, exemplar, semantic associate, unrelated) (Figure 1C). If the prior naming experience with the old anchors has resulted in perceptually sharper tuning - with cells responding more selectively to the anchor picture alone, then related deviant pictures should exhibit greater recovery from adaptation when following old versus new anchors - perhaps in occipital and ventral temporal brain regions, shifting the tuning curves upward to a more image-selective pattern. On the other hand, if the naming experience helps to strengthen conceptual relationships among related stimuli in brain regions more involved in conceptual processing (e.g. temporal and prefrontal brain regions) by repeatedly co-activating conceptual associates and enhancing cell overlap, then activity should remain more adapted to related deviant pictures when following old versus new anchors, shifting the tuning curves downward to be broader and more concept-selective. Given the nature of the adaptation paradigm (no overt responses during the adaptation sequences), we assessed the magnitude of repetition priming to old versus new anchor pictures for each participant in a final picture naming session conducted just after fMRI. This permitted an evaluation across participants of the relationship between sharpened neural tuning and behavioral priming magnitude.

2.1. Material and methods

2.1.1. Participants—Eighteen right-handed, adult volunteer participants (10 female) with a mean age of 26.2 years (SD = 5.0 years) were recruited and paid for their participation in

the study. All participants had normal or corrected-to-normal vision and were native English speakers. Participants completed health questionnaires and none reported a history of head injury or other neurological problems. In accordance with the National Institutes of Health (NIH) Institutional Review Board protocols, all participants read and signed informed consent documents.

2.1.2. Behavioral Methods

2.1.2.1. Pre-fMRI Picture Naming: Prior to the fMRI session, participants named a set of 30 animal and 30 man-made object grayscale pictures from a variety of conceptual categories. This picture naming session was divided into 5 experimental blocks, in which each of the 60 pictures was presented in a pseudorandom order for overt naming. Participants were instructed to name each picture as quickly and as accurately as possible. In each naming trial, the picture to be named was presented for 200 ms in the center of the screen (subtending approximately $6^\circ \times 5^\circ$ of visual angle, horizontal $\times$ vertical), followed by a central black fixation cross for 1800 ms, yielding a total inter-trial interval of 2000 ms. Naming responses and response times were automatically recorded through the use of a microphone and voice key on the display computer (Presentation® software package, Version 11.3, www.neurobs.com), although correct and error naming responses were also transcribed by the experimenter during the session.

2.1.2.2. fMRI Behavioral Methods: During the fMRI experiment, participants were exposed to adaptation sequences of grayscale animal pictures (each presented foveally and subtending the central $7.8^\circ \times 6.2^\circ$ of visual angle, horizontal $\times$ vertical), as well as pictures of man-made objects and phase-scrambled baseline pictures created from the animal images (Figure 2). Man-made objects and scrambled baselines occurred randomly between adaptation sequences, with the objects occurring at an average rate of approximately 1 every 14 seconds (~ 30 total per run) and baselines making up 30% of all images. Participants were instructed to respond to pictures of man-made objects with a button press but were asked to attend to all images. Anchor pictures in the adaptation sequences were either named in the pre-fMRI session (“old”) or were new for the fMRI session (“new”), with old and new anchors counterbalanced across participants and each condition matched in conceptual category membership and name frequency/familiarity (using HAL frequency and lexical decision times in the English Lexicon Project database: Balota et al., 2007). In each sequence, a single anchor picture was repeated anywhere from 3 to 6 times (uniform distribution) at a rate of 1 picture per second (stimulus duration = 200 ms, fixation screen = 800 ms). After the final presentation of the anchor picture, a single deviant animal picture - all new for the fMRI session - was presented and shared a relationship with the anchor at 1 of 3 levels: 1) a different exemplar picture of the same type of object shown in partial view (e.g. just the face) or different left/right profile to minimize low-level image overlap, 2) a close semantic associate within the same conceptual category (selected among categories of land animals, water creatures, birds, insects, and reptiles/amphibians; e.g. “donkey” for the anchor “cow”), or 3) an unrelated picture (e.g. “lobster” for the anchor “cow”). Unrelated anchor-deviant pairs were constructed by re-pairing deviants used as close semantic associates with unrelated anchors from different categories, allowing each deviant to serve with equal likelihood in the semantic associate and unrelated conditions (see Supplementary

Table 1 for a complete list of anchor-deviant pairs). Together with the last anchor condition, this resulted in a total of four levels of anchor-deviant relatedness: identical, exemplar, semantic associate, and unrelated. The overall design of the experiment involved sampling each of the 6 unique deviant conditions (old vs. new anchors crossed with exemplar, semantic, and unrelated deviants) 7–8 times in each of the 8 experimental runs for a total of 60 trials per deviant condition over the course of the experiment. Each of the individual anchor stimuli (old and new) served in a total of 6 adaptation sequences over the course of the experiment, serving twice for each of the three deviant conditions. Individual experimental runs had a duration of 6 minutes, 58 seconds for a total scanning duration of 55 minutes, 44 seconds. The order of the deviant conditions and the placement of the baseline trials were determined through the use of the program “optseq2” (<http://surfer.nmr.mgh.harvard.edu/optseq/>) and then modified to allow variable-length adaptation sequences and the insertion of man-made object stimuli.

2.1.2.3. Post-fMRI Picture Naming: Immediately after completion of the fMRI session, a follow-up picture naming session was conducted to confirm that participants exhibited repetition priming for the old relative to the new anchor stimuli shown during fMRI. Trial timing was identical to that used during the pre-fMRI picture naming session. The post-fMRI picture naming session was performed in a single block of trials, with old and new anchor stimuli presented in a randomized order, along with the previously named man-made objects and thirty new man-made objects for the post-fMRI naming session. The reaction times and accuracy to the man-made object pictures were included mainly to permit comparisons of the overall response times in the pre-fMRI versus post-fMRI naming sessions. Magnitude of repetition priming was calculated as raw differences in the mean response time to old versus new anchor pictures, as well as in units of “effect size” (the difference in the mean response times of the two conditions divided by the pooled standard deviation; Dunlop et al., 1996). The effect size measure of priming was used for later correlation with fMRI effects since this is the most direct measure of effect strength that adjusts for overall reaction-time variability per participant. The need for such an adjustment is high, given that base reaction time and reaction time variability are known to differ substantially across participants in picture naming (with mean reaction times ranging from approximately 600 milliseconds up to 1100 milliseconds in the current study). However, results were also checked using more traditional normalized measures such as “proportion priming” (i.e. dividing the raw priming magnitude by the mean reaction time to the new condition).

2.1.2.4. Picture Naming Error Analyses: When adult control participants make errors while naming pictures, the error responses are typically omissions (i.e. failing to give a response), names of objects that are visually and/or conceptually related to the target object (for example, saying “tiger” to the picture of a lion), or whole-word “perseverations” - inappropriate repetitions of a previous response (for example, saying “tiger” to the picture of a lion when “tiger” was recently given as a response) (e.g. Christman et al., 2004; Gotts & Plaut, 2004; Hodgson & Lambon Ralph, 2008; Mirman, 2011; Moses et al., 2004; Sandson & Albert, 1984; Vitkovitch & Humphreys, 1991; Vitkovitch et al., 1993). When perseverations are produced, they are also typically related both visually and conceptually to

the target picture. Naming errors produced by participants in the pre- and post-fMRI picture naming sessions were scored according to the basic scheme introduced by Lhermitte & Beauvois (1973), and used subsequently by Plaut and Shallice (1993) and Gotts et al. (2002). Non-perseverative errors were initially scored as “Omissions” (no response provided), “Visual” errors (visually similar to the target picture), “Phonological” errors (phonologically similar to the target), “Semantic” errors (conceptually related to the target), mixtures of these commission types (e.g. Visual/Semantic), or “Other” for responses such as general/superordinate errors and circumlocutions. “Perseverations” were defined as error responses to the current target picture that were uttered previously in the session by that participant, and they were tabulated separately according to the relationship with the current target name (e.g. Visual, Semantic, Phonological, Visual/Semantic, etc.). After initial coding, the scheme was simplified to the following error categories due to the lack of pure Visual and Phonological errors: Omissions (O), Visual/Semantic errors (V/S), Perseverations that are Visual/Semantic with respect to the current target (V/S+P), and Other. Errors were tabulated separately for each block in the pre-fMRI session versus the single-block, post-fMRI session. A complete list of Visual/Semantic, Perseverative, and Other errors, pooled across participants, is given in Supplementary Table 2.

2.1.3. fMRI Methods—Functional MRI data were collected using a GE Signa 3 Tesla whole-body MRI scanner and 8-channel head coil at the NIH Clinical Center NMR Research Facility. Prior to the fMRI-adaptation experiment, a high-resolution magnetization-prepared rapid gradient-echo anatomical sequence (MPRAGE) was performed [124 axial slices, 1.2 mm thickness, Field of View (FOV) = 24 cm, acquisition matrix = 256×256]. fMRI data were collected using a gradient-echo echo-planar series (TR = 2000 ms, TE = 30 ms, FOV = 24 cm, acquisition matrix = 64×64). A total of 35 axial contiguous interleaved slices were collected for each functional volume (single-voxel volume = $3.75 \times 3.75 \times 3.5 \text{ mm}^3$). Each participant had 8 functional runs with 209 volumes per run.

2.1.4. fMRI Analyses—Functional MRI data were analyzed using a random-effects approach within the general linear model, as implemented in the AFNI software package (Cox, 1996). Preprocessing steps for each functional run consisted of time series outlier removal (AFNI's 3dDespike), the removal of the first 3 TRs prior to equilibrium magnetization, slice-time correction, volume registration of all TRs to the beginning of the first run and to the anatomical scan, spatial smoothing with a 6-mm full-width half-maximum Gaussian filter, and mean-based intensity normalization of all volumes to units of percentage signal change. Time series were modeled using 13 event-related regressors of interest: first, middle, and last anchor stimuli and 3 deviant conditions (exemplar, semantic, and unrelated) for new versus old anchors, and one regressor for the man-made object stimuli to which participants were responding. Temporal jitter between the onset of the first and the last anchors in the adaptation sequences was achieved through varying the number of anchor presentations (3-6 repetitions; Figure 3), with anchors between the first and last marked as “middle.” The regressors of interest were then convolved with the standard hemodynamic response function, combined with a set of regressors of no interest (e.g. head motion parameters from the output of volume registration and regressors representing

AFNI's model of baseline activity), and compared through multiple regression to a baseline of phase-scrambled versions of the animal pictures used in the experiment. The regression model provided the beta weights for the response to each stimulus type in each voxel for each participant, and these beta weights were then transformed into the standardized Talairach and Tournoux (1988) volume using each participant's anatomical scan for purposes of group analyses.

Group-level data were analyzed using a 2-way mixed-effects analysis of variance (ANOVA), performed on each voxel in standardized space with a fixed-effects contrast performed on the 12 stimulus conditions related to the adaptation sequences and participants acting as the random-effect repeated measure. The overall effect of adaptation was evaluated as a weighted contrast between the regressors for the first and last anchor stimuli in the adaptation sequence, pooling new and old anchors (first > last), thresholded at $P < .025$ (1-tailed) and corrected for whole-brain comparisons to $P < .05$ using cluster size (AlphaSim in AFNI). The overall effect of recovery from adaptation was evaluated as a weighted contrast between the beta weight for the last anchor in the adaptation sequence and those for deviant levels 1-3, pooling across new and old anchors (last < deviant levels 1-3), thresholded at $P < .025$ (1-tailed) and corrected for whole-brain comparisons to $P < .05$ using cluster size. As in Gotts et al. (2011), relatively permissive voxel-wise alpha levels were chosen to afford a more comprehensive set of possible recovery patterns in task-relevant brain regions. The intersection of the corrected adaptation and recovery masks then served as the conjunction of the two effects, with a corrected P -value equal to the maximum of the P -values of the two individual effects (i.e. $P < .05$; see Nichols et al., 2005, and Friston et al., 2005, for discussion). As noted by Nichols et al. (2005), this statistic holds without qualification in situations where the effects being combined are not fully independent of one another, as is the case for the adaptation and recovery effects evaluated here (both involving the “last” anchor condition), permitted that the individual effects are corrected for multiple comparisons prior to conjunction.

Differences in recovery curves for new and old anchors were evaluated first by testing differences in the slopes of the curves over deviant levels 1-3. As in Gotts et al. (2011), the overall magnitudes of the responses to the deviant conditions were of less interest than the relative shapes of the curves. Accordingly, the beta weights in each voxel for each participant were rescaled for all four points on the tuning curve (last anchor, deviant levels 1-3) between 0 and 1 (minimum to maximum) and separately for new and old anchors. While it would be possible, in principle, to perform the same complex analysis of tuning curve shape used by Gotts et al. (2011), we opted for a simpler approach in the current study by estimating the average slope of the recovery curve over deviant levels 1-3, which afforded rapid detection of relative effects of “sharpened” and “broadened” tuning. The best-fit slope over the rescaled beta weights of deviant levels 1-3 was calculated separately for new and old curves (excluding the data point for the “last” anchor). The difference in slopes was then calculated in each voxel for each participant, tested at the group level against a value of 0 with a one-sample t -test ($P < .05$, 2-tailed). Corrections for multiple comparisons involved combining a cluster-size correction with a Bonferroni correction for 2 whole-brain tests (a test for slope differences and a test for repetition suppression using the first, middle,

and last anchor stimuli), finding the clustersize threshold for each test needed to yield $P < .05/2$ or $.025$ (see Gotts et al., 2012c, for discussion). Following this cluster-size correction, the results of these two tests were individually conjoined with voxels exhibiting significant adaptation and recovery. Whole-brain testing of differences in slope for new and old recovery curves was checked with a test for a 2×4 interaction (new, old $\times$ last, deviants 1, 2, and 3) in a mixed-effects ANOVA using the original beta weights to confirm that results were not introduced by the rescaling operation.

2.2. Results

The goal of the fMRI experiment was to manipulate experience with a set of pictured objects by having participants name them several times prior to fMRI, and then 1) evaluate changes in neural tuning using fMRI adaptation, and 2) evaluate the association of these tuning changes with behavioral priming magnitude assessed just after fMRI. Results are first shown for the behavioral sessions pre- and post-fMRI, followed by the fMRI results and then the interrelationship of fMRI and behavioral results.

2.2.1. Repetition Priming in Picture Naming—Prior to fMRI, participants were required to name a set of briefly presented pictures of animals and man-made objects at a rate of one every two seconds. The entire set was repeated 5 times in a pseudorandom order, allowing participants short breaks in-between blocks. As expected from prior studies (e.g. van Turennout et al., 2003), response times to individual pictures decreased over repetitions [Repeated-measures ANOVA, main effect of repetition: $F(4,68) = 17.66$, $P < .0005$] (see Figure 4A). Pre-fMRI repetition also improved naming accuracy from 89.4% correct on the first repetition up to 96.1% correct on the final, fifth repetition [$F(4,68) = 24.99$, $P < .0005$]. In the post-fMRI session, the old and new anchor stimuli used during fMRI (animals) were randomly intermixed along with the previously named man-made objects and a matched set of man-made objects that were new for the session. As expected, participants exhibited robust repetition priming to old versus new pictures when pooling the animal and man-made object stimuli [mean (SE) response time to old pictures: 819.0 ms (15.8 ms); mean (SE) response time to new pictures: 895.2 ms (18.7 ms); mean priming magnitude: 76.2 ms; Repeated-measures ANOVA, $F(1,17) = 90.7$, $P < .0005$] (see Figure 4B). Similarly, naming accuracy was significantly higher for old (95.7%) than for new pictures (91.6%) [$F(1,17) = 18.7$, $P < .0005$]. When considering only the animal stimuli that served as anchors in the fMRI session, priming magnitudes were comparable to those for the entire stimulus set [mean (SE) response time to old pictures: 867.4 ms (16.3 ms); mean (SE) response time to new pictures: 948.0 ms (19.8 ms); mean priming magnitude: 80.7 ms; $F(1,17) = 64.5$, $P < .0005$]. These results demonstrate that repetition priming initiated by the pre-fMRI picture naming session is maintained throughout the duration of the fMRI experiment. The magnitude of the response time change over the 5 pre-fMRI repetitions (~ 100 – 110 ms) is also similar to that observed when comparing new and old pictures in the post-fMRI naming session (~ 80 ms). However, the measurements in the post-fMRI session are more appropriate for estimating the magnitude of repetition priming since the responses in the pre-fMRI session may include some non-specific improvement in the picture naming task. Priming magnitudes for subsequent analyses are therefore derived from the post-fMRI session.

2.2.2. fMRI: Voxels Exhibiting Adaptation and Recovery—During the fMRI experiment, participants viewed adaptation sequences of repeated anchor pictures (3-6 times) followed immediately by single deviant pictures used to measure recovery from adaptation. Half of the anchor pictures were named in the pre-fMRI session (“old”) and half were new for the fMRI session, while all of the deviant pictures were new for fMRI (Figure 3). As in our initial study applying this basic paradigm to measure neural tuning to objects along perceptual and conceptual dimensions (Gotts et al., 2011), we first identified voxels that exhibited both adaptation to the anchor stimuli (first > last in the sequence) and a significant effect of recovery from adaptation (last < average of deviant levels 1-3). The results of this conjunction analysis identified visually responsive brain regions in bilateral occipital, ventral temporal, parietal, and lateral prefrontal cortex, in good accord with our prior study (Gotts et al., 2011) (see Figure 5 and Supplementary Figure 1).

2.2.3. fMRI: Voxels Exhibiting Repetition Suppression and Changes in Tuning—We next identified voxels exhibiting repetition suppression for previously named anchors and those exhibiting some change in the recovery curves as a function of prior naming in two separate whole-brain tests. Repetition suppression was defined as larger beta weights to the New relative to the Old anchor stimuli (combining first, middle, and last conditions), thresholding the voxel-wise, weighted contrasts at $P < .025$ (1-tailed), and correcting for whole-brain comparisons and 2 separate tests to $P < (.05/2) = .025$. Changes in tuning were assessed by measuring the change in the linear slope of the recovery curves. Our prior study utilizing this same range of anchor-deviant relationships found that recovery curves in visually responsive regions lie between the extremes of purely image-selective (fully adapted to an identical picture and fully recovered to exemplar, semantically related and unrelated pictures) and category-selective (fully adapted to identical, exemplar, and semantically related pictures and fully recovered to unrelated pictures). If the prior naming experience has shifted curves from a more category-selective pattern to a more image-selective pattern that is consistent with perceptual sharpening, then the best-fit slope calculated over the beta weights to the exemplar, semantic, and unrelated conditions should be closer to 0 (more horizontal) for old than for new anchors (see Figure 1C). On the other hand, if the prior naming experience has shifted curves from a more image-selective pattern to a more category-selective pattern that is consistent with conceptual broadening, then the best-fit slope across the exemplar through unrelated conditions should be more positive for old than for new anchors. The virtue of utilizing single values in each voxel (i.e. slope) to characterize curve shape and change is that it facilitates the examination of the relationship to priming magnitude and other behavioral measures, although results were also checked using more standard interactions within the ANOVA model. As outlined above in **Section 2.1.4**, recovery curves were constructed for each participant from the beta weights to the “last” and deviant levels 1-3. Variation in BOLD response magnitude across participants that could skew the slope estimates was eliminated by first re-scaling the curves to lie between 0 and 1, from the minimum to maximum values of the original beta weights (see Gotts et al., 2011, for further discussion). The best-fit linear slope was then estimated in each voxel and for each participant across deviant levels 1-3 (exemplar, semantic, and unrelated) following old versus new anchors. Changes in the slopes of the recovery curves were then evaluated statistically in each voxel across participants using a paired *t*-test,

thresholding the voxel-wise slope differences at $P < .05$ (2-tailed), and correcting for whole-brain comparisons to $P < (.05/2)$ using cluster size. Clusters of voxels surviving correction for multiple comparisons (either repetition suppression or slope changes) were then conjoined with the voxels exhibiting overall effects of adaptation and recovery.

Two large clusters of voxels were identified in the left and right occipitotemporal cortex that showed a significant effect of repetition suppression to previously named anchor pictures (Figure 6A; see also Supplementary Table 3). While the cluster in the left occipitotemporal cortex failed to survive correction for multiple comparisons, it showed a non-significant trend ($P < .1$, corrected) and was retained given similar results in many prior studies. Treating these two clusters as regions of interest (ROIs), the rescaled beta weights depicting the shapes of the recovery curves, averaged across the entire ROI in each hemisphere, are shown in Figure 6B. In both ROIs, adaptation remained to an identical picture and was fully recovered to the exemplar and semantic deviant conditions relative to the unrelated condition, consistent with image-selective tuning and serving as a good match to the results from our prior study throughout much of occipitotemporal cortex (Gotts et al., 2011). However, the slopes of the recovery curves in these ROIs failed to be significantly modulated by old versus new anchors ($P > .6$ for both), with both conditions displaying image-selective tuning. This pattern remained unchanged when using the peak location of repetition suppression in both ROIs rather than the entire ROI average.

While the slopes of the recovery curves failed to be modulated in occipitotemporal cortex, slope differences were found to be significant ($P < .05$, corrected for two whole-brain comparisons) in the left lateral frontal cortex along the inferior frontal sulcus (see right panels of Figure 7 and Supplementary Table 3). In contrast to the predictions of the perceptual sharpening model, the recovery curves following old anchors had a significantly more positive slope, with more residual adaptation to the exemplar and semantic associate deviant conditions (left panel of Figure 7). An ROI analysis was conducted on this left frontal cluster of voxels using the original beta weights to determine which deviant conditions exhibited significant differences between old and new anchors. A repeated-measures ANOVA revealed a significant interaction between anchor type (old, new) and recovery pattern (last, deviant 1, 2, 3) [$F(3, 51) = 3.929$, $P < .02$], re-capitulating the effects on the slopes of the rescaled beta weights. Follow-up paired t -tests revealed a significant difference between old and new adaptation sequences for the exemplar condition [deviant level 1: $t(17) = 4.18$, $P < .001$] and a statistical trend for the semantic condition [deviant level 2: $t(17) = 1.75$, $P < .1$], both indicating greater residual adaptation following old than new anchors. Examining the old and new anchor conditions separately, the exemplar and semantic deviant conditions both showed a statistical trend for residual adaptation relative to the unrelated condition following old anchors [$t(17) > 1.75$ for both, $P < .1$], and no significant differences were observed following new anchors ($P > .3$ for both). Comparing the shapes of these recovery curves to our prior study (Gotts et al., 2011), the recovery curve following new anchors serves as a good match to an image-selective curve, whereas the recovery curve following old anchors is a good match to a more conceptual tuning curve, with a positive slope across the deviant conditions.

Finally, we examined whether the positive slope changes observed in the left frontal ROI were significantly larger than those in the occipitotemporal ROIs that exhibited significant effects of repetition suppression but without significant slope changes. These tests were conducted on the rescaled beta weights in order to prevent any differences in overall MR signal strength in occipitotemporal and frontal regions from influencing the results. Slope changes in the left frontal ROI were indeed significantly more positive than those in the left occipitotemporal ROI [paired t -test: $t(17) = 2.41$, $P < .03$] and in the right occipitotemporal ROI [$t(17) = 2.84$, $P < .02$]. Underlying these results, the only individual condition with a slope different from zero was in the left frontal ROI for the old anchor condition, with a significantly positive slope [$t(17) = 2.57$, $P < .02$]; all other slopes failed to be significantly different from zero. These results establish that not only were the slope changes significantly positive in the left frontal region, they were also significantly larger than any effects in occipitotemporal regions, constituting a significant interaction of old/new recovery curve slope by brain region.

In summary, occipitotemporal regions displayed repetition suppression to previously named anchors without significant changes in tuning. Changes in tuning were indeed observed in the left lateral frontal cortex, but these changes failed to support the perceptual sharpening model and instead provided support for a broadening of neural tuning along a conceptual dimension.

2.2.4. Relationship Between Changes in Neural Tuning, Repetition Priming, and Conceptual Naming Errors—In the previous section, we identified a region of the left lateral frontal cortex that showed a significant alteration in neural tuning following previously-named relative to new anchors. However, the pattern of change failed to support sharpening and instead supported a conceptual broadening of neural representations. This observation led us to take a closer look at the picture naming performance of our participants in the pre-fMRI and post-fMRI sessions in order to evaluate whether this broadening might have some relationship to behavior - either in terms of repetition priming magnitude in the post-fMRI session or in terms of elevated semantic errors in picture naming. First, we present an analysis of the speech errors made by the participants during the naming session. This is followed by analyses of the relationship between slope changes in the left frontal ROI, the magnitude of repetition priming in the post-fMRI naming session, and the incidence of semantic errors in the pre- and post-fMRI naming sessions.

2.2.4.1. Analysis of Picture Naming Errors: We classified picture naming errors according to the basic taxonomy used by Lhermitte and Beauvois (1973) (see also Gotts et al., 2002; Plaut & Shallice, 1993), in which whole-word commissions are labeled according to their relationship to the target name (e.g. visual, semantic, or phonological). The rate of the different error types is shown in Figure 8, averaged across participants by pre- and post-fMRI run and normalized both by the total number of trials (top) and the total number of errors (bottom) (see Supplementary Table 2 for a complete list of errors). Across the pre-fMRI naming runs, Omissions (O) and Visual/Semantic errors (V/S) became less frequent, although the decrease was more pronounced for Omissions, leading the errors that remained to be predominantly visual/conceptual in nature. The only error type with apparent increases

from the pre- to post-fMRI session was Visual/Semantic Perseverations (V/S+P). We evaluated this increase statistically with a Chi-Square test in a manner similar to Gotts et al. (2002) by utilizing the number of trials with versus without the occurrence a perseverative error (pooled across participants), and it was found to be highly significant [X^2 (df 1) = 10.13, $P < .0025$]. This increase was not likely due to fatigue over the sessions, since the average response times and accuracies were well-matched across sessions (see Figure 4). In the analyses below, we examine the relationship between the overall incidence of picture naming errors with a conceptual component (V/S and V/S+P errors), the change in slope following old versus new anchors, and the magnitude of repetition priming. For each participant, errors were pooled across the pre and post-fMRI sessions in order to minimize error counts of zero, and the conceptual error count was then normalized by the total number of errors in order to adjust for differences in overall accuracy across the participants.

2.2.4.2. Left Frontal ROI analysis: For each participant, ROI-averaged values of the slope change (old-new) for the rescaled beta weights were calculated for the left lateral frontal region identified in *Section 2.2.3*. These values were then correlated (Pearson) across participants with the magnitude of repetition priming to the anchor stimuli observed in the post-fMRI picture naming session using effect size (e.g. Dunlop et al., 1996), as well as the proportion of conceptual naming errors observed in the pre- and post-fMRI sessions. We also evaluated the correlation of priming magnitude with the proportion of conceptual errors, adjusting a significance level of $P < .05$ for 3 comparisons using Bonferroni correction ($P < .05/3 = .0167$). The magnitude of the slope change in the left frontal ROI failed to be correlated with priming magnitude in the post-fMRI session [$r(16) = 0.212$, $P > .3$] but was significantly and positively correlated with proportion of conceptual errors in the naming task [$r(16) = 0.562$, $P < .0153$], surviving Bonferroni correction (see scatterplot in Figure 9). The correlation of priming magnitude with proportion of conceptual errors showed a statistical trend prior to correction [$r(16) = 0.457$, $P < .057$], but failed to survive correction (see Supplementary Table 4 for results using alternate metrics). The correlation between slope change and proportion of conceptual errors establishes that the effect of conceptual broadening in left frontal cortex is associated with behavior, albeit not significantly with the magnitude of priming.

2.3. Discussion

In Experiment 1, we used fMRI-Adaptation to examine the influence of repeated object identification on changes in neural tuning to object concepts. Inconsistent with the perceptual sharpening theory of repetition suppression and repetition priming, we found that rapid adaptation to previously named objects transferred *more*, not less, to related objects for a region in left lateral prefrontal cortex. This was particularly true for the different exemplar condition but also showed a statistical trend for conceptually related objects. The recovery curve following previously named anchors in the left lateral frontal region was reminiscent of conceptual tuning curves in our prior fMRI-Adaptation study (Gotts et al., 2011), with a relatively linear recovery from adaptation for greater conceptual distances. In contrast, the curve in the same region following anchors that were new for the fMRI session showed a pattern consistent with “image-selective” tuning seen in our prior study - suggesting a shift in tuning from stimulus-selective tuning towards conceptual tuning following object

identification. In further support of this interpretation, the change in the slopes of the recovery curves was significantly correlated with the proportion of conceptual naming errors committed in the pre and post-fMRI picture naming sessions, and this was accompanied by an overall shift toward a greater proportion of conceptual naming errors in the pre-fMRI runs and a significant increase in the number of visual/conceptual perseverative naming errors from the pre- to the post-fMRI picture naming sessions.

Overall, these findings seem to indicate that tuning preferences of neurons are not changing much in posterior occipitotemporal regions, and the changes that do occur in the left frontal cortex are consistent with a conceptual broadening rather than a perceptual sharpening of object representations. However, given the post-hoc nature of the picture naming error analyses and the relative weakness of the purely conceptual effects (excluding the exemplar condition), we conducted a behavioral follow-up experiment using a semantic priming paradigm with picture naming as the basic task. If the effects seen in Experiment 1 were indeed conceptual in nature, then the prediction is that repeated picture naming should lead to greater semantic priming when using previously named pictures as briefly presented primes.

3. EXPERIMENT 2: SEMANTIC PRIMING EXPERIMENT

In Experiment 2, we conducted a behavioral experiment with a new group of participants in order to examine the relationship between stimulus repetition and a more common behavioral measure of conceptual similarity that is used to probe the structure of long-term knowledge representations: semantic priming (e.g. Meyer & Schvaneveldt, 1971; Meyer et al., 1975; see Neely, 1991, and Hutchison, 2003, for reviews). If repeatedly naming pictures leads individual pictures to more readily activate representations of conceptual associates, then presenting previously named pictures as briefly presented primes should lead to larger semantic priming magnitudes than if the prime was not named previously. Furthermore, participants with larger repetition priming effects for the previously named set should exhibit a larger enhancement of semantic priming; recall that in Experiment 1 (2.2.4.2. *Left Frontal ROI analysis*), there was a statistical trend for repetition priming magnitude to be positively correlated across participants with the proportion of conceptual naming errors prior to correction for multiple comparisons. While semantic priming effects are typically very short-lived in tasks such as lexical decision performed on word stimuli (up to ~ 500–1000 ms; see Neely, 1991, for review), there have been demonstrations of longer-lasting effects when multiple items from the same category are interleaved within a block of trials (e.g. Becker et al., 1997; Joordens & Becker, 1997). The novel prediction from the fMRI results presented above is that repetition priming and semantic priming should interact with one another.

In order to test this prediction, we adapted a previous semantic priming paradigm using picture naming as the basic task (Dell'Acqua & Grainger, 1999). As in Experiment 1, participants first named a set of objects in a pseudorandom order 5 times. Immediately following this first picture naming session, participants were administered a semantic priming experiment in which they viewed briefly presented primes with backward masking and named a probe picture after a brief delay. Half of the prime pictures were previously

named and half were new for the semantic priming session. In an analogous fashion to the deviants used in fMRI-Adaptation, the probe pictures were all new for the semantic priming experiment. Crossed with the old/new prime conditions was the conceptual relatedness of the prime to the probe stimuli, with half of the trials being conceptually related versus half unrelated. Response times and accuracy were measured to the probe picture naming responses. Immediately after the semantic priming session, a final picture naming session was conducted to assess the magnitude of repetition priming (ES) to the old versus new prime pictures used in the semantic priming experiment.

3.1. Materials and Methods

3.1.1 Participants—An additional 16 right-handed, healthy adult participants (9 female) took part in Experiment 2, none of whom had participated in Experiment 1 (mean age = 26.1 years, SD = 4.0 years). All participants had normal or corrected-to-normal vision, were native English speakers, reported no history of neurological problems, and read and signed informed consent documents that were approved by the NIH Institutional Review Board.

3.1.2. Behavioral Methods

3.1.2.1. Pre-Semantic-Priming Picture Naming: As in Experiment 1, participants first named a set of objects (a total of 50 pictures of living and non-living things) in a pseudorandom order 5 times, divided into 5 experimental blocks. Pictures were shown in color rather than black-and-white, as in the first experiment. Otherwise, the trial timing, stimulus display details, and data recording procedures were identical to the picture naming sessions in Experiment 1.

3.1.2.2. Semantic Priming Behavioral Methods: Immediately following the initial picture naming session, participants were administered a semantic priming experiment using picture naming as the basic task (adapted from Dell' Acqua & Grainger, 1999). In each trial, participants viewed a fixation cross for 500 ms, followed by a briefly presented prime picture for 100 ms that was either previously named (“old”) or “new” for the semantic priming experiment. The prime was then masked for 50 ms by a phase-scrambled image constructed from grayscale versions of the pictures used in the experiment, followed by a blank screen for 200 ms, and then finally by the probe picture (200 ms duration) that the participant was instructed to name as quickly and as accurately as possible (Figure 10). Probe pictures were all new for the semantic priming experiment and were either semantically related or unrelated to the prime picture, with each probe picture serving equally in both related and unrelated conditions over the course of the experiment. Following the probe picture, a blank screen was presented for 2450 ms to allow for the naming response, for a total inter-trial interval of 3500 ms. The semantic priming session consisted of 4 total blocks of 100 trials each. In each block, every prime picture (50 new and 50 old) was presented once with either a semantically related or an unrelated probe picture (see Supplementary Table 5 for a list of related and unrelated prime-probe pairs used), leading to 100 total trials of each type presented during the experiment (old/related, old/unrelated, new/related, new/unrelated). Similarly, each probe picture was presented exactly once in each block for naming, either as related or unrelated to the prime in alternating blocks. Lists of old and new prime pictures were counterbalanced across participants to

prevent any bias due to item effects at the group level, although lists were carefully constructed to be matched in conceptual category membership and name frequency/familiarity (using HAL frequency and lexical decision times in the English Lexicon Project database: Balota et al., 2007). All response times on correct trials within 4 standard deviation units from the mean for each participant were retained for analysis, and fewer than 2% of trials were eliminated as outliers for any given participant.

3.1.2.3. Post-Semantic-Priming Picture Naming: As in Experiment 1, repetition priming for the old versus new prime pictures used during semantic priming was assessed in an additional picture naming session administered immediately after the semantic priming task. The trial timing and stimulus display details were identical to other picture naming sessions, randomly interleaving the old and new prime pictures in a single block for a total of 100 trials (50 of each type). Magnitude of repetition priming in this post-semantic-priming session was calculated as raw differences in the mean response time to old versus new prime pictures, as well as in units of effect size (e.g. Dunlop et al., 1996).

3.2. Results

A repeated-measures ANOVA of the response times to correct trials in the post-semantic-priming picture naming session first established that there was a significant effect of repetition priming [$F(1,15) = 29.6$, $P < .0005$; mean (SE) response times to old: 765.6 (25.6) ms; mean (SE) response times to new: 841.9 (28.5) ms; priming magnitude (new-old): 76.3 ms]. A repeated-measures ANOVA then applied to the probe picture response times on correct trials in the semantic priming session failed to yield significant main effects of prime type (old vs. new), probe relatedness (semantically related vs. unrelated), or an interaction of the two factors. However, the magnitude of change in semantic priming (unrelated - related response time) for old versus new primes was significantly correlated across participants with the magnitude of repetition priming measured in the post-semantic-priming picture naming session [$r(14) = 0.561$, $P < .025$]: the larger the repetition priming, the larger the semantic priming following old versus new primes (Figure 11). This effect was then further clarified by evaluating the dependence of semantic priming in the separate prime conditions (old vs. new) on the magnitude of repetition priming. Semantic priming magnitude was positively correlated with the magnitude of repetition priming following old primes [$r(14) = 0.634$, $P < .01$], but not following new primes [$r(14) = -.239$, $P > .3$]. Using Steiger's Z -transform to test for significant differences in two Pearson correlation coefficients that share a common variable (i.e. repetition priming magnitude), the correlation for old primes was also significantly more positive than that for new primes ($+.634$ vs. $-.239$, $Z = 2.31$, $N = 16$, $P < .05$).

Given these relationships, we revisited the failure to observe significant semantic priming or modulation by old/new primes in the repeated-measures ANOVA across all participants. As the scatterplot in Figure 11 makes clear, a number of subjects failed to exhibit strong repetition priming in the post-semantic-priming picture naming session. On the initial hypothesis for the experiment, weak or non-existent repetition priming would not predict much alteration in semantic priming. If one limits the analysis accordingly to participants who exhibited significant repetition priming ($N = 9$ out of the original 16), then the prime

type X probe relatedness interaction is marginally significant [$F(1,8) = 5.128, P < .06$], with robust semantic priming following old primes [$F(1,8) = 16.203, P < .005$; semantic priming magnitude = +20.2 ms] and a lack of significant semantic priming following new primes [$F(1,8) = 0.46, P > .5$] (Figure 12).

3.3. Discussion

Greater semantic priming was observed following previously named prime pictures, and this relationship was directly related to the amount of repetition priming observed to the prime pictures across participants. These results provide further evidence that repetition priming at typical delays is associated with a conceptual broadening of representations such that named objects activate conceptual associates more readily, producing conceptual errors with some likelihood.

4. GENERAL DISCUSSION

In two experiments, one fMRI and one behavioral, we examined the influence of repeated object identification on changes in the neural representations of objects. The perceptual sharpening theory of repetition suppression and repetition priming holds that repetition-related decreases in activity are mediated by the selective dropping out of poorly responsive and poorly tuned cells with experience - cells that are presumably tuned better to different but related stimuli, leaving representations more stimulus-selective as a result. While the linking assumptions needed to explain how these changes could lead to facilitated response times and improved accuracy in identification have not been put forward in sufficient detail (a point discussed in Gotts et al., 2012a), any evidence that repetition leads to more prominent activation of related object representations (e.g. visual and/or conceptual associates) would have to be taken as evidence that conflicts with this basic account of how repetition suppression could give rise to priming. In a task such as picture naming, these related representations support different naming responses, which if anything, may have the effect of slowing participants down in the task and producing visual and conceptual errors rather than facilitating the correct response (e.g. Dell, 1986; Dell et al., 1997; Humphreys et al., 1988; Levelt, 1989; Mirman, 2011). In the fMRI experiment (Experiment 1), we found evidence that short-term adaptation to animal pictures transferred significantly more to visually and conceptually related objects in the left lateral frontal cortex when the adapted anchor picture was named several times prior to the fMRI experiment (see also Gronau et al., 2008, for similar results). The degree to which this tuning change occurred was directly related to the proportion of conceptual errors that participants made in the picture naming sessions just before and after the fMRI scanning session. Participants also made more conceptual perseverative error responses in the naming session just after the fMRI session, consistent with stimulus repetition leading to a larger number of experience-dependent conceptual errors (for similar evidence in normal controls and aphasic patients, see Cohen & Dehaene, 1998; Gotts et al., 2002; Hirsh, 1998; Howard et al., 2006; Lee et al., 2009; Martin et al., 1998; Santo Pietro & Rignodsky, 1986; Vitkovitch et al., 1993). In the semantic priming experiment, participants showed larger semantic priming magnitudes as a direct function of how much repetition priming they exhibited just after the experiment - a marker for how much experience-dependent change was induced by repeated object identification in

the pre-semantic-priming session. While it was perhaps surprising that overall semantic priming was not observed in this experiment (e.g. following new prime pictures), the use of a task requiring individuation rather than classification may be partly responsible, since the briefly presented prime picture will activate a different naming response than the probe picture to be named. Nevertheless, the interaction between long-term repetition priming and short-term semantic priming was a direct prediction of our fMRI results. It is also consistent with a prior demonstration of long-term semantic priming using words in lexical decision and category decision (Becker et al., 1997; Joordens & Becker, 1997). When exposing participants to several sets of categorically related words that were presented in an interleaved fashion, response times in a later block to related words were facilitated relative to unrelated words, particularly in the category decision task (see also Woltz, 2010, for another demonstration of long-term semantic priming). Taken together, all of these data appear to present a major challenge for the perceptual sharpening theory of repetition suppression and repetition priming, the implications of which we discuss more fully below.

4.1. Conceptual Interference in Object Identification

This study is obviously not the first study to find conceptually-related phenomena in object identification, or even in object repetition (see Howard et al., 2006; Mirman et al., 2013; Oppenheim et al., 2007, 2010, for discussion). A variety of paradigms have been used to study conceptual effects in picture naming in normal controls and brain-damaged patients, such as the Picture-Word Interference paradigm (PWI: e.g. Glaser & Dunganhoff, 1984; Glaser & Glaser, 1989; Janssen et al., 2008, 2010; Mahon et al., 2007; Schnur & Martin, 2012), blocked cycling naming (e.g. Lee et al., 2009; Schnur et al., 2006, 2009), and speeded picture naming (e.g. Hodgson & Lambon Ralph, 2008; Mirman, 2011; Vitkovitch et al., 1991, 1993). Interference of conceptually related object names has been readily demonstrated in all of these paradigms, and repeating a set of conceptually related pictures multiple times leads to the accumulation of semantic interference (e.g. Belke et al., 2005; Damian et al., 2001; Hodgson et al., 2003; Maess et al., 2002; Schnur et al., 2006). The potential for these effects to be long-lasting (hours or longer) has not always been emphasized (although see Becker et al., 1997; Lee et al., 2009), and it may help to explain why the literatures on semantic interference and repetition suppression/repetition priming have remained separate when entertaining proposals such as perceptual sharpening. However, the current results highlight the importance of considering these literatures more simultaneously.

One critical role of enhanced conceptual inter-relationships is that they facilitate the generalization of knowledge. Our long-term knowledge representations aren't only responsible for identifying isolated objects, for which improved discriminability and more selective representations may be useful. Rather, conceptual inter-relationships serve as the basic foundation of memory and action in most daily tasks (see Squire & Wixted, 2011, and Martin, 2007, for reviews), and they constitute the basic elements of our understanding of the world around us. In terms of our dynamical interactions with common objects and words in real-world contexts, many have also noted that related concepts tend to be encountered in close temporal proximity to one another (e.g. Lund & Burgess, 1996; Landauer & Dumais, 1997) - a statistical property of the environment that would be in good agreement with the

conceptual broadening phenomena observed in the current experiments. All of these considerations point to the importance of ongoing, incremental plasticity mechanisms that help to maintain robust conceptual interrelationships among our long-term knowledge representations (e.g. McClelland & Rumelhart, 1985; McClelland et al., 1995; Oppenheim et al., 2010). While sharpening may indeed be useful in early sensory regions for improving stimulus discriminability, its utility will be more limited thereafter.

It is also worth commenting on the relevance of the specific location in which conceptual broadening was observed here. Dobbins et al. (2004) found that changing the task being performed on a visual object picture from initial exposure (“bigger than a shoebox?”) to later exposure (“smaller than a shoebox?”) reduced repetition priming and repetition suppression in left lateral frontal cortex and eliminated repetition suppression in the left fusiform gyrus, with the largest covariation between repetition suppression and priming magnitudes across this manipulation occurring in the left lateral frontal cortex. This is the likely explanation as to why we failed to observe significant repetition suppression to the anchor stimuli in left lateral frontal cortex in the current experiment, changing the task from picture naming in the pre-fMRI session to man-made object detection during fMRI (see also Horner, 2012; Horner & Henson, 2008, 2012; Wig et al., 2009; Race et al., 2009, 2010, for further discussion). The alteration in repetition suppression and priming with a task change is what led Dobbins et al. (2004) to propose that the left lateral frontal cortex in the territory of the inferior frontal junction is responsible for binding together particular stimuli with particular responses in a certain task, an idea recently reviewed and elaborated by Henson, Horner and colleagues (Henson et al., 2014). We view this idea as promising in terms of the precise systems-level role of this region, and it fits well with larger views of the organization and function of the lateral frontal cortex (e.g. Boettiger & D’Esposito, 2005; Cole et al., 2013; Corbetta & Shulman, 2002; Miller & Cohen, 2001; Rougier et al., 2005). The role of this region in conceptual processing (“semantic control”) and concept selection has also been emphasized by a variety of researchers (e.g. Badre & Wagner, 2007; Corbett et al., 2009a; 2009b; Jeffries & Lambon Ralph, 2006; Jeffries et al., 2008; Schnur et al., 2009; Thompson-Schill et al., 1997). We therefore think it unlikely that the conceptual broadening that we observed in the fMRI experiment reflects large permanent changes to long-term semantic memory - which would have the potential to be catastrophic if 15–20 minutes of practice could lead to such a result. Rather, it is more likely that this broadened tuning reflects alteration to context-sensitive representations in the prefrontal cortex that help to bind stimuli to conceptually and contextually relevant responses.

4.2. Is There Still Hope for Perceptual Sharpening in Explaining Repetition Suppression and Repetition Priming?

It is important to clarify that we do not think that our results undermine the behavioral relevance of experience-dependent perceptual sharpening of object representations in the experimental contexts in which most of those effects have been reported, namely extensive practice with a set of visual objects over weeks and months (e.g. Baker et al., 2002; Freedman et al., 2006; Jiang et al., 2007; Rainer & Miller, 2000). In perhaps the most rapid of these demonstrations, Jiang et al. (2007) provided evidence using fMRI adaptation of sharpened visual object representations in right lateral occipital cortex after training

participants to classify visually similar (morphed) car pictures into arbitrary categories for an average of 5+ hours of training that was spread out over several days (1 hour per day and up to 2 weeks). However, experiments examining tuning in the same basic regions that employ a relatively small number of repetitions within a single experimental session have tended to find evidence of proportional scaling of neural responses rather than sharpening (e.g. De Baene & Vogels, 2010; Li et al., 1993; McMahon & Olson, 2007; Miller et al., 1993; Weiner et al., 2010). Our current experimental results in occipitotemporal regions are consistent with this last point in the sense that decreased responses were observed with little or no detected alteration in tuning (proportional scaling leaves the width of the tuning curves unchanged). However, the changes observed in the left lateral frontal cortex are distinct from scaling in that the tuning range is actually expanded. We are quite open to the point that our stimulus set did not include many stimuli that were highly visually similar, with a large degree of retinotopic overlap (as in Jiang et al., 2007). Indeed, we explicitly limited this kind of overlap by forcing anchors and deviants to have different left-right profiles and partial versus whole views. This choice may have limited repetition-related plasticity in earlier occipital areas (see Martin & Gotts, 2005; Wig, 2012, for discussion). However, there is nothing particularly remarkable about these stimulus sets with regard to repetition priming studies of visual objects, nor the basic task used (i.e. picture naming), and any satisfactory theory of the relationship between repetition suppression and priming must be able to address the details of the most common paradigms used to elicit these effects. If perceptual sharpening doesn't occur for short-term repetitions over several seconds or those that occur over longer durations within an experimental session - which produce the largest effects of both repetition priming and repetition suppression (e.g. van Turennout et al., 2003; McKone, 1998), then these durations were already going to require alternative mechanisms to explain the relationship. Of course, this doesn't rule out the possibility that perceptual sharpening makes an important contribution over longer durations of practice, but given the lack of success at the most typical durations of practice, one is forced to conclude that this is a relationship that currently lacks important experimental evidence.

4.3. Conceptual Broadening or Conceptual Sharpening?

One reaction to the pattern of greater transfer of adaptation effects to related objects (or greater semantic priming) after experience is that the conceptual representations aren't "broader", they are "sharper". In other words, if the effect of experience has been to form more clearly delineated category representations above the basic level (e.g. superordinate), then the results aren't ruling out representational sharpening, per se, but providing evidence consistent with sharpening at a conceptual level. We view this interpretation as quite plausible, and there is nothing in our current results that would rule it out. What would be needed to clarify the underlying picture better is to sample deviant conditions more densely around particular category boundaries (e.g. land animal versus sea creature; living versus non-living things) in order to detect whether the recovery curves at these boundaries have become steeper following experience. An alternate possibility is that the category boundaries aren't sharp and the conceptual inter-relationships are more graded. In either case, though, there has been an expansion of inter-relatedness of object representations along a conceptual dimension that we have termed "broadening" here. If this expansion corresponds best to category sharpening, this form of sharpening is not obviously helpful in

individuation tasks such as picture naming, and the puzzling relationship between repetition suppression and repetition priming remains.

4.4. Alternate Mechanisms

If perceptual sharpening isn't mediating repetition suppression and repetition priming in these experiments, then what is? As discussed above, conceptual broadening would be expected to slow participants down somewhat in a task requiring individuation, since support for competing responses is increasing. It's not obvious how this could serve as the underlying mechanism of either repetition suppression or repetition priming in naming, although as we have just demonstrated, there does appear to be a direct relationship between priming magnitude and broadening. One possible mediating mechanism that we have proposed previously is repetition-related enhancements in the neural synchronization of activity within and across task-engaged brain regions (e.g. Gotts et al., 2012a; see also Brunet et al., 2014; Engel & McCarthy, 2014; Ghuman et al., 2008; Gilbert et al., 2010; Gotts, 2003). On this view, activity is decreased overall while the temporal coordination of spikes is simultaneously improved, with coordinated volleys of spikes having a more effective impact on downstream brain regions despite the overall reduction in activity level. Enhanced synchronization could contribute an influence to the dynamics of activity that is somewhat independent of tuning changes (i.e. *when* cells are active rather than *which ones*), permitting either sharpening or broadening to occur in concert. However, other mechanisms are also possible, such as an earlier onset and offset of activity (i.e. the “facilitation” model; Henson, 2003; 2012), and a Bayesian “explaining away” of activity in earlier, more sensory regions within a hierarchical predictive coding theoretical framework (e.g. Friston, 2005; Friston & Kiebel, 2009). Future studies will need to test the specific predictions of these views in contexts that exhibit robust repetition suppression and repetition priming effects (see Gotts et al., 2012b, for discussion). Regardless of which one(s) of these possibilities is correct, our current results provide valuable constraints about the nature of representational changes that accompany the repeated identification of common visual objects.

5. CONCLUSIONS

Perceptual sharpening has long been touted as a good candidate mechanism for explaining improved stimulus identification in the face of repetition-related decreases in activity. In two experiments, one fMRI and one behavioral, we have shown that perceptual sharpening is unlikely to be this mediator for typical within-session repetition priming experiments that involve a small number of overall repetitions. Instead, we have found direct counter-evidence that repeated objects more readily activate the representations of conceptual associates. We conclude that within the context of object naming, repetition-related changes in neural synchronization and/or predictive coding mechanisms are better candidate mechanisms for explaining the joint observation of repetition suppression and repetition priming.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We test the perceptual sharpening theory of repetition suppression / priming in fMRI
- Repeated naming led to repetition priming but broader conceptual tuning in left PFC
- Repetition suppression in ventral stream was not associated with tuning change
- Broader PFC conceptual tuning was associated with increased semantic naming errors
- Repeated naming further led to increased semantic priming in a separate experiment

Figure 1. Using fMRI adaptation to measure neural tuning preferences and alterations in tuning with experience

(A) The BOLD response within stimulus-responsive fMRI voxels is temporarily reduced as the same image ("anchor") is repeated several times (3-6) at a rate of 1 per second. These temporary decreases, referred to as "adaptation", are thought to be cell- and synapse-specific. (B) By this logic, tuning preferences can then be inferred in individual fMRI voxels by the level of the recovered response to a new stimulus that shares a relationship with the adapted stimulus (e.g. visual form, conceptual, etc.). A greater recovered response is thought to indicate less neural representational overlap (i.e. fewer cells in common), whereas a weaker recovered response indicates a higher degree of overlap. (C) Changes in tuning preferences can be inferred by a change in the pattern of recovery from adaptation. If adapting to the picture of a cow (as in A) initially yields a "conceptual" recovery curve (retaining adaptation to identity, exemplar, and semantically related images), sharpening would be reflected as a shift in the curve toward a more image-selective curve (retaining adaptation only to an identical image and fully recovered to the other conditions) (i.e. shifting from "high overlap" toward "low overlap"). Conceptual broadening would be reflected as a shift in the opposite direction (from low overlap toward high overlap).

Figure 2. Trial structure of adaptation sequences in Experiment 1

Anchors were repeated at a rate of 1 per second (stimulus duration=200 ms), anywhere from 3 to 6 repetitions, and were followed immediately by a single deviant picture used to assess recovery from adaptation. Phase-scrambled baseline images of the animal pictures used in the experiment and pictures of man-made objects were randomly interleaved between adaptation sequences. Participants were instructed to press a response button to the man-made object pictures but were told to attend to all pictures. There were no additional delays or gaps in the stimulus displays, such that a single image of one of these types (anchor, deviant, baseline, man-made object) was being presented each second (duration of 200 ms followed by fixation for 800 ms).

Figure 3. Experimental design for Experiment 1

Repeated anchor stimuli (animals) were either named in the pre-fMRI picture naming session (Old) or were new for the fMRI session (New). Old and New anchors were counterbalanced across participants, and lists were matched for item properties and conceptual category membership. The deviant stimuli were all new for the fMRI experiment and shared one of three relationships with the anchor pictures: a different exemplar picture of the same type of animal, a semantic associate, or an unrelated picture. Anchor type (Old, New) was fully crossed with deviant condition (Exemplar, Semantic, Unrelated) for a total of 6 trial types.

Figure 4. Repetition priming effects in picture naming

(A) Mean response times to correctly named pictures in the pre-fMRI naming session decreased as a function of repetition number (1–5), while naming accuracy simultaneously increased (see text for description). (B) Repetition priming was assessed and found to be present in the post-fMRI picture naming session. The response times (and accuracies) to New and Old pictures in the post-fMRI session were comparable to those observed to the 1st and 5th repetitions, respectively, in the pre-fMRI session, suggesting that fatigue over the course of the three testing sessions was not an issue. Errors bars in both A and B depict the standard error of the mean (SE).

Figure 5. Regions showing significant effects of adaptation and recovery from adaptation Voxels exhibiting both adaptation (First Anchor > Last Anchor) and recovery from adaptation (Last Anchor < Deviants 1-3) were identified through conjunction analysis (shown in green). The two individual effects were first corrected for whole-brain comparisons to $P < .05$, and voxels showing both effects were retained and used to constrain later analyses of repetition suppression and changes in neural tuning.

A Repetition Suppression: **NEW** > **OLD** Anchors

B Image-Selective Tuning in Occipitotemporal Regions

Figure 6. Repetition suppression for previously named anchors in bilateral occipitotemporal cortex

(A) Repetition suppression was found bilaterally in occipitotemporal cortex by comparing New and Old anchor stimuli in the adaptation sequences, combining First, Middle, and Last conditions in a weighted contrast (New > Old). The effect in right occipitotemporal cortex survived multiple comparisons correction ($P < .05$), while the effect on the left showed a statistical trend ($P < .1$). Beta weights are shown separately for the New and Old anchors in units of percent signal change, averaged across participants and all voxels in the two ROIs (combined). (B) Shape of the recovery curves following New and Old anchors is shown separately for the two occipitotemporal ROIs using the beta weights that have been rescaled between 0 and 1 in each voxel for each participant, displayed to start from the same value in the identical condition to facilitate comparison of curve shape. Slope estimates calculated over the Exemplar through the Unrelated conditions (deviant levels 1-3) are displayed for each curve as thick dashed lines. Line plots have been used rather than bar plots for trends across the deviant conditions, although it is important to keep in mind that the deviant conditions along the x-axes are on an ordinal rather than a cardinal numerical scale. Little or no change in tuning was observed, with image-selective tuning (adaptation remaining only for an identical image) observed for both New and Old anchors in the ROI-averaged data.

Figure 7. Conceptual broadening of object representations in the left lateral prefrontal cortex
 The slope of the recovery curve (calculated for the rescaled beta weights using the Exemplar, Semantic, and Unrelated conditions) was more positive following Old than following New anchors for a region in the left lateral prefrontal cortex, starting in the inferior frontal junction and extending anteriorly along the inferior frontal sulcus. Shown in the right panels is the conjunction of significant slope differences with overall effects of adaptation and recovery (all effects corrected to $P < .05$ prior to conjunction). Rescaled beta weights are shown to the left for the left prefrontal ROI (conventions as Figure 6), with slope estimates displayed as thick dashed lines.

Figure 8. Incidence of picture naming error types in the pre- and post-fMRI sessions

(Top) Error types in the pre- and post-fMRI picture naming sessions, shown by session (1st repetition in the pre-fMRI session, 2nd and 3rd repetitions combined, 4th and 5th repetitions combined, and post-fMRI session), and normalized by the total number of trials in each condition to yield the average error rate. Error types included omissions (O), visual/semantic errors (V/S), visual/semantic perseverations (V/S+P), and Other (see text for definitions/examples). (Bottom) Same data shown normalized instead by the total number of errors rather than the total number of trials.

Figure 9. Conceptual broadening in left lateral prefrontal cortex predicts the proportion of conceptual naming errors

Scatterplot across participants ($N=18$) of the relationship between the overall proportion of conceptual naming errors in all picture naming sessions (pooling V/S and V/S+P types) and the change in the slopes of the recovery curves in the left lateral prefrontal ROI (slope Old - slope New). A greater proportion of conceptual naming errors was significantly associated with a more positive slope change (i.e. a shift to more conceptual tuning).

Figure 10. Experimental design for Experiment 2

(A) Prime type of Old (previously named) versus New was crossed with prime-probe relatedness (Related semantically versus Unrelated). Each condition occurred with equal frequency during the course of the experiment. (B) Timing of events for an individual trial in the semantic priming session involved fixation (500 ms), followed by a briefly presented prime picture (Old or New) for 100 ms with backward masking (50 ms), a blank screen for 200 ms, and finally the probe picture to be named (200 ms). Probe pictures were either semantically related or unrelated to the prime picture.

Figure 11. Semantic priming increases for previously named primes

A scatterplot across participants ($N=16$) shows the positive relationship between the magnitude of repetition priming (in units of effect size) observed in the post-semantic-priming session and the change in semantic priming, or SP (Unrelated-Related probes), following previously named primes (Old) versus primes that were new for the semantic priming session (New) (SP Old - SP New). A box with dashed outline highlights the participants ($N=9$) with repetition priming magnitudes that were significant at $P < .05$.

Figure 12. Semantic priming for participants with significant repetition priming in the post-semantic-priming session

Response times and semantic priming effects are shown for the participants who exhibited significant repetition priming in the post-semantic-priming session ($N=9$, highlighted by the dashed box in Figure 11). Mean response times to the four conditions are shown in the left panel, and semantic priming effects (Unrelated-Related probe response times) across participants are shown separately for New versus Old primes in the right panel. Errors bars depict the standard error of the mean (SE) for each condition.