

Priming Effects in the Fusiform Gyrus: Changes in Neural Activity beyond the Second Presentation

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Repetition priming typically leads to a decrease in the activation of sensory cortical areas upon a second exposure to the same visual stimulus. This effect is thought to reflect more efficient or fluent re-processing of previously seen stimuli so that less neural activity is required. Fluent re-processing has been hypothesized to be a potential link from repetition priming to neural changes associated with visual expertise. To examine this potential connection, the neural correlates of priming were examined across eight stimulus repetitions using functional magnetic resonance imaging. Sizeable regions of bilateral ventral occipito-temporal cortex (including the fusiform gyrus) exhibited reduced responses to the second presentation of a stimulus. Most of these areas displayed no further reduction in response to subsequent repetitions of the same stimuli. Because expertise accrues over many exposures, these areas, while clearly involved in priming, do not exhibit an activity pattern consistent with the development of expertise. In contrast, an area in the right posterior fusiform gyrus exhibited reductions in evoked response that grew in magnitude for stimulus repetitions from the second to the eighth presentations. This region exhibits a pattern of activity consistent with a gradual and cumulative enhancement of the fluency effect across trials, suggesting that it may mediate the link between priming and the development of visual expertise.

Keywords: expertise, fMRI, memory, nondeclarative

Introduction

The phenomenon of priming refers to the behavioral effects of prior exposure to a stimulus, even when explicit memory of the prior experience is not available. The consequences of priming include facilitation in identifying, naming or perceiving an object or word and can also include a tendency for a word to 'pop into mind', as in a stem-completion task (for reviews, see Schacter *et al.*, 1993; Roediger and McDermott, 1993). Priming occurs after a single prior presentation of a stimulus, and while the durations of the effects can be fairly transient (e.g. Graf *et al.*, 1984), in some cases effects have been shown to persist for an extended period of time (Cave and Squire, 1992; Cave, 1997). Because priming can produce an increase in perceptual speed (e.g. Feustel *et al.*, 1983; Biederman and Cooper, 1991) or response time performance, it has been proposed to be the first step in the development of automaticity that accompanies expertise (Logan, 1990; Poldrack *et al.*, 1999). The neural correlates of priming have been extensively studied in both neuropsychological and neuroimaging studies (for a review, see Schacter and Buckner, 1998). However, the possible relationship of priming and the development of automaticity and/or perceptual expertise has only begun to be explored with functional magnetic resonance imaging (fMRI).

Priming reflects the operation of a nonconscious memory system that can remain spared by the type of medial temporal lobe (MTL; including the hippocampus and adjacent cortical areas) damage that leads to impairment of conscious, declarative memory (Warrington and Weiskrantz, 1974; Graf *et al.*, 1984). Amnesic patients with total loss of the medial temporal lobe memory system can still exhibit normal repetition priming (Hamann and Squire, 1997; Stark and Squire, 2000), even though they are unaware of having seen the stimulus previously. These neuropsychological studies established that the neural basis of priming is outside of the MTL.

The most common finding across neuroimaging studies of priming is a reduction in activity in ventral occipito-temporal cortical areas for a repeated presentation of a visual stimulus (Schacter and Buckner, 1998). The activity reduction for a second presentation of a stimulus has been hypothesized to be the neural substrate of the priming phenomenon. The reductions observed with BOLD fMRI are consistent with single-unit neurophysiological studies that have reported 'repetition suppression' of neural firing when a visual object is re-presented (Desimone, 1996; for a review, see Wiggs and Martin, 1998).

Connecting repetition suppression phenomena to the development of expertise will require two critical extensions of tasks used to demonstrate repetition priming. First, priming effects need to be observed beyond the second presentation of a stimulus. While priming occurs after a single prior presentation, expertise and automaticity only develop over a large number of trials (e.g. Schneider and Shiffrin, 1977; Logan, 1988). In addition, expertise is typically thought of as extending over a domain, not being applied to a specific set of stimuli. Repetition priming has typically been shown in domains where exact stimuli are repeated and generalization to variations of stimuli is less well explored (but see Koutstaal *et al.*, 2001; Simons *et al.*, 2003). The focus of the current report is on the first element, multiple repetitions of stimuli. Because expertise develops after the second presentation of a stimulus, brain areas participating in the development of expertise should exhibit changes beyond the second repetition. If it is not possible to identify a brain region in which activity changes after the second presentation, this would suggest that the mechanism of repetition suppression might not play a role in the development of expertise (or that fMRI is not a suitable technique for addressing this question).

The neural correlates of the emergence of expertise with practice probably vary with the domain being studied. The ability to rapidly identify objects was chosen here as a relatively pure perceptual process that would be expected to improve with repeated exposure. James *et al.* (2000) reported improvements in object identification speed and reduced neural activity

for repeated presentations of an object, although the evolution of the change in activity was not assessed across repetitions (i.e. it is unclear whether the learning happened after a single presentation or reflected gains with each subsequent repetition). As a paradigm, an object identification task is intended to capture the kind of visual expertise that can be developed for specific categories of stimuli (e.g. dogs, birds, cars). The task has the additional advantage that the stimuli are recognizable, but the specific images being shown are initially novel.

Priming across repeated presentations has been explored for verbal stimuli. Buckner *et al.* (2000) examined changes in activity over five blocks of repeated covert word-stem completion (and verb generation in one experiment). Less activity was evoked (compared with rest) in visual processing areas and left inferior prefrontal cortex for the second to fifth presentations compared with initial presentation. Priming effects in the prefrontal and inferior temporal cortical areas were also found to occur when the cueing stimuli were presented auditorily, suggesting that these effects were not specifically tied to the visual modality. The magnitude of the priming effect did not change across repetitions in this study, suggesting that these priming effects did not necessarily contribute to learning after the first repetition, which would be required in the development of expertise.

Two studies have examined the neural response to faces that were repeated up to five times. In a study by Jiang *et al.* (2000), participants performed a delayed-match-to-sample task in which the non-target stimuli were repeated up to five times. Fusiform areas, which are often found to exhibit elevated responses to faces (Kanwisher *et al.*, 1997), exhibited decreasing activity to repeated presentations of the face stimuli. Henson *et al.* (2000) found a similar pattern of decreasing activity in the fusiform gyrus for familiar faces, while unfamiliar faces appeared to evoke successively increasing activity over repetitions. The changes in activation over multiple stimulus repetitions suggest that these fusiform regions might play a role in developing expertise in recognizing faces.

Activity in the fusiform gyrus during face perception has inspired the hypothesis that this area contains a module specialized for face perception (Kanwisher *et al.*, 1997). However, recent reports have suggested that this region of fusiform cortex may support processing of a wide range of complex stimuli for which visual expertise has been developed (Tarr and Gauthier, 2000). From this alternate theoretical perspective, this area of the fusiform gyrus is involved generally in visual expertise, and activity during face perception reflects the fact that humans are experts in face perception due to extensive experience. Participants who are experts in other domains, such as recognition of types of birds or cars, exhibited increased activity in this posterior fusiform region for those stimuli (Gauthier *et al.* 2000). Increased activity in this region for stimuli has also been reported for artificial stimuli in which participants acquired expertise (Gauthier *et al.*, 1999). These findings have sparked a debate over whether this brain region is involved narrowly in material-specific processing of faces (Kanwisher, 2000) or more broadly in the representation of expert visual knowledge (Tarr and Gauthier, 2000). This debate suggests that the fusiform gyrus is likely to play an important role in understanding the neural correlates of perceptual expertise and complex visual processing.

Other studies of the neural correlates of the development of expertise have focused on identifying shifts in patterns of

activity as expertise is developed. These studies have used procedural learning tasks and observed shifts from one network of activity early in learning to another after expertise is acquired (e.g. Petersen *et al.*, 1998). Poldrack (2001) reviewed a variety of skill learning procedures and found a tendency for increased ventral temporal lobe activity for relevant stimuli after learning. These studies have not examined the evolution of the cortical response to repeated stimuli and how this phenomenon may be related to development of perceptual expertise.

In the current study, priming was examined over eight presentations of novel pictures of familiar objects. Eight presentations allows for examining the changes in evoked activity beyond the second presentation, but is not sufficient to support the establishment of definite expertise for this task. Objects were used as stimuli instead of faces to provide an opportunity to examine processing changes for simple visual stimuli that do not have the special salience of faces. The level of evoked activity for each successive repetition of pictured objects was assessed throughout ventral visual cortical areas in order to identify areas exhibiting decreases from the first to the second presentation and/or exhibiting a consistent change in activity from the second to the eighth presentations. This analysis supported the assessment of different types of response curves (examining the magnitude of the response as a function of number of presentations), extending prior studies that have used multiple repetitions but focused mainly on the magnitude of the response after the multiple repetitions (e.g. Buckner *et al.*, 1998; Koutstaal *et al.*, 2001; Simons *et al.*, 2003).

Experiment 1: Neural Correlates of Priming over Multiple Stimulus Presentations

Materials and Methods

Participants

Nine healthy right-handed volunteers participated in the experiment (three men, six women, age range 18–38 years). Participants were screened for compatibility with MRI and history of neurological or psychiatric problems. All participants provided informed consent according to the guidelines of the Northwestern University Institutional Review Board.

Materials

A set of 72 pictures of simple, everyday objects was selected from a catalog of images (Photodisc, <http://www.photodisc.com>). Objects used included an assortment of office items, household items, small animals, and musical instruments. Each picture shows a single object on a white background (see Fig. 1). Pictures were back-projected onto a screen visible from within the scanner via a mirror mounted over the participant's eyes. Images subtended a visual angle of 3–5°. The objects were organized into 12 separate lists (each containing six items) and each participant was shown a randomly selected set of four or five of the lists. Within each list, stimuli were presented pseudo-randomly with the constraint that no stimulus was ever presented twice consecutively. In addition, two of the stimuli that were to be presented once only were introduced at the end of the scan in order to decrease the correlation between repetition number and stimulus order during a scan.

Procedure

Participants were shown pictures of objects one at a time, each for 750 ms. A picture of a baseball was designated as the 'target' object and was shown to all participants prior to scanning. For each stimulus presentation, the participants had to indicate whether or not it was the baseball. Within each scanning run, 30 stimuli were shown, including

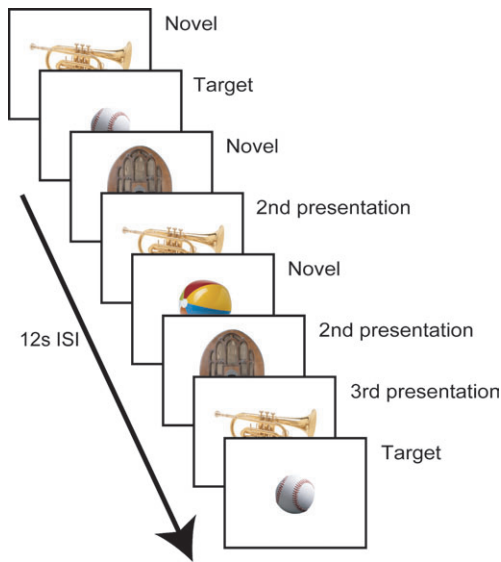


Figure 1. Example stimulus sequence presented during scanning. Participants responded via button press whether or not the object was the target (baseball). Objects were presented every 12 s. Non-target objects repeated up to eight times within a scanning run. All objects were novel to each run (except the target).

the target item four times. To respond correctly, participants should respond ‘yes’ (via fiber-optic button press) to the four targets and ‘no’ (via button press) to the 26 non-targets. Six different non-target stimuli were shown in each run. Two stimuli were shown eight times within the run, two were shown four times and two were shown only once. Thus, there were six instances of non-target objects being shown for the first time, four instances in which an object was shown for a second, third or fourth time, and two instances of an object being shown for either the fifth, sixth, seventh or eighth time. After each presentation there was an 11.25 s inter-trial interval to allow for separation of the hemodynamic response to each stimulus. Participants each completed five or six runs (two and seven participants respectively) of the priming task.

Imaging Methods

A Siemens Vision 1.5 T magnet and head coil were used. The subject’s head was comfortably secured using padding and a vacuum-immobilizer pillow. Stimuli were displayed with an LCD projector onto a rear-projection screen and viewed through a mirror. In all but one run, 16 4-mm slices of T2*-weighted gradient-recalled echoplanar images (EPI) were collected during the study task ($T_R = 2000$ ms, $T_E = 40$ ms, flip angle = 90° , FOV = 25.6cm). Slices were oriented along the AC/PC line (slightly oblique from transverse) and placed to cover primary and ventral visual areas and the inferior frontal lobe with a resolution of 4 mm^3 . In each run, 184 volumes were collected (four initial volumes to reach steady state and 180 volumes during the priming task). In the final functional run, four slices (4 mm) of EPI data were collected with a T_R of 750 ms with two slices placed to cover the calcarine sulcus and two through the ventral visual cortical areas. Participants performed the same priming task during this run and the increased temporal resolution of this data was used to better estimate the individual hemodynamic response to visual stimuli in the data analysis. For anatomical localization, 3DFLASH T1-weighted images ($T_R = 15$ ms, $T_E = 5.6$ ms, flip angle = 20° , 160 1-mm axial slices, FOV = 240mm, 256×256 matrix) were acquired at the end of the session.

Data Analysis

Data were motion corrected through time, spatially smoothed (3-D Gaussian kernel, 7.5 mm full-width half-maximum) and transformed to standard stereotactic space (MNI_305). Low frequency noise (e.g. linear drift) was removed from all time series prior to further analysis.

The hemodynamic response to object presentation was estimated individually for each participant based on the final, rapid scan in which the $T_R = 750$ ms provided 16 points along the 12 s hemodynamic response

curve. All responsive voxels were averaged together for all trials to provide a single estimate of the hemodynamic response function (*brf*) for each participant. For the other four or five runs, the response to each object presentation was modeled as a best-fitting single parameter multiplied by the participant’s *brf* (using a general linear model for each object response). This parameter is an estimate of the strength of response, with higher numbers indicating a stronger evoked response to the object presentation. These strength parameters were treated as the main elements for analyses examining areas exhibiting different types of priming responses. To identify visually responsive areas, the average response strength was compared with zero. To identify areas exhibiting a reduction in response strength from the first to the second stimulus presentation, the strength parameters for those presentations was compared. Linear regression on the response strengths was used to estimate change from the second to the eighth presentation. Each of these three analyses was performed on each voxel within each participant. Identification of areas exhibiting consistent, reliable activity change was done using a random effects analysis on the effect sizes across the group of participants. Areas exhibiting reliable changes in activity were clusters of greater than 350 mm^3 in which the statistical difference in each voxel was $t(8) > 3.353$ ($P < 0.01$ uncorrected). Simulations of the data analysis process with random numbers indicated a probability of falsely identifying a cluster meeting these criteria as reliable was < 0.05 across the volume imaged.

Results

Task Performance

Participants performed the target-identification task at near-ceiling levels. No error responses were observed on non-target trials (the majority, 26/30, of trials per run). For one participant, the button box failed to record a response on 66/180 (37%) trials although the participant reported responding. Two participants each failed to record a ‘yes’ response to one target over the five or six runs (20 or 24 targets), which could reflect either a miss or a response box failure. One participant made two errors (of 24 targets), responding ‘no’ (followed by a ‘yes’ response) to the target in addition to having two target trials with no response. Because of the overall high accuracy rate, all trials were included for analysis of the fMRI data.

Difficulties with the fMRI-compatible response box led to a failure to record reaction times (RT) for two participants (for an additional participant, reaction times were only recorded on 28% of trials). The limited amount of RT data made the examination of the behavioral effect of priming difficult to assess in the fMRI Experiment (see experiment 2). The mean \pm SE RT to the first presentation of stimuli in the available data was 585 ± 18.9 ms and that to the second and subsequent presentations was 561 ± 25.5 ms, although this difference was not reliable [$t(7) = 1.47$, $P < 0.20$]. Average reaction times from the second through the eighth presentations were 564, 564, 562, 566, 567, 560 and 558 ms, respectively. No trials were eliminated due to unusually long RTs.

Neuroimaging

Reliable evoked responses were observed throughout occipital and temporal visual cortical areas. To identify areas exhibiting priming effects, changes in the level of evoked activity were assessed for all non-target items across the (up to) eight presentations. Two different types of repetition effects were assessed with two separate analyses. The first analysis examined areas that exhibited the most common repetition effect, a change in activity between the first and second presentation. The brain areas exhibiting reliably reduced after a single

repetition (from the first to the second presentation) are shown in red/orange in Figures 2 and 3.

A second analysis identified areas that exhibited changes in activity beyond the second presentation by assessing linear changes from the third to the eighth stimulus repetition. Brain areas exhibiting reliable decreases from the second presentation through the eighth presentation are shown in blue in Figures 2 and 3. In particular, this analysis identified an area in the right fusiform cortex ($x = +34, y = -55, z = -13$) that exhibited a linearly decreasing response across all eight presentations among the group of participants (Fig. 2, shown in blue). Because the two analyses are independent, it is possible for both effects to be observed in the same voxels although the two effects were largely observed in separate areas. A small area of overlap in the right fusiform gyrus is shown in green in Figure 2 ($x = +34, y = -59, z = -11$) that exhibits both a reliable decrease from the first to the second presentation and additional decreases from the second to the eighth presentation. A summary of the regions in which reduced activity (priming)

was observed for the second presentation or from the second to the eighth presentations is shown in Table 1.

Because the fifth to eighth stimulus repetitions are necessarily presented at the end of an fMRI scan, a trend towards smaller responses later in the scan (e.g. due to fatigue or loss of attention) might produce a similar effect to the observed linear decreases. Since there are novel presentations of objects at both the beginning and end of each scan (see Materials), we examined the average responses to just these stimuli as a function of stimulus order. No brain regions were identified that exhibited a reliable decrease in activity to novel stimuli presented towards the end of a scan compared with novel stimuli presented at the beginning of a scan.

To examine whether the responses over stimulus repetitions were reliably different in these two regions of right fusiform cortex, an ANOVA was used to compare the response patterns [2 regions of interest (ROIs) \times 8 presentations, within-subjects]. This analysis indicated a main effect of repetition [$F(1,8) = 41.8, P < 0.001$], a significant ROI \times repetition interaction

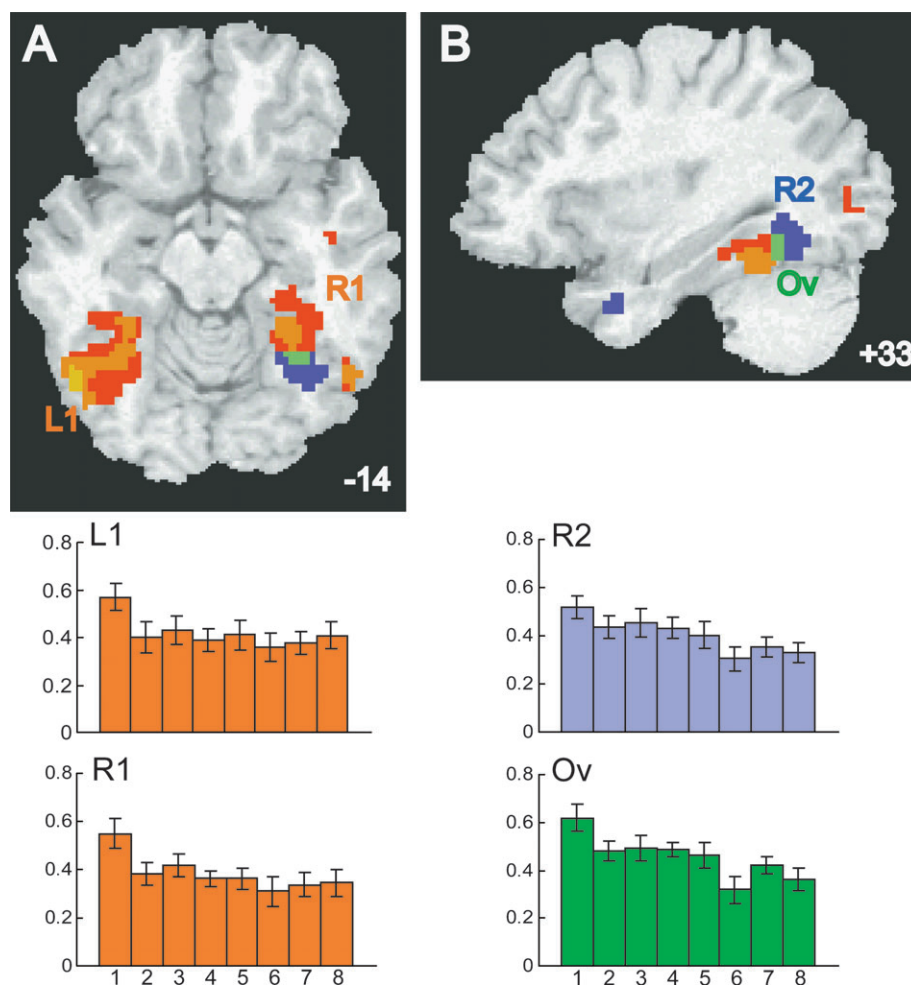


Figure 2. Priming responses in ventral occipito-temporal cortex (BA 19/37). Areas exhibiting a reliable decrease for the second presentation of a stimulus (compared with novel stimuli) are shown in red/orange colors. Areas exhibiting a reliable decrease in activation across the second to the eighth presentation of a repeated stimulus are shown in blue. The green region reflects an area of overlap in which the responses were significantly lower from first to second presentation and then continued to decrease from the second to the eighth presentation. (A) Axial slice at the level of -14 mm in atlas space. Left side of the brain is shown on the left side of the image. (B) Sagittal slice 33 mm right of midline. Average response strength for four regions of interest across the eight presentations is shown at the bottom. Values on the y-axis reflect the average strength of response estimated for each stimulus presentation (see Materials and Methods) from the first to eighth stimulus presentation (x-axis). (L1) Average response in the large left ventral occipito-temporal region exhibiting priming for the second presentation. (R1) Average response in the right ventral occipito-temporal region exhibiting priming for the second presentation. (R2) Average response for the right posterior fusiform region exhibiting a linear decrease in response from the second to the eighth presentation. (O) Average responses in the overlap region.

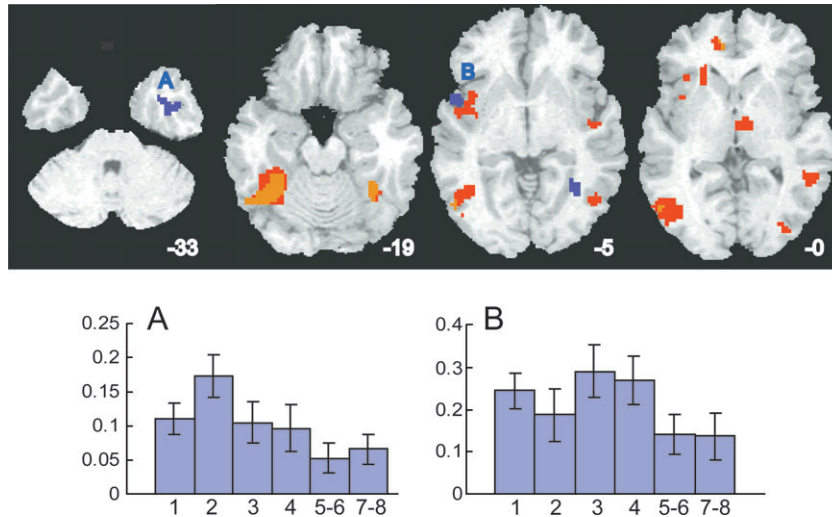


Figure 3. Additional areas of the brain exhibiting priming effects. Areas exhibiting a reliable decrease for the second presentation of a stimulus (compared with novel stimuli) are shown in red/orange colors. Areas exhibiting a reliable decrease in activation across the second to the eighth presentation of a repeated stimulus are shown in blue. Average response strengths are shown at the bottom for two areas exhibiting a reliable linear decrease across the eight presentations. Values on the y-axis reflect the average strength of response parameter for each stimulus presentation (see Materials and Methods). Stimulus presentation numbers are shown on the x-axis with the fifth/sixth and seventh/eighth responses averaged for clarity. (A) Anterior inferior temporal cortex. This region appears to exhibit an increased response for the second presentation although the overall pattern of response is decreasing across stimulus repetitions. (B) Insula. This region appears to exhibit an increased response for the third and fourth presentations although the overall pattern is also decreasing across stimulus repetitions.

[$F(1,8) = 6.16, P < 0.05$] and no reliable difference in overall activity across ROIs [$F(1,8) = 0.131$]. The linear decrease reflects the fact that, for both ROIs, the response to the first presentation is higher than the others. The interaction between repetition and ROI reflects the fact that these two regions have different patterns of response decrease over the eight stimulus presentations.

Several additional areas were identified in which there was a consistent linear trend for a decrease from the second to the eighth trials, but this effect appears to be driven by an increase in activity that was observed for the second or third presentation (Fig. 3). Caution should be applied to the interpretation of these apparently non-linear results as the analysis that identified these regions was validated to identify a reliable slope (from the second to the eighth presentation) and estimates of the individual points along the response curve could be highly variable.

Discussion

The most widespread effect of repeated presentation of visual objects was a reduction in activity from the first presentation of the object to the second presentation. A smaller region of the posterior fusiform cortex exhibited additional decreases over multiple repetitions, suggesting that additional learning was occurring beyond the second presentation of a stimulus. The observed neural correlates of priming are qualitatively similar to previous studies of repetition priming. The absence of a reliable behavioral correlate of priming (RT decrease) in experiment 1 was addressed in experiment 2.

Experiment 2: Assessing the Behavioral Effect of Priming

The difficulties with accurately assessing the behavioral correlate of priming in experiment 1 left open the question of whether the simple object recognition paradigm used here would lead to a faster, primed response on the second and subsequent stimulus presentations. A

Table 1

Brain regions exhibiting priming effects

Region	Talairach atlas coordinates			Volume (mm ³)
	x	y	z	
Areas exhibiting decreased response for the second presentation				
Left fusiform gyrus (BA 37)	-42	-58	-10	11 469
Included subclusters:				
Left middle occipital gyrus	-47	-71	0	
Left posterior fusiform gyrus	-36	-72	-13	
Left anterior fusiform gyrus	-34	-38	-19	
Right fusiform gyrus (BA 37)	33	-46	-15	3016
Right middle temporal gyrus (BA 22/37)	54	-53	4	1516
Right middle occipital gyrus (BA 19/37)	50	-64	-9	1062
Right thalamus	8	-9	3	1016
Right superior temporal gyrus (BA 22)	47	-11	-8	984
Left insula	-43	1	-5	859
Left insula/prefrontal cortex (BA 13/45)	-30	24	2	594
Left anterior cingulate (BA 32)	-11	44	-1	438
Right middle occipital gyrus (BA 18/19)	38	-84	4	422
Left superior temporal gyrus (BA 41)	-47	-26	9	422
Areas exhibiting linearly decreasing responses for the second to the eighth presentations				
Right fusiform gyrus (BA 37)	34	-59	-11	2094
Right inferior temporal lobe (BA 20/38)	39	2	-34	719
Left insula	-51	7	-7	609

separate group of participants performed the same task without fMRI data collection in order to assess the magnitude of priming in reaction time to repeated stimulus presentations.

Materials and Methods

Participants

Forty-two undergraduate students at Northwestern University received partial course credit for participation.

Procedure

Each participant performed the same simple object recognition task as the participants in experiment 1 (respond 'yes' to the target baseball, 'no' to all other objects). To increase the number of responses that could be collected during the experiment, the inter-trial interval was reduced

from 11.25 to 2 s. Each participant received 11 randomly selected stimulus lists, each containing 30 trials (4 targets/list).

Results

Average reaction times are shown in Figure 4. Reaction time to trials when an object was presented for the second time were reliably faster than the initial presentation of the object [$t(42) = 8.20, P < 0.001$]. There was no additional decrease in reaction time to objects presented from the second to the eighth repetition [$F(1,41) = 0.823$].

Discussion

The reaction time data are consistent with the overall pattern of effects observed as the neural correlates of repeated object presentation. The majority of brain regions exhibit the largest change in activity from the first to the second presentation, and this is reflected in the largest drop in reaction time from the first to the second presentation. Although our major finding was that the posterior right fusiform region exhibited additional decreases in activity from the second to the eighth presentation (experiment 1), this effect was not reflected in the reaction times observed in experiment 2. The fact that the reaction times were not observed to decrease from the second to the eighth presentations suggests that eight repetitions is insufficient to establish behaviorally detectable expertise in this task. One possibility is that the target-detection task is so simple that participants have achieved a maximally fast response by the second presentation, i.e. any further learning is hidden by a floor effect in the reaction times. In this case, visual expertise with the stimuli may be developing that is not reflecting in the available behavioral measure.

General Discussion

The posterior fusiform cortex of the right hemisphere exhibited a continually decreasing response across all eight stimulus presentations and is therefore a good candidate to be a brain area supporting the development of visual expertise. Sizeable additional areas in both the right and left fusiform cortex showed a reliable decrease on the second stimulus presentation, but no further reductions. These areas may be involved in visual repetition priming or novelty detection, but are unlikely to be involved in the acquisition of visual expertise. The development of visual expertise requires many trials, and the brain areas supporting it should show an incremental influence of multiple presentations, as in the case of the right posterior fusiform cortex. Neither of the response analyses was biased

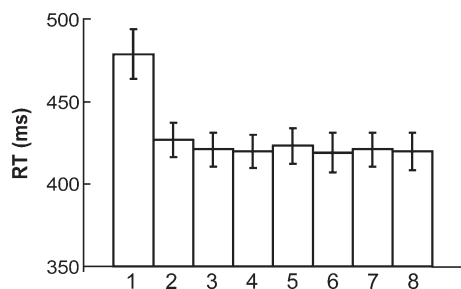


Figure 4. Reaction times over multiple repetitions of stimuli. Participants were faster to identify non-target stimuli on the second and subsequent repetitions of those stimuli. No reliable decrease in reaction times occurred from the second to the eighth stimulus presentations.

towards identifying decreases over increases in activity, but no significant brain regions were identified that exhibited a reliable increase in activity from the first to the second presentation or exhibited a consistent linear increase from the second to the eighth presentations. However, it should be noted that the imaging protocol used here selectively focused on the visual cortex and temporal lobes, so that other areas that may have exhibited increases over multiple repetitions (e.g. the parietal cortex or cerebellum) would not have been observed.

Response Curves

The key findings are based on the identification of the shapes of the curves relating the strength of response to the number of repetitions of the object. The shape of this curve was shown to be reliably different in the right posterior fusiform cortex compared with the anterior fusiform cortex. The anterior areas bilaterally (and posterior fusiform on the left) exhibit a response pattern that appears to follow a step function, with a large drop in activity followed by a consistent response to additional stimulus presentations. In the posterior fusiform area, there is a non-overlapping area that didn't exhibit the large reduction from the first to second presentation but did exhibit a linearly decreasing response for each stimulus repetition. A small overlapping area exhibited both the initial drop and subsequent decreases. This overlap region may reflect a mixture of the two types of response either due to blurring (via spatial smoothing and anatomical co-registration) or reflecting overlapping neural correlates of two cognitive processes.

In behavioral studies of expertise, the relationship between improvement in performance and stimulus repetition has been assessed and generally found to follow a power law in shape (e.g. Logan, 1988). The shape of a power-law curve has a both a steep initial change (drop) followed by continual gains with practice. Previous studies of visual priming have consistently reported a reliable decrease in activity from the first to the second presentation, indicating there was no real question that we would identify a response curve that looked like the initial, steep, part of a power law function. To address the main theoretical question, whether there would be additional changes in activity over additional presentations, is equivalent to distinguishing between a power-law curve and a true step function. The most effective way to accomplish this is to examine the change in activity across the second to eighth repetitions and identify regions that showed a reliably non-zero slope (indicating learning, whereas a zero slope suggests a step function). Our approach of fitting a linear decrease in response from the second to the eighth presentation captures learning effects that follow a power law shape. It should additionally be noted that the power law of learning has typically been used to describe the end result (in behavior) of the cumulative effect of the learning effects across different regions of the brain. Our results have identified two distinct learning profiles in different areas of the brain that represent separate processes that support the expression of learning in behavior.

Hypotheses about the shape of the response curve to multiple repetitions can also be drawn from neurophysiological studies of 'response suppression' in the monkey. This phenomenon describes the observed reduction in neural firing in inferior temporal lobe for repeated stimuli (Desimone, 1996). Wiggs and Martin (1998) proposed that the observed reductions in BOLD activity during studies of priming are based on a similar phenomenon in humans. Wiggs and Martin (1998) also

pointed out that repetition suppression is a graded phenomenon that increases in magnitude with additional repetitions of stimulus presentation (Li *et al.*, 1993). By examining activity reductions (via BOLD fMRI) across multiple repetitions, our findings extend the idea of Wiggs and Martin to suggest that there are different types of repetition suppression in visual cortex: one type for which the suppression is equal for all stimulus repetitions after the first, and a more specific response for which the suppression is graded over repetitions.

Two previous studies have examined the evolution of repetition suppression effects over multiple repetitions (Henson *et al.*, 2000; Jiang *et al.*, 2000). Both of these studies found continuing decreases in activity over five repeated presentations of faces or symbols (but only for familiar faces and symbols in Henson *et al.*, 2000). However, these reports found relatively smaller areas exhibiting priming effects and did not identify areas exhibiting different response curves over stimulus repetitions. Object repetition produces more widespread priming effects and serves as a better paradigm for examining the shape of response curves to multiple repetitions across a variety of brain regions.

A previous study of word-stem completion (Buckner *et al.*, 2000) did not identify any regions exhibiting continually decreasing responses after the second repetition. This report found robust priming effects in left fusiform cortex in regions similar to our priming effects from the first to second presentation. The differences between those results and ours may be due to the use of word-stem stimuli in that study. Word-stems are text that is more abstract than the photographs and may also be more familiar (due to our extensive experience with text in general). However, the differences could have arisen because Buckner *et al.* (2000) relied on a block design in which an entire list of words was repeated whereas the event-related design with individually estimated hemodynamic response functions used here may be more effective at estimating the response curve.

The reduction in response found in both neurophysiological and neuroimaging data suggests a learning mechanism within visual cortical areas that increases efficiency in visual processing for repeated stimuli (e.g. by creating 'sharper' representations). This type of mechanism can be captured within a connectionist system using a Hebbian learning mechanism (e.g. Stark and McClelland, 2000). Models based on specific mechanisms will be strongly constrained by the shapes of the priming-response curves observed in neuroimaging experiments. Additional time-course hypotheses can be evaluated with this technique as well. For example, Hauptmann and Karni (2002) suggested that repetition priming has to 'saturate' before long-term consolidation can occur for perceptual learning. If this hypothesis is accurate, then it should be possible to identify the saturation point in repetition priming and observe the neural correlates of the effects of perceptual learning that lasts for a longer period of time.

To test detailed theories of learning mechanisms within visual cortex, it would be useful to be able to conclude that the responses observed in areas such as the right and anterior left fusiform are truly equivalent from the second to the eighth presentation. While we found that the response curves in those regions are reliably different from the right posterior fusiform, most learning models propose negatively accelerated response curves (e.g. following a power law or exponential). Thus, there could be small learning effects over later repetitions that would

require a high degree of sensitivity for detection. Further complicating the interpretation of the apparently flat response curves is the report by Henson *et al.* (2000) of increased activity over repetitions for unfamiliar stimuli. Since familiarity would also develop over repetitions, there could be regions exhibiting a complex response curve that reflected a combination of repetition priming effects (decreases) and the development of familiarity with the specific stimuli (increases). These concerns do not challenge the interpretation of our principle findings about the response curves in fusiform cortex, but suggest that this initial result is likely to be identifying only part of the network of brain areas supporting the development of visual expertise.

Two brain regions with unusual response curves may provide examples of areas supporting specific processes in expertise. In the left insula and right anterior temporal lobe there was increased activity in the second or third presentation, although the general trend was for a decrease in activity over the course of the eight stimulus repetitions, (Fig. 3A,B). Increased left insula activity was reported by van Turennout *et al.* (2000) during the second presentation of an object that was to be named. Although the current task was simply to detect a target, participants might have spontaneously named the objects and the transient increase might reflect an increase in processing verbal labels during the second presentation. The anterior, inferior temporal lobe has been associated with memory storage (Miyashita, 1993) and the apparent transient increase may reflect some element of declarative memory storage. However, detailed interpretation of the fine-grained structure of the time course is essentially speculative, as the data analysis was not designed to identify areas of transient increase. A detailed study of the effect of multiple repetitions on these types of cognitive processes would need a whole-brain imaging protocol and a procedure designed to provide some external validity about the processing associated with each stage of the experiment (e.g. assessing naming, examining the role of declarative memory).

Priming and the Fusiform Gyrus

Most previous reports examining priming-related response reductions for objects reported effects in regions similar to the large bilateral fusiform regions found here to show a reduction in activity from the first to the second stimulus presentations (e.g. Buckner *et al.*, 1998, 2000; van Turennout *et al.*, 2000; Koutstaal *et al.*, 2001; Vuilleumier *et al.*, 2002). This region was suggested to be the site of an amodal component of word-repetition priming in Buckner *et al.* (2000). The common finding of priming effects in this area across stimulus types and modality suggests that this region is involved in aspects of semantic memory retrieval that are facilitated with repetition.

Previously reported priming effects may also overlap with the region of right posterior fusiform cortex identified here as being involved in the acquisition of expertise, but the different response curves cannot be observed in paradigms that rely on a single stimulus repetition. Koutstaal *et al.* (2001) suggested that the right posterior fusiform cortex was involved in identification of specific objects as this region was found to exhibit a greater priming response to specific object repetition compared with priming across objects within a category (other brain regions exhibited greater category-specific priming). Similarly, Simons *et al.* (2003) found that right posterior fusiform activity exhibited greater priming for object repetition

than for category repetition. An interaction between the left and right fusiform activity was reported in Simons *et al.* (2003) that, like our results, suggests different types of processing across hemispheres. Our result is consistent with the conclusion of these reports that repeated experience with specific exemplars affects processing selectively in the right fusiform gyrus and extends this to suggest that this region supports the development of expertise with specific stimuli.

The right posterior fusiform area implicated here in supporting the development of perceptual expertise is intriguingly close to the fusiform area that has been implicated in the processing of human faces (FFA; Kanwisher *et al.* 1997). Tarr and Gauthier (2000) have suggested that this part of the fusiform gyrus may instead be activated by fine-grained discrimination among similar stimuli for which perceptual expertise has been established (such as faces). Gauthier *et al.* (2000) found increased activity in this area for specific visual domains in participants who were experts in that domain (birds, cars) and also when participants had acquired expertise with artificial stimuli (Gauthier *et al.* 1999). The current result linking the right posterior fusiform cortex to the acquisition of expertise is consistent with the idea that this brain region is involved in domain-general processing of well-learned stimuli. However, since we did not identify the FFA individually for these participants, we cannot be sure that the right fusiform area identified here is precisely in the same location as the FFA.

To connect our finding based on repetition priming to the development of domain expertise, it will be necessary to resolve a difference in the pattern of activity observed in the fusiform cortex in these two types of studies. Here, activity was found to decrease with stimulus repetitions, whereas in the Gauthier *et al.* (1999, 2000) reports, increased activity was observed in this area in response to stimuli for which expertise had been acquired. The different direction of activity change does not rule out the possibility that similar perceptual expertise processes are involved in both the current task and the findings of Gauthier *et al.* (1999, 2000). Both increases and decreases have been observed for stimulus repetitions, depending on the familiarity of the stimuli (Henson *et al.* 2000). In addition, our simple object identification task may not require the difficult, fine-grained discriminations suggested to be crucial in Gauthier *et al.* (1999, 2000). Perhaps most significantly, increases were observed when examining domain expertise generalized to novel stimuli, where the current task focused on multiple stimulus repetitions (without generalization). As noted previously, connecting priming to the development of expertise will require two elements: continuing effects over multiple repetitions and generalization to novel stimuli in the domain. Our procedure focused on the former, while studies of perceptual changes in experts reflected both components.

Conclusion

Extensive areas of bilateral fusiform cortex exhibited the traditional priming response to a second presentation of a stimulus, namely a reliable decrease in activity that is analogous to the repetition suppression effect observed in non-human primates. Posterior right fusiform cortex exhibited a continually decreasing response as stimuli were repeatedly presented up to eight times, a different response pattern than the majority of areas that exhibited priming effects. This response curve makes this area a prime candidate to support the acquisition of visual expertise in the perception of objects. The localization of this

process in right posterior fusiform cortex suggests that it may be part of the system supporting domain-general expertise described by Gauthier *et al.* (1999, 2000).

Notes

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