

Visual Scene Processing in Familiar and Unfamiliar Environments

Russell A. Epstein, J. Stephen Higgins, Karen Jablonski and Alana M. Feiler
J Neurophysiol 97:3670-3683, 2007. First published Mar 21, 2007; doi:10.1152/jn.00003.2007

You might find this additional information useful...

This article cites 61 articles, 19 of which you can access free at:

<http://jn.physiology.org/cgi/content/full/97/5/3670#BIBL>

Updated information and services including high-resolution figures, can be found at:

<http://jn.physiology.org/cgi/content/full/97/5/3670>

Additional material and information about *Journal of Neurophysiology* can be found at:

<http://www.the-aps.org/publications/jn>

This information is current as of May 21, 2007 .

Visual Scene Processing in Familiar and Unfamiliar Environments

Russell A. Epstein, J. Stephen Higgins, Karen Jablonski, and Alana M. Feiler

Department of Psychology and Center for Cognitive Neuroscience, University of Pennsylvania, Philadelphia, Pennsylvania

Submitted 2 January 2007; accepted in final form 15 March 2007

Epstein RA, Higgins JS, Jablonski K, Feiler AM. Visual scene processing in familiar and unfamiliar environments. *J Neurophysiol* 97: 3670–3683, 2007. First published March 21, 2007; doi:10.1152/jn.00003.2007. Humans and animals use information obtained from the local visual scene to orient themselves in the wider world. Although neural systems involved in scene perception have been identified, the extent to which processing in these systems is affected by previous experience is unclear. We addressed this issue by scanning subjects with functional magnetic resonance imaging (fMRI) while they viewed photographs of familiar and unfamiliar locations. Scene-selective regions in parahippocampal cortex (the parahippocampal place area, or PPA), retrosplenial cortex (RSC), and the transverse occipital sulcus (TOS) responded more strongly to images of familiar locations than to images of unfamiliar locations with the strongest effects (>50% increase) in RSC. Examination of fMRI repetition suppression (RS) effects indicated that images of familiar and unfamiliar locations were processed with the same degree of viewpoint specificity; however, increased viewpoint invariance was observed as individual scenes became more familiar over the course of a scan session. Surprisingly, these within-scan-session viewpoint-invariant RS effects were only observed when scenes were repeated across different trials but not when scenes were repeated within a trial, suggesting that within- and between-trial RS effects may index different aspects of visual scene processing. The sensitivity to environmental familiarity observed in the PPA, RSC, and TOS supports earlier claims that these regions mediate the extraction of navigationally relevant spatial information from visual scenes. As locations become familiar, the neural representations of these locations become enriched, but the viewpoint invariance of these representations does not change.

INTRODUCTION

As we move through the world, we use visual information to orient ourselves in space. Orientation can occur on many different spatial scales. In the simplest case, we can use local cues to determine our location and bearing within the currently visible environment. We can do this even if we are unaware of how the local environment relates to the wider world—for example, after emerging from a subway at an unfamiliar location. However, if we have prior experience with the environment—for example, with the neighborhood around the subway stop—then an additional degree of orientation becomes possible. In this case, inspection of the local visual scene can provide information about where we are within a larger space that extends beyond the current horizon. As these observations indicate, the degree to which visual scenes provide information relevant to spatial orientation depends on their familiarity. As such, it is reasonable to suppose that visual scene processing might be modulated by prior experience.

In the current study, we tested this idea by using functional magnetic resonance imaging (fMRI) to measure the neural response to familiar and unfamiliar scenes. By “visual scene” we mean a section of the world that is potentially visible from a single vantage point, such as a view of a room, a landscape, a city street, or an image of such a section of the world (Henderson and Hollingworth 1999; Intraub 1997) (see Fig. 1). In this usage, the term “scene” contrasts with the term “object,” which we use to refer to decontextualized compact entities such as faces, cars, and chairs (Epstein 2005). We hypothesized that scenes from familiar environments might engage orientational or memory systems not engaged by scenes from unfamiliar environments or engage qualitatively different representations within these systems. We further hypothesized that these differences might be relatively automatic, occurring even when subjects do not explicitly attempt to use the scenes for spatial orientation.

Previous neuroimaging studies have identified three regions that respond more strongly to visual scenes than to visual objects: the parahippocampal place area (PPA) (Epstein and Kanwisher 1998), retrosplenial cortex (RSC) (O’Craven and Kanwisher 2000), and the transverse occipital sulcus (TOS) (Epstein et al. 2005; Grill-Spector 2003; Hasson et al. 2003). The current study focused primarily on these regions, which we previously argued might play a role in extracting information from visual scenes that is useful for spatial orientation (Epstein 2005; Epstein and Kanwisher 1998). Consistent with this idea, neuroimaging studies that have found increased PPA and RSC activity during simulated and mental navigation (Aguirre et al. 1996; Ghaem et al. 1997; Ino et al. 2002; Maguire et al. 1997, 1998; Rosenbaum et al. 2004), and neuropsychological studies indicate that damage to these regions leads to impaired ability to recognize scenes and orient oneself spatially within the larger environment (Aguirre and D’Esposito 1999; Bohbot et al. 1998; Epstein et al. 2001; Habib and Sirigu 1987; Katayama et al. 1999; Maguire 2001; Mendez and Chierri 2003; Takahashi et al. 1997).

Although these results suggest the possibility that scene processing in the PPA, RSC, and TOS might be affected by familiarity with the environment from which the scene is drawn, previous studies have not found clear evidence for this idea. For example, an earlier study from our group observed no significant main effect of environmental familiarity on the response to scenes in the PPA (Epstein et al. 1999). However, the number of subjects was relatively small ($n = 8$) and response in the TOS and RSC was not examined. Indeed, somewhat counter to our results, a recent study by Rosenbaum

Address for reprint requests and other correspondence: R. Epstein, Dept. of Psychology, University of Pennsylvania, 3720 Walnut St., Philadelphia PA, 19104-6241 (E-mail: epstein@psych.upenn.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.



FIG. 1. Examples of stimuli. Three views were taken of each campus location. Locations were selected to be easily recognizable to students from the respective campuses and consisted of landmarks such as buildings, statues, street scenes, and crossways.

and colleagues (2004) found greater response to familiar landmarks than to unfamiliar buildings in a posterior parahippocampal/lingual region that may adjoin the PPA. However, the data in this study were analyzed using a whole-brain analysis rather than a region of interest analysis, so the overlap between the activated region and the PPA was unclear. Furthermore, the possibility of familiarity effects in the RSC and TOS could not be excluded.

fMRI studies have also examined the degree to which representations in scene processing regions are viewpoint specific (i.e., different views of a scene evoke different representations) versus viewpoint invariant (i.e., different views of a scene evoke the same representation). An initial experiment with unfamiliar tabletop scenes indicated that scene processing within the PPA is largely viewpoint specific (Epstein et al. 2003) consistent with behavioral results (Chua and Chun 2003). More recent results indicate that some degree of viewpoint invariance might develop within the PPA as subjects become familiar with the scenes over the course of an experimental session (Epstein et al. 2005) or if the differences between viewpoints are relatively small (Ewbank et al. 2005). These results suggest that familiarity with scenes obtained through real-world experience with a familiar environment might lead to the formation of viewpoint-invariant representations that might facilitate the recognition of real-world locations from different views. Alternatively, these results might simply reflect a temporary within-session facilitation of scene processing that has little to do with long-term changes caused by real-world navigational experience. The current study was intended to distinguish between these possibilities within the PPA and also to extend the previous results to scene-processing regions outside of the PPA.

Subjects in the current study were students from the University of Pennsylvania and Temple University, and stimuli were photographs of locations on the two university campuses. Subjects were highly familiar with their own college campus but had only minimal experience with the other college campus. We tested for effects of environmental familiarity in two ways. First, the overall magnitude of the fMRI response to photographs of the familiar college campus was compared with the magnitude of response to photographs of the unfamiliar college campus. We reasoned that cortical regions involved in spatial orientation would be more strongly engaged when viewing images of the familiar campus than when viewing images of the unfamiliar campus because information about the world extending beyond the boundaries of the photograph is only available for the familiar campus. Second, the reduction of response observed on repetition of a scene was compared for scenes obtained from familiar and unfamiliar environments. These repetition suppression (RS) effects (sometimes referred

to as fMRI adaptation effects) are believed to index processing overlap between the original and repeated item (Grill-Spector and Malach 2001). In particular, reduction in response observed on repetition of the same item from a different viewpoint is taken as evidence for processing that has at least some degree of viewpoint invariance, whereas reduction of response observed only on repetition of the same item from the same viewpoint is taken as evidence for processing that has at least some degree of viewpoint specificity (Epstein et al. 2003, 2005; Ewbank et al. 2005; Grill-Spector et al. 1999; James et al. 2002; Vuilleumier et al. 2002). We hypothesized that the degree to which scenes are processed in a viewpoint-invariant versus viewpoint-specific manner might vary as a function of environmental familiarity.

We present data from two experiments. *Experiment 1* examined the effects of long-term (i.e., real world) familiarity on scene processing, whereas *experiment 2* examined the effects of both long-term familiarity with a college campus and short-term (i.e., within-scan-session) familiarity with specific scene images. To anticipate, we find that scene processing regions respond more strongly to familiar locations than to unfamiliar locations and that the viewpoint invariance of the processing depends on short-term (within-scan-session) familiarity; however, we find little evidence that long-term familiarity with a location leads to more viewpoint-invariant processing.

METHODS

Subjects

Healthy right-handed volunteers (28) were recruited from the University of Pennsylvania and Temple University communities and scanned with fMRI after giving written informed consent according to procedures approved by the University of Pennsylvania institutional review board. Of these 28 volunteers, 14 (7 from Penn; 7 from Temple) were run in *experiment 1*, and 14 (7 from Penn; 7 from Temple) were run in *experiment 2*. All subjects had normal or corrected-to-normal vision and were highly familiar with their home campus (average length of experience 3.0 ± 1.0 yr) but had at most minimal familiarity with the other campus.

MRI acquisition

Scanning was performed at the Hospital of the University of Pennsylvania on a 3 Tesla Siemens Trio equipped with a Siemens body coil and a four-channel head coil. T2*-weighted images sensitive to blood-oxygenation-level-dependent contrasts were acquired using a gradient-echo echo-planar pulse sequence (TR = 2,000 ms, TE = 30 ms, matrix size = 64×64 , voxel size = $3 \times 3 \times 3$ mm or $2.9688 \times 2.9688 \times 3$ mm, 33 axial slices). Stimuli were rear projected onto a Mylar screen at the head of the scanner with an Epson 8100 3-LCD projector equipped with a Buhl long-throw lens and viewed through a mirror mounted to the head coil.

Stimuli

A digital camera was used to collect images of various locations from the University of Pennsylvania and Temple University campuses. Three images of each location were taken from different views. *View 2* was a head on view of the scene, whereas *views 1* and *3* were viewpoint shifts of ~ 60 – 70° to the left and the right of the central view, respectively (Fig. 1). Stimuli were normalized for familiarity by a group of students at each school (Penn: $n = 12$; Temple: $n = 55$). The students rated the pictures on a scale of 1–4 in response to the question: “Do you recognize this place?” with 1 indicating the

response “Yes, and I am pretty sure where it is,” 2 indicating “Yes, but I don’t know where it is,” 3 indicating “Maybe, it looks familiar, but I am not sure,” 4 being “No.” The final stimulus set consisted of 144 pictures from each school (3 images each of 48 locators). Within this set, ratings on the normalization ranged from 1 to 2. The average score for Penn was 1.25 ± 0.27 and for Temple was 1.37 ± 0.30 .

Procedure

EXPERIMENT 1. Scan sessions consisted of six experimental scans followed by two functional localizer scans. Experimental scans were 9 min 16 s long and were divided into 80 6-s stimulus trials interspersed with 30 2-s “null” trials and a 16-s fixation period at the end of the scan. Functional localizer scans were 8 min 12 s in length and were divided into 16-s epochs during which subjects viewed digitized color photographs of faces, common objects, scenes, and other stimuli presented at a rate of 1.25 pictures/s in a blocked design as described previously (Epstein et al. 2005).

Each stimulus trial (Fig. 2) began with a 500-ms fixation cross followed by a 500-ms gray screen with a black outline, which alerted subjects to the forthcoming presentation of the visual scenes. After a 500-ms interval, two scenes were sequentially presented for 500 ms each with a 500-ms interstimulus interval. This was followed by a 3,000-ms poststimulus interval in which a fixation cross appeared on the screen and subjects used a button box to report whether the two scenes depicted the same location or different locations (irrespective of viewpoint). Response latencies were measured after the onset of the second stimulus. In null trials, the fixation cross remained on the screen for 2 s, and subjects made no response. In each trial, the two stimuli could either be identical (no-change trials), different views of the same location (viewpoint-change trials) or different locations from the same campus (place-change trials). These three trial types were crossed with environmental familiarity (Penn vs. Temple) in a 3×2 design.

As noted in the preceding text, the complete stimulus set consisted of three views each of 48 Penn and 48 Temple locations. Of these, images from eight Penn and eight Temple locations (2 views each, 1 of which was always the “head-on” view) were chosen for each scan and paired in different combinations to construct 16 Penn no-change, 8 Penn viewpoint-change, 16 Penn place-change, 16 Temple no-change, 8 Temple viewpoint-change, and 16 Temple place-change trials. Thus all three conditions for each campus were constructed from the exact same set of images. All told, subjects saw 192 different images ($2 \text{ campuses} \times 48 \text{ places} \times 2 \text{ views}$), each of which was shown five times within a scan but was not repeated across scans.

After completion of the experiment, participants completed a computer survey in which they had to rate all 96 images of the stimulus set in terms of real-world familiarity with the locations depicted. The

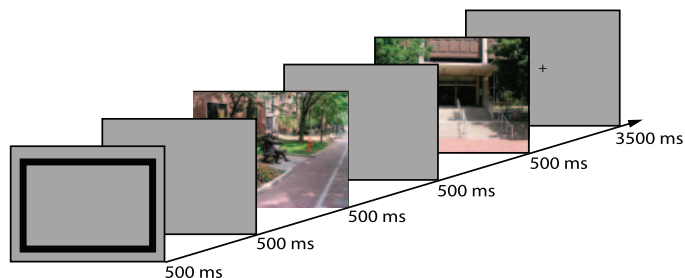


FIG. 2. Experimental procedures for *experiment 1*. Two scenes were shown sequentially in each trial. Scenes could either be identical (no-change trial), different views of the same location (viewpoint-change trial), or different locations from the same campus (place-change trial; depicted here). Subjects used a button box to indicate whether the two scenes depicted the same location or different locations. The procedure for runs 1–6 of *experiment 2* was similar.

pictures were rated on a scale of 1–4; 1 being “I know where this place is,” 2 being “I recognize the place but am not sure where it is,” 3 being “It looks somewhat familiar,” and 4 being “I have never seen this place before today.”

EXPERIMENT 2. The procedure for *experiment 2* was similar to the procedure for *experiment 1* with the following exceptions. A primary goal of this experiment was to measure the effect of within-session experience on scene processing. In particular, we aimed to compare the effects of short-term familiarity gained from displaying scenes multiple times within a scan session with the effects of long-term familiarity gained from multiple real-world encounters with the locations depicted in the scenes. To maximize the effects of within-session experience, we increased the number of exposures to each image beyond the five exposures in the preceding experiment. Given constraints on total scan session length, this was done by reducing the size of the stimulus set presented to each subject. For each subject, two views each of 16 Penn and 16 Temple locations were chosen from the larger stimulus set to serve as stimuli in scans 1–6. The choice of these locations was counterbalanced across subjects. Images of half of the chosen locations (8 Penn; 8 Temple) were used to construct trials in scans 1, 3, and 5, whereas images of the other half of the chosen locations were used to construct trials in scans 2, 4, and 6. All told, subjects saw 64 different images ($2 \text{ campuses} \times 16 \text{ places} \times 2 \text{ views}$), each of which was shown 15 times. Each image was presented for 700 ms.

Scans 1–6 were followed by two additional scans (7 and 8), which were intended to measure the net effect of within-session familiarity on scene processing. Each of these scans was 6 min 26 s long and was divided into 64 4-s-long stimulus trials interspersed with 64 2-s null trials and a 12-s fixation period at the end of the scan. Stimulus trials consisted of a 500-ms fixation cross, followed by the presentation of a single scene for 500 ms and then a 3,000-ms poststimulus fixation interval. Subjects used a button box to report whether or not the scene depicted a famous world landmark. Subjects were not informed of the identities of the famous landmarks beforehand but all were easily identifiable (e.g., the Taj Majal; Big Ben), and none were from the local Philadelphia area. Famous landmarks were presented in 16 of the 64 stimulus trials of each run, scenes from the Penn campus in 24 trials, and scenes from the Temple campus in 24 trials. Of the 24 scenes from each campus, 8 were images that had been presented in scans 1–6 (old view condition), 8 were previously unseen views of the campus locations presented in scans 1–6 (new view condition), and 8 were images of locations that had not been presented in scans 1–6 (new place condition). These three trial types were crossed with environmental familiarity (Penn versus Temple) in a 3×2 design.

In sum, the design of *experiment 2* allowed us to examine how repeated exposure to two views of each location during scans 1–6 affected subsequent processing of these views and also a previously unseen third view in scans 7 and 8. It also allowed us to simultaneously measure the effects of real-world familiarity with these locations. Note that the use of different behavioral tasks in scans 1–6 and 7–8 ensured that any cross-scan repetition effects could be attributed to repetition of the view/place itself rather than to repetition of the response (Dobbins et al. 2004). However, a disadvantage of this design was that inconsistencies between the scans 1–6 and 7–8 repetition effects could arise for two reasons: first, because different repetition intervals were used in scans 1–6 and 7–8 (within-trial vs. between trial); second, because different tasks were used in scans 1–6 and 7–8 (same/different place vs. famous/nonfamous).

Data analysis

Functional images were corrected for differences in slice timing by resampling slices in time to match the first slice of each volume, realigned with respect to the first image of the scan, spatially normalized to the Montreal Neurological Institute (MNI) template, resampled

into 3-mm isotropic voxels and spatially smoothed with an 8-mm FWHM Gaussian filter. Data were analyzed using the general linear model as implemented in VoxBo (www.voxbo.org) including an empirically derived $1/f$ noise model, filters that removed high and low temporal frequencies, regressors to account for global signal variations, and nuisance regressors to account for between-scan differences. Each stimulus condition was modeled as an impulse response function (experimental scans) or a boxcar function (functional localizer scans) convolved with an estimate of the hemodynamic response function (HRFs). Subject-specific HRFs were used in *experiment 1*; however, as the choice of HRF appeared to make little difference to the results, we simplified the data analysis procedure by using a canonical HRF in *experiment 2*. Regressors reflecting the first and second derivatives of the predicted hemodynamic response to each stimulus condition were also included. Both region of interest (ROI) and whole-brain analyses were performed.

For ROI analyses, data from the functional localizer scans were used to identify subject-specific regions responding more strongly to scenes than to common objects in the PPA, RSC, and TOS. Thresholds were set for each region in a subject-by-subject manner so that the ROIs were consistent with those identified in previous studies; thresholds ranged from $t > 2.5$ to $t > 5.0$. Using these criteria, the PPA was identified in both cerebral hemispheres and the RSC in the left hemisphere in all subjects. Right RSC was identified in 12/14 subjects of *experiment 1* and 14/14 subjects of *experiment 2*, left TOS in 14/14 subjects of *experiment 1* and 13/14 subjects of *experiment 2*, and right TOS in 14/14 subjects of *experiment 1* and 13/14 subjects of *experiment 2*. Mean sizes for each ROI were: left PPA $3.0 \pm 1.6 \text{ cm}^3$, right PPA $4.1 \pm 2.0 \text{ cm}^3$, left RSC $1.3 \pm 1.0 \text{ cm}^3$, right RSC $2.4 \pm 1.6 \text{ cm}^3$, left TOS $2.3 \pm 1.3 \text{ cm}^3$, right TOS $3.0 \pm 1.8 \text{ cm}^3$. The time course of MR response during the main experimental scans was extracted from each ROI (averaging over all voxels) and entered into the general linear model to calculate parameter estimates (beta values) for each condition that were used as the dependent variables in a second-level random-effects ANOVA. We also explored a more anatomically restrictive method for defining ROIs in which voxels were included if they responded more strongly to scenes than to objects at $t > 2.5$ and were within 3 mm of the voxel showing the strongest value for this contrast. This method of defining the ROIs gave substantially identical results, so these data are not reported.

For whole-brain analyses, subject-specific t -maps were calculated for contrasts of interest and then smoothed to 12-mm FWHM to facilitate between-subject averaging before entry into a random effects analysis. Voxels were considered to be sensitive to environmental familiarity if the significance of this effect exceeded $P < 0.001$, uncorrected. Voxels were considered to exhibit either a viewpoint-specific or viewpoint-invariant repetition effect when the following two conditions were met: the significance of the tested effect exceeded $P < 0.001$, uncorrected and the response when all information was repeated (no change or old view condition) was significantly less ($P < 0.001$) than the response when no information was repeated (place change or new place condition). The second condition restricted the analysis to voxels showing the predicted ordered reduction of response when an increasing fraction of information is repeated (e.g., place change $>$ viewpoint change $>$ no change or new place $>$ new view $>$ old view), as the response of voxels not showing this pattern is not easily interpretable in terms of fMRI adaptation. Clusters containing seven or more above-threshold voxels are reported. Note that insofar as these tests were not corrected for multiple comparisons across voxels, the results should be considered exploratory.

RESULTS

Experiment 1

BEHAVIORAL DATA. On each trial, the subjects' task was to report whether the two presented images depicted the same place or different places. The correct response was "same" for

viewpoint-change and no-change trials and "different" for place-change trials. The two images in the viewpoint-change trials depict the same objects and surfaces (from different views), whereas the two images in the place-change trials depict different objects and surfaces. As such, it is possible to perform the task solely by using visual information locally available in the images, although knowledge about the environment from which the images are drawn can potentially facilitate performance. Accuracies and reaction times are plotted in Fig. 3.

Analyses of variance performed on the accuracy data revealed significant main effects of familiarity [$F(1,13) = 15.3$, $P < 0.002$] and change type [$F(2,26) = 48.7$, $P < 0.001$] and a significant familiarity \times change type interaction [$F(2,26) = 48.7$, $P < 0.005$]. Specifically, subjects were more accurate when performing the task on images of the familiar college campus ($M = 92.9\%$) than on images of the unfamiliar college campus ($M = 89.4\%$) and more accurate on no-change ($M = 95.1\%$) and place-change trials ($M = 93.8\%$) than on viewpoint-change trials ($M = 84.5\%$). Performance on viewpoint-change trials was particularly impacted by familiarity: post hoc t -test revealed that the familiar versus unfamiliar difference was significant for viewpoint-change trials [$t(13) = 3.2$, $P <$

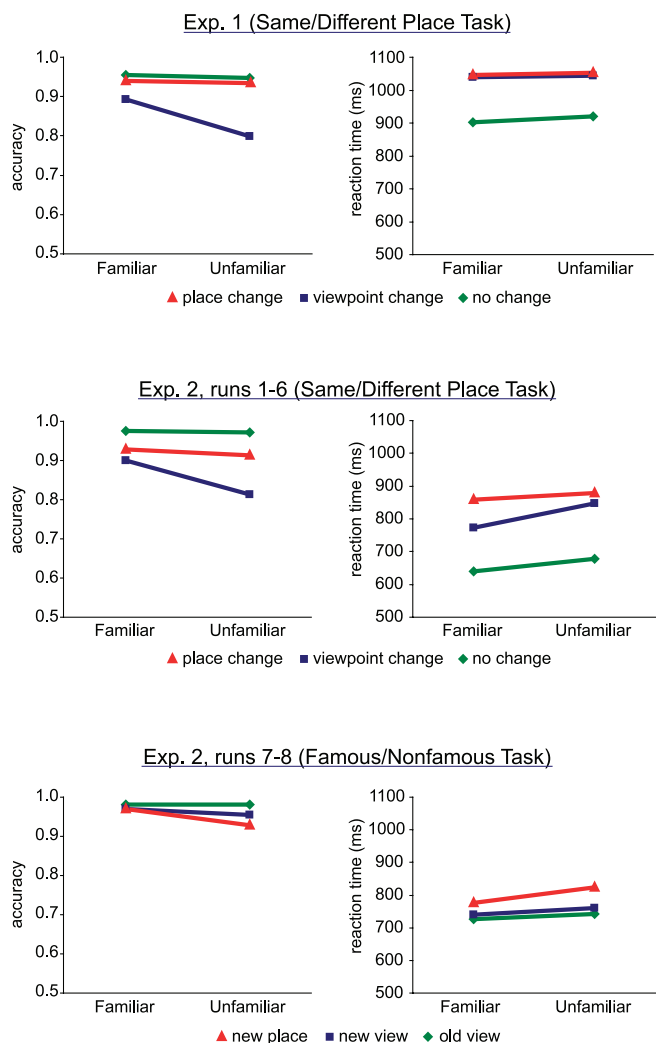


FIG. 3. Behavioral data for *experiments 1* and *2*. Reaction times are for correct trials only.

0.01] but not for place-change [$t < 1$, n.s.] or no-change [$t(13) = 1.7$, $P = 0.10$, n.s.] trials. These results suggest that subjects activated long-term representations of the spatial structure of the familiar environment to aid performance of the task. In particular, they appear to have used their knowledge of the familiar campus to facilitate their ability to correctly respond "same place" on viewpoint-change trials.

Reaction times for correct trials were affected by change type [$F(2,26) = 40.0$, $P < 0.001$] but not familiarity [$F(1,13) = 3.2$, $P = 0.10$, n.s.]. Specifically, responses were faster in no-change trials ($M = 888$ ms) than in viewpoint-change ($M = 1,039$ ms) and place-change trials ($M = 1,040$ ms), consistent with results from previous studies (Epstein et al. 2003, 2005). Post hoc t -test confirmed that responses were faster to no-change than to viewpoint-change [$t(13) = 6.2$, $P < 0.001$] and place-change [$t(13) = 7.8$, $P < 0.001$] trials, but response times to place- and viewpoint-change trials did not differ ($t < 1$, n.s.). No interaction of change type and familiarity was observed ($F < 1$, n.s.).

In the computer survey after the experiment, subjects reported that they were highly familiar with the locations from their campus and highly unfamiliar with the locations from the other campus. The subjectwise average rating for familiar locations ranged from 1 to 2.02 with a mean of 1.18 ± 0.28 . (These numbers do not include 1 subject, who was dropped from the analysis due to a failure to follow instructions.) For the unfamiliar locations, the subjectwise average responses ranged from 1.8 to 4 with a mean of 3.60 ± 0.35 . The rating difference for familiar and unfamiliar locations was significant [$F(1,11) = 483.9$, $P < 0.0001$]. There was no interaction between rating of familiarity or unfamiliarity and type of student [$F(1,11) = 0.79$, $P = 0.39$, n.s.], reflecting the fact that Penn students did not report greater relative familiarity with Penn versus Temple images than Temple students did with Temple versus Penn images.

FUNCTIONAL ROIS. Data from the functional localizer scans were used to define scene-responsive regions of interest in PPA, RSC, and TOS. ANOVA revealed significant main effects of familiarity [left PPA $F(1,13) = 7.2$, $P < 0.05$; right PPA $F(1,13) = 10.7$, $P < 0.01$; left RSC $F(1,13) = 34.0$, $P < 0.0001$; right RSC $F(1,11) = 30.3$, $P < 0.0002$; left TOS $F(1,13) = 3.6$, $P = 0.08$; right TOS $F(1,13) = 4.9$, $P < 0.05$] and within-trial repetition [left PPA $F(2,26) = 30.9$; right PPA $F(2,26) = 28.2$; left RSC $F(2,26) = 24.8$; right RSC $F(2,22) = 38.2$; left TOS $F(2,26) = 21.2$; RTOS $F(2,26) = 21.0$; all P 's

< 0.00001] in all three regions during the main experimental scans. The familiarity effects were most dramatic in RSC, where response to familiar locations was $>50\%$ higher than response to unfamiliar locations (Fig. 4).

The within-trial repetition effects can be separated into two components. First, we interpret smaller response to viewpoint-change trials than to place-change trials as evidence for viewpoint-invariant processing as this indicates that response is reduced when place information is repeated from a different viewpoint compared with the case where place information is not repeated. Second, we interpret smaller response to no-change trials than to viewpoint-change trials as evidence for viewpoint-specific processing as this indicates that response is reduced when a specific view of a place is repeated compared with the case in which the place is repeated from a different view. Note that both of these effects can coexist: this would indicate partial but not complete view invariance.

We performed additional ANOVAs to analyze these two effects separately. The viewpoint-specific repetition effect (viewpoint-change $>$ no-change) was highly significant in both hemispheres for all three regions [all F 's > 24 , all P 's < 0.001]. In contrast, there was no evidence for a viewpoint-invariant repetition effect in any region, except for a marginal effect in right RSC [$F(1,11) = 3.8$, $P = 0.08$]. These patterns are also apparent from visual inspection of the data (Fig. 4). Interestingly, the viewpoint-specific effect did not vary with environmental familiarity in any region, but there was a significant familiarity \times repetition interaction for the viewpoint-invariant effect in right RSC [$F(1,11) = 5.6$, $P < 0.05$]. Specifically, scene processing in the right RSC was more viewpoint invariant for scenes drawn from familiar environments than for scenes drawn from unfamiliar environments.

In sum, these results indicate that all three scene-processing regions respond more strongly to scenes drawn from familiar environments than to unfamiliar scenes with the strongest effects in RSC. We found little evidence that familiar and unfamiliar scenes are processed with different degrees of viewpoint specificity except for a weak effect of greater viewpoint invariance for familiar scenes in the right RSC.

WHOLE-BRAIN ANALYSES. Exploratory whole-brain analyses were performed to determine whether the familiarity and repetition effects observed in the PPA, RSC, and TOS were specific to these regions, or also found in other regions of the brain. The results (Table 1) indicated that the effects were largely restricted to the target regions. Notably, the only three

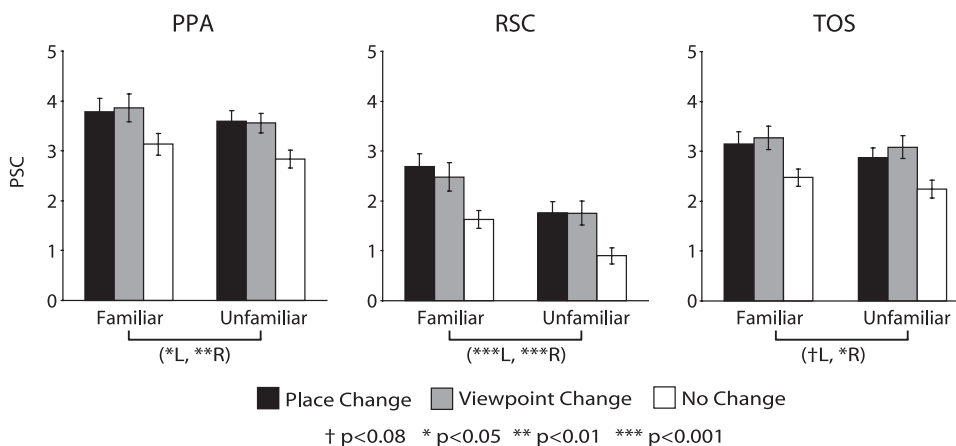


FIG. 4. Results of the region of interest analyses for *experiment 1*. The main effects of environmental familiarity are indicated by greater response to familiar locations than to unfamiliar locations in all 3 regions (significance level in each hemisphere indicated by symbols). Viewpoint-specific repetition effects are indicated by reduced response to no-change trials compared to viewpoint-change trials and were highly significant in all regions. Responses to viewpoint- and place-change trials did not differ, indicating an absence of viewpoint-invariant repetition effects. Data were averaged over both hemispheres before creating the plots. Error bars indicate 1 SE. PSC, percent signal change relative to fixation baseline.

TABLE 1. Results of random effects group analyses for experiment 1

Familiarity effect (familiar>unfamiliar)	x	y	z
Left RSC	-12	-55	11
Right RSC	11	-52	8
Left PHC/medial fusiform gyrus	-24	-39	-13
Left parietal-occipital junction (near TOS)	-44	-78	33
Right parietal-occipital junction (near TOS)	41	-76	29
Viewpoint-specific adaptation (view change>no change AND place change > no change)			
Right RSC	17	-58	11
Left PHC/medial fusiform	-31	-49	-14
Right PHC/medial fusiform	26	-45	-15
Left parietal-occipital junction (near TOS)	-37	-83	26
Right parietal-occipital junction (near TOS)	35	-83	26
Left inferior frontal gyrus	-51	18	31

Coordinates are in Montreal Neurological Institute (MNI) space. RSC, retrosplenial cortex; TOS, transverse occipital sulcus; PHC, parahippocampal cortex.

areas responding more strongly to familiar versus unfamiliar locations were posterior parahippocampal cortex (overlapping the PPA), RSC, and a parietal-occipital region adjoining but not completely overlapping the TOS. Similar results were observed for the whole-brain analysis of the viewpoint-specific adaptation effect: outside of the target ROIs, the only region showing a significant repetition effect was the left inferior frontal gyrus, a region that has been demonstrated to exhibit repetition reduction effects in a number of studies using a variety of different stimulus materials (Buckner et al. 1998; Demb et al. 1995). No region exhibited a viewpoint-invariant adaptation effect that exceeded the significance threshold.

Figure 5 illustrates the striking degree of overlap among regions responding more strongly to the familiar campus than to the unfamiliar campus, regions exhibiting (viewpoint specific) adaptation for repeated scenes, and regions responding more strongly to scenes than to nonscene objects in the functional localizer scans. For all three contrasts, parahippocampal, retrosplenial, and parietal-occipital regions respond more strongly to the stimuli that convey more (or more novel) information about the spatial structure of the surrounding environment. The fact that these three independent comparisons isolate similar regions strongly supports the idea that these areas mediate navigationally relevant spatial processing.

Experiment 2

This experiment was motivated by an apparent discrepancy between the results of *experiment 1* and the results of a previous study (Epstein et al. 2005). *Experiment 1* found little evidence for viewpoint-invariant processing in any cortical region, except for a marginal viewpoint-invariant adaptation effect for familiar scenes in right RSC. In contrast, the earlier study found evidence for viewpoint-invariant processing in the PPA after subjects viewed images of unfamiliar locations multiple times over the course of a scan session. These results led us to predict that real-world experience with familiar locations might lead to viewpoint-invariant processing in the PPA (as well as other cortical regions). Although the failure to find this pattern in *experiment 1* might simply reflect the fact that the viewpoint changes examined were fairly large (60–70 vs. 35° in the previous experiment), an alternative possibility is that the viewpoint-invariant adaptation observed in the earlier

study might reflect a short-term facilitation of scene processing that generalizes across views rather than long-term learning of viewpoint-invariant place representations. To test this idea, *experiment 2* simultaneously measured the effects of both long-term (i.e., real world) and short-term (i.e., within scan session) familiarity.

The effects of within-scan-session familiarity were measured in two ways. First, the same small set of images was used to construct all of the trials in scans 1–6; this meant that each image was presented 15 times. This allowed us to determine whether scene processing became more viewpoint invariant as the images became more familiar by monitoring the evolution of viewpoint-specific and -invariant within-trial adaptation effects over the course of the scan session. Second, two scans were appended at the end of the session (scans 7 and 8) in which subjects made famous/nonfamous judgments on scenes that were either repeated from scans 1–6 (old view), repeated but from a different view (new view) or not previously seen in the experiment (new places). This allowed us to measure the net effect of within-session familiarity by comparing response to “old” views of a place with response to new views of the same place and also to new places. Note that these manipulations are similar to those used in (Epstein et al. 2005).

BEHAVIORAL DATA. Accuracies and reaction times for the same/different place task (scan runs 1–6) and the famous/nonfamous landmark task (scan runs 7 and 8) are reported in

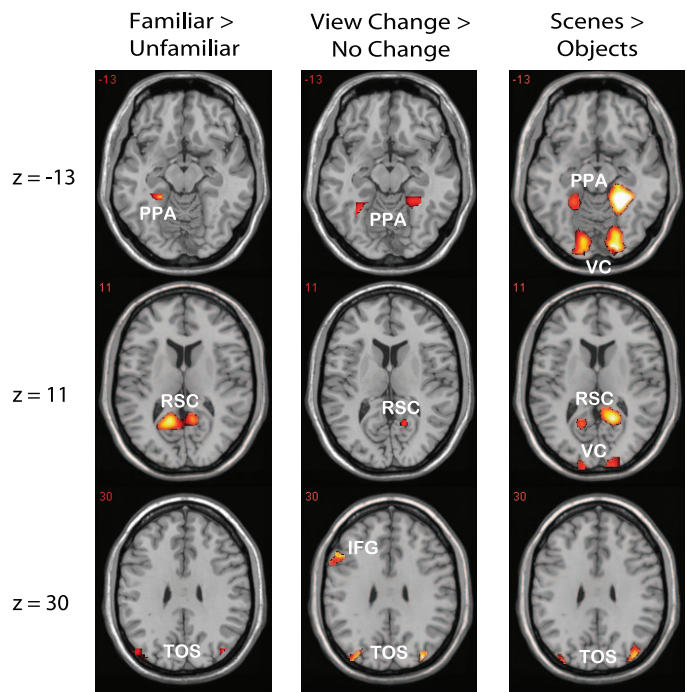


FIG. 5. Whole-brain analyses for *experiment 1*. The familiar vs. unfamiliar and view change vs. no change contrasts were performed on the data from the main experimental scans. The scenes vs. object contrast was performed on the data from the functional localizer scan. Note the striking correspondence among the parahippocampal (PPA), retrosplenial (RSC), and transverse occipital/parietal-occipital (TOS) regions activated for each contrast. In addition, the inferior frontal gyrus (IFG) responded more strongly to viewpoint-change trials than to no-change trials, and visual cortex (VC) responded more strongly to scenes than to objects. Voxels responding to each contrast at the appropriate significance level (see text) are indicated in color and overlaid on a reference brain in standard space. Right hemisphere is on the right. Complete results are listed in Table 1.

Fig. 3. The pattern of errors in the same/different place task was similar to that observed in *experiment 1*. ANOVA revealed significant main effects of familiarity [$F(1,13) = 9.5$, $P < 0.01$] and change type [$F(2,26) = 15.0$, $P < 0.0001$] and a significant familiarity \times change type interaction [$F(2,26) = 3.7$, $P < 0.05$]. Specifically, subjects were more accurate when performing the task on images of the familiar college campus than on images of the unfamiliar college campus, and more accurate on no-change and place-change trials than on viewpoint-change trials. As in *experiment 1*, familiarity with the locations depicted in the stimuli was associated with improved performance on viewpoint-change trials [$t(13) = 2.7$, $P < 0.02$] but not on place-change or no-change trials [both t 's < 1.2 , n.s.].

Reaction times for correct trials on the same/different place task were significantly affected by campus familiarity [$F(1,13) = 8.9$, $P < 0.02$] and change type [$F(2,26) = 46.2$, $P < 0.00001$], and there was also a significant familiarity \times change type interaction [$F(2,26) = 4.2$, $P < 0.05$]. Specifically, response times were faster for images of familiar locations ($M = 757$ ms) than for images of unfamiliar locations ($M = 804$ ms), and faster for no-change trials ($M = 659$ ms) than for viewpoint-change trials ($M = 810$ ms), which were in turn faster than responses on place-change trials ($M = 869$ ms). Post hoc t -test confirmed that both viewpoint-specific and -invariant priming effects were observed [viewpoint-change vs. no-change $t(13) = 6.2$, $P < 0.0001$; place-change vs. viewpoint-change $t(13) = 3.6$, $P < 0.01$], which contrasts with the results of *experiment 1* in which only viewpoint-specific priming effects were found. Interestingly, the viewpoint-invariant priming effect was larger with images of the familiar campus than with images of the unfamiliar campus [$F(1,13) = 5.4$, $P < 0.05$], suggesting that campus familiarity speeded the matching of locations across views (in addition to improving accuracy in the viewpoint-change condition). In contrast, the magnitude of the viewpoint-specific priming effect did not vary as a function of campus familiarity [$P > 0.15$, n.s.].

An additional analysis in which run was added as a factor found little of interest. Accuracy effects did not vary significantly by run, with the exception of the familiarity advantage [$F(2,26) = 3.7$, $P < 0.05$], which for unclear reasons was largest on runs 5 and 6 and smallest on runs 3 and 4. Nor did reaction time effects vary significantly by run, with the exception of the main effect of familiarity, which was larger at the beginning of the experiment (runs 1 and 2) than on subsequent runs [$F(2,26) = 4.1$, $P < 0.05$].

Accuracies and reaction times for the famous/nonfamous task used in runs 7 and 8 are also plotted in Fig. 3. We analyzed the trials in which images of Penn and Temple were shown, ignoring the responses to the famous lures that were not of theoretical interest. Accuracy was quite high ($M = 96.4\%$) and was significantly modulated by between-trial repetition [$F(2,26) = 4.1$, $P < 0.05$] but not campus familiarity [$P > 0.1$, n.s.]. In particular, accuracy on old view trials ($M = 98.2\%$) was higher than accuracy than on new view trials ($M = 96.2\%$), which was in turn higher than accuracy on new place trials (94.8%). Reaction times were modulated in a similar way by between-trial repetition [$F(2,26) = 8.4$, $P < 0.002$]: specifically, responses on old view trials ($M = 734$ ms) were slightly faster than responses on new view trials ($M = 749$), which were in turn faster than responses on new place trials

($M = 800$ ms). Note that this means that the viewpoint-invariant between-trial priming effect (new place vs. new view) was relatively large (51 ms), whereas the viewpoint-specific between-trial priming effect (new view vs. old view) was relatively small (15 ms); indeed, only the viewpoint-invariant priming effect was significant [$t(13) = 3.1$, $P < 0.01$]. Subjects responded marginally faster to images of the familiar campus than to images of the unfamiliar campus [$F(1,13) = 3.6$, $P = 0.08$], but there was no significant interaction of campus familiarity and between-trial repetition [$F < 1$, n.s.].

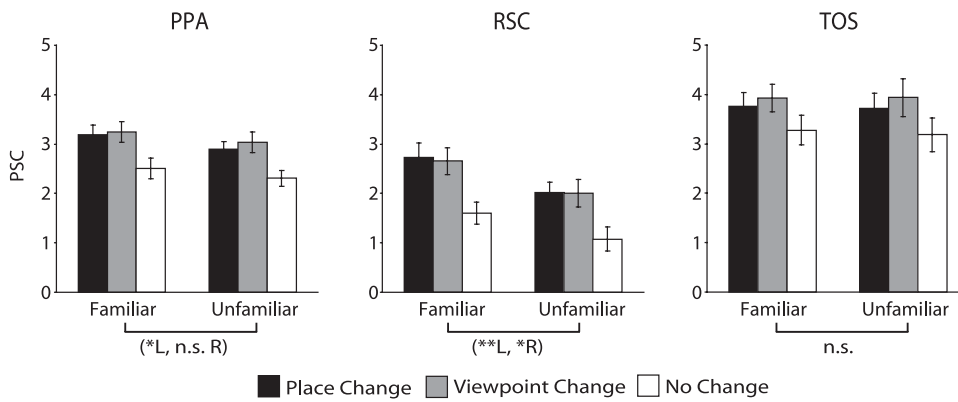
In sum, behavioral performance was facilitated by both real-world familiarity with the locations and within-scan-session familiarity with the images. The strongest effects of real-world familiarity were observed in scans 1–6, where performance on viewpoint-change trials was facilitated by real-world experience with the depicted location. The strongest effects of within-scan-session familiarity were observed in scans 7 and 8, where performance on old view and new view trials was facilitated by previous exposure to images of the locations during scans 1–6.

FUNCTIONAL ROIS. The results from scans 1–6 broadly replicated the pattern observed in *experiment 1*, although some of the effects of campus familiarity were not significant in all ROIs (Fig. 6, *top*). In particular, greater response to images of the familiar campus was observed in the left PPA [$F(1,13) = 4.9$, $P < 0.05$], left RSC [$F(1,13) = 12.6$, $P < 0.01$], and right RSC [$F(1,13) = 8.0$, $P < 0.02$] but not in right PPA, right TOS, or left TOS [P 's > 0.2 , n.s.]. As before, within-trial repetition effects were significant in all regions [all F 's > 18 , all P 's < 0.0001]. Separate analyses of viewpoint-specific and -invariant repetition effects found highly significant viewpoint-specific adaptation effects [all F 's > 36 , all P 's < 0.0001] but no significant viewpoint-invariant effects except for a marginal effect in left PPA [$F(1,13) = 3.6$, $P = 0.08$].

We also performed a second analysis of the data from runs 1–6 in which a separate set of regressors was used to model each run. This allowed us to examine how the effects of familiarity and within-trial repetition changed over the course of the scan session. Results are shown in Fig. 7. Counter to our expectations, we found no evidence that the magnitude of the environmental familiarity effect or the between-trial repetition effects varied over the course of the scan session in any of the ROIs (all P 's > 0.2 , n.s.). Separate analyses of the viewpoint-specific and -invariant adaptation effect found no interaction of the magnitude of either effect with run number (all P 's > 0.14 , n.s.). In fact, the only significant effect of run number was a nonspecific diminution of response in the later runs of the experiment in the left and right PPA [left $F(2,26) = 6.7$, $P < 0.01$; right $F(2,26) = 4.7$, $P < 0.02$]. Thus at first glance, our results suggest that within-session familiarity gained over the course of scans 1–6 had no effect on the viewpoint specificity of scene processing.

The results from scans 7 and 8, in contrast, told a quite different story (Fig. 6*B*). In these scans, the effects of within-scan-session experience were indexed by the between-trial repetition effects (i.e., differences in response among old view, new view, and new place trials) rather than by modulation of within-trial repetition effects over time. These between-trial repetition effects were highly significant in all ROIs (all F 's > 18 , all P 's < 0.0001).

Runs 1-6 (Within-Trial Repetition Effects)



Runs 7-8 (Between-Trial Repetition Effects)

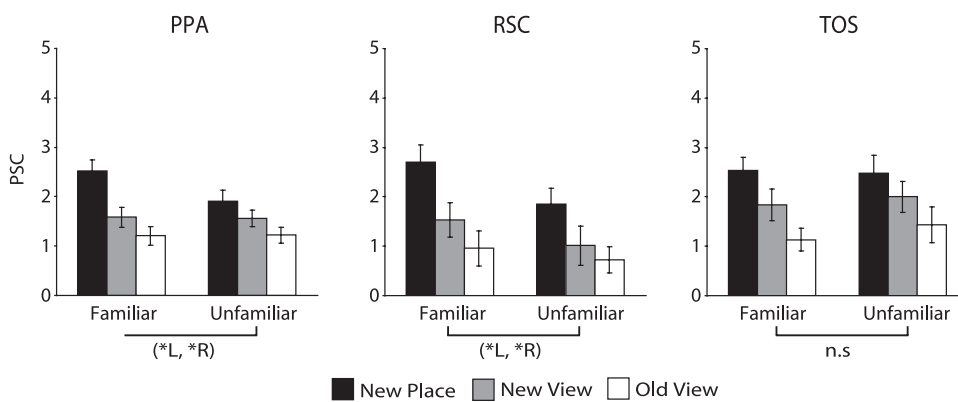


FIG. 6. Region of interest analyses for experiment 2. Top: data from runs 1-6 (same/different view task); bottom: data from runs 7 and 8 (famous/nonfamous task). The within-trial repetition effects measured in runs 1-6 were entirely viewpoint specific as indicated by equal response to place-change and viewpoint-change trials coupled with reduced response to no-change trials. In contrast, the between-trial repetition effects measured in runs 7 and 8 were largely viewpoint invariant as indicated by reduced response to new view trials relative to new place trials. Main effects of environmental familiarity were observed in the PPA and RSC. Significance levels for the familiarity effect are indicated by symbols (see Fig. 3 for key). Data were averaged over both hemispheres before creating the plots. Error bars indicate 1 SE.

Separate analyses of viewpoint-specific (new vs. old view) and viewpoint-invariant (new place vs. new view) repetition effects found that both effects were significant in all ROIs (view-specific $F_s > 4.9$, $P_s < 0.05$; view-invariant $F_s > 14$, $P_s < 0.01$). This contrasts notably with the within-trial adaptation effects measured in scans 1-6, which were exclusively viewpoint specific. Indeed, if anything, the viewpoint-invariant repetition effects were dominant in scans 7 and 8, consistent with the pattern found with the behavioral priming data. Thus within-session experience with different views of a place can lead to (partially) viewpoint-invariant processing, but this effect is only indexed by between-trial, not within-trial, repetition effects. One possible interpretation of these results is that within- and between-trial repetition effects are engendered by different neural mechanisms, a point we will take up further in the discussion.

Greater response to images of the familiar campus than to images of the unfamiliar campus were observed in the left and right PPA and the left and right RSC in scans 7 and 8 ($F_s > 4.8$, $P_s < 0.05$) but not in the TOS (both hemispheres, $P > 0.2$, n.s.). Along with the results from scans 1-6 and of experiment 1, these data provide a third replication of the finding that the PPA and RSC are sensitive to environmental familiarity. There was no interaction between environmental familiarity and either viewpoint-specific or -invariant between-trial repetition in either region (PPA: $P > 0.05$, n.s.; RSC: $F < 1$, n.s.).

WHOLE-BRAIN ANALYSES. Results of exploratory whole-brain analyses were largely consistent with those observed in experiment 1 although as noted in the preceding text, the effects of environmental familiarity were not significant in all scene-

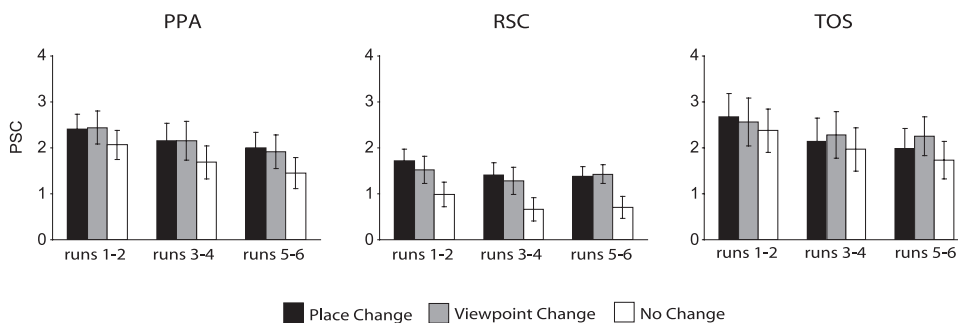


FIG. 7. Within-trial repetition effects for experiment 2 plotted by run. Despite the fact that the same stimulus set was used to construct runs 1 and 2, 3 and 4, and 5 and 6, there was little evidence that these effects became more viewpoint invariant as the images became more familiar. Data are averaged over both hemispheres. Error bars indicate 1 SE.

TABLE 2. Results of random effects group analyses for experiment 2

Familiarity effect (familiar>unfamiliar)	x	y	z
A. Runs 1–6			
L RSC	–19	–55	16
R RSC	8	–55	15
L parietal-occipital junction (near TOS)	–47	–76	30
Viewpoint-specific adaptation (view change>no change AND place change>no change)			
L RSC	–18	–61	14
R RSC	12	–55	12
L PHC/fusiform gyrus	–29	–43	–13
R PHC/fusiform gyrus	26	–41	–17
L middle occipital gyrus (near TOS)	–39	–82	27
L superior parietal lobule	–24	–69	52
R TOS	30	–81	32
R orbital frontal cortex	30	28	–5
R inferior frontal gyrus	46	24	25
L inferior frontal gyrus	–52	6	33
B. Runs 7–8			
Familiarity effect (familiar>unfamiliar)			
L RSC	–13	–63	14
R RSC	11	–61	14
R PHC	6	–37	–4
Viewpoint-invariant adaptation (new place>new view AND new place>old)			
L RSC	–11	–56	5
R RSC	9	–50	6
L PHC	–24	–39	–12
R PHC	27	–39	–19
Viewpoint-specific adaptation (new view>old AND new place>old)			
L middle occipital gyrus (near TOS)	–35	–87	26

responsive regions (see Table 2). Specifically, greater response to familiar locations than to unfamiliar locations was observed in RSC and a parietal-occipital region adjoining TOS in scans 1–6 and in RSC and right parahippocampal cortex in scans 7 and 8. Viewpoint-specific adaptation effects were observed in RSC, PPA, and TOS (as well as several additional frontal-parietal regions) during scans 1–6, whereas viewpoint-invariant adaptation effects were observed in RSC and PPA during scans 7 and 8. Figure 8 shows the striking degree of overlap between the PPA and RSC voxels showing viewpoint-specific adaptation in scans 1–6 and those showing viewpoint-invariant adaptation in scans 7–8.

Taken as a whole, the results from *experiment 2* confirm the idea that PPA, RSC, and TOS are the regions of the brain most sensitive to repetition of scene information, although the extent to which these repetition effects are viewpoint specific versus viewpoint invariant appears to depend strongly on the repetition interval. These results also indicate that RSC is the single region of the brain whose activity level is most strongly related to familiarity with the location depicted in the scene.

DISCUSSION

We examined the effect of familiarity on cortical processing of complex visual scenes. In particular, we tested two hypotheses. First, we predicted that previously identified scene-responsive regions such as the PPA, RSC, and TOS would respond more strongly to images of familiar locations than to images of unfamiliar locations. This prediction was supported by the data. Second, we predicted that representations of

familiar scenes would be more viewpoint invariant than representations of unfamiliar scenes. This prediction was only partially supported: we found some evidence for viewpoint invariance relating to familiarity with specific scene images but no evidence for viewpoint invariance relating to familiarity with the real-world environment from which they were drawn. A third, unexpected result was that the degree of viewpoint invariance observed on stimulus repetition depended on the repetition interval. Specifically, viewpoint-invariant fMRI response reductions were observed when new views of previously viewed scenes were presented in subsequent experimental trials but not when different views of the same scene were presented within the same experimental trial. This result may have important implications for interpretation of fMRI adaptation data. We now address each of these three results in turn.

Main effects of environmental familiarity

Greater response to images of familiar locations than to images of unfamiliar locations was observed in the PPA, RSC, and TOS in *experiment 1* and in RSC and left PPA in *experiment 2*. The sensitivity to environmental familiarity was most striking in RSC, which responded 50% more strongly to photographs of familiar environments than to photographs of unfamiliar environments. In contrast, the familiarity effects in PPA and TOS were weaker and not always reliable. Exploratory whole-brain analyses confirmed that familiarity effects were largely restricted to the PPA, RSC, and TOS. We draw two conclusions from these results.

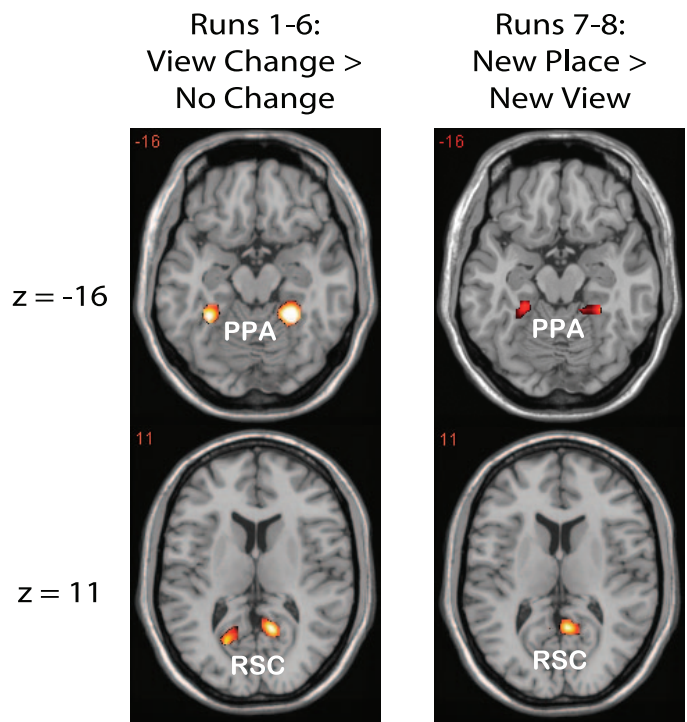


FIG. 8. Whole-brain analyses for *experiment 2*. The PPA and RSC regions responding more strongly to viewpoint-change than to no-change trials in runs 1–6 were almost identical to the regions responding more strongly to new places than to new views in runs 7 and 8. Voxels responding to each contrast at the appropriate significance level (see text) are indicated in color and overlaid on a reference brain in standard space. Right hemisphere is on the right. Complete results are listed in Table 2. Note that left RSC also responded more strongly to new places than to new views; however, this activation is not visible at the chosen elevation.

First, the sensitivity to environmental familiarity observed in the PPA, RSC, and TOS supports the claim that these regions mediate processes important for spatial orientation. We initially made this claim based on the fact that these regions respond more strongly to visual stimuli that have the potential to convey information about one's spatial whereabouts (i.e., images of scenes and landmarks) than to visual stimuli that are less likely to convey such information (i.e., images of objects and faces). However, the possibility remained open that this preferential response to scenes might simply reflect low-level physical differences between scenes and objects, such as the fact that scene images often extend further into the periphery of the visual field (Levy et al. 2001). The results of the current experiments indicate that the PPA, RSC, and TOS show the following three effects: they respond more strongly to scenes than to nonscene objects during the functional localizer runs, they respond more to scenes drawn from familiar environments than to scenes drawn from unfamiliar environments, and they show response reduction when scenes are repeated. In other words, these regions respond more strongly when navigationally relevant visual information is present versus absent, more strongly when the visual stimulus conveys information about one's location within a larger, familiar space than when it simply conveys information about one's location within the immediate environment, and more strongly when navigationally relevant information is novel than when it is repeated. Furthermore, these are the only regions of the brain that show all three of these effects. We conclude that the previous association of the PPA, RSC, and TOS with spatial orientation processes is not spurious as multiple different tests designed to isolate navigation-related processes converge on the same network of brain regions (see also Aguirre and D'Esposito 1999; Burgess et al. 2001; Janzen and van Turennout 2004; Maguire et al. 1998).

Second, our results suggest that there is a certain amount of functional differentiation within the PPA-RSC-TOS cortical network. In particular, the large size of the familiarity effect in RSC suggests that this region may be especially involved in retrieving information about the spatial environment that extends beyond the immediate horizon as this kind of information can only be retrieved for the familiar scenes (Epstein and Higgins 2006; Park et al. 2006). In contrast, the familiarity effects in PPA and TOS were smaller and less reliable, suggesting that these regions might be primarily involved in perception of the local scene. The general pattern observed in PPA/TOS is approximately equal response to both familiar and unfamiliar locations (Epstein et al. 1999) but with a slight boost for familiar locations under some circumstances. The factors driving the presence or absence of this familiarity effect in PPA/TOS are currently unclear, although one possibility is that stronger response to familiar locations is found when familiarity with the depicted location facilitates the interpretation of local spatial geometry. In any case, the current results are consistent with previous neuroimaging and neuropsychological studies that strongly implicate RSC in retrieval of spatial information that extends beyond the currently visible scene (Aguirre and D'Esposito 1999; Ino et al. 2002; Katayama et al. 1999; Park et al. 2006; Takahashi et al. 1997; Wolbers and Buchel 2005) and PPA/TOS in perception of the current scene (Epstein 2005; Epstein and Higgins 2006; Men-

dez and Chierri 2003). Thus PPA/TOS and RSC appear to play distinct but complementary roles in spatial navigation.

Results from two recent studies are particularly relevant for interpreting the current results. First, Suguira and colleagues (2005) reported greater fMRI response in posterior cingulate/RSC when subjects viewed places and objects that were personally familiar to them than when they viewed places and objects that were unfamiliar, suggesting that RSC may be a subset of a larger complex that is generally involved in linking the current stimulus to the broader spatial or episodic context from which it was drawn (cf. Bar 2004). This linking process may operate automatically, even when subjects do not explicitly retrieve information about the context or familiarity of the visible scene, as in the same/different place task of the present experiment. Importantly, Suguira and colleagues found a subset of the posterior cingulate/RSC region that only showed a familiarity effect for places, which may correspond to the RSC as defined by the functional localizer in the current experiment. Second, Cabeza and colleagues (2004) reported greater activity in the medial prefrontal cortex, hippocampus, parahippocampal cortex, and the cuneus/RSC when subjects viewed photographs of a familiar campus that were taken by themselves than when they viewed photographs of a familiar campus taken by other subjects. These earlier results indicate that the PPA and RSC play a role in episodic retrieval, perhaps because spatial codes mediated by these regions are a critical component of any remembered episode.

Effects of familiarity on viewpoint invariance

The second hypothesis we tested was that familiarity would cause scenes to be processed in a more viewpoint-invariant manner. This prediction was based in part on the intuitive notion that view-invariant representations are particularly useful for recognition (Biederman 1987; Marr 1982; Tarr et al. 1998) but can only be acquired after experience with multiple specific views (Booth and Rolls 1998; Eger et al. 2005). We used two fMRI adaptation paradigms to test the view specificity of scene processing: within-trial repetition (*experiments 1 and 2*, runs 1–6), and between-trial repetition (*experiment 2*, runs 7 and 8). In both cases, we interpreted reduced response when a location was repeated from a different viewpoint as evidence for viewpoint-invariant processing and reduced response when a location was repeated from the same viewpoint as evidence for viewpoint-specific processing. We examined how these effects were modulated by familiarity with the environment (*experiments 1 and 2*) and by familiarity with specific scene images (*experiment 2*).

Contrary to our expectations, familiarity with the depicted environment did not have strong effects on the viewpoint invariance of scene processing within the target cortical regions. Consistent with most of our previous results, within-trial repetition effects were entirely viewpoint specific in the PPA and TOS (Epstein et al. 2003, 2005). These effects were not modulated by environmental familiarity. In RSC, there was a marginally significant viewpoint-invariant repetition effect in the right hemisphere in *experiment 1* that was significantly larger for images of the familiar campus than for images of the unfamiliar campus. Although interesting, this interaction was not replicated in *experiment 2*. In general, our results suggest that images of familiar and unfamiliar environments are pro-

cessed with the same degree of viewpoint specificity, at least when relatively large viewpoint changes ($>60^\circ$) are considered.

These results were somewhat surprising to us because an earlier study suggested that familiarity with specific scenes could lead to more viewpoint-invariant processing (Epstein et al. 2005). However, this earlier study examined familiarity with scene images acquired within a scan session rather than familiarity with locations acquired from real-world experience. *Experiment 2* was designed to simultaneously measure the effects of real-world and within-scan-session experiences on the viewpoint specificity of scene processing. Both viewpoint-specific and -invariant repetition reductions relating to within-scan-session familiarity were observed in the PPA and RSC in scans 7 and 8 of this experiment, replicating and extending our previous results. These results suggest that within-scan session familiarity *can* lead to a temporary facilitation of processing (and corresponding reduction of fMRI response) that generalizes to some extent across views (see also Ewbank et al. 2005). However, these within-scan-session facilitation effects (both behavioral and neural) do not seem to be the precursor to long-term changes in the quality of scene processing as the effects were equally viewpoint-invariant for images of familiar and unfamiliar locations rather than being more viewpoint-invariant for familiar locations as we originally predicted.

One possible interpretation of these results is that scene representations in the PPA, RSC, and TOS are as important for orienting and localizing the observer within the scene as they are for place recognition (Byrne et al. 2007). Although viewpoint invariance is desirable for place recognition, viewpoint specificity is necessary if orientation and within-scene position are to be computed. If this is the case, then we might expect real-world interaction with the physical environment to cause an increase in the richness of both the viewpoint-specific and -invariant aspects of scene representations (hence increasing the effectiveness of both orientation/localization and recognition processes) but no proportional increase in viewpoint-invariance. In contrast, within-scan session experience might lead to priming for image features (or representations of scene geometry) that are at least partially invariant across views.

Two kinds of fMRI repetition suppression?

An assumption often made in fMRI adaptation/priming studies is that behavioral priming effects, within-trial fMRI adaptation effects, and between-trial fMRI adaptation effects all index identical representations and thus should give similar results (Buckner et al. 1998; Schacter and Buckner 1998). Several studies have identified cases where such correspondences do indeed exist (Henson et al. 2000; Wig et al. 2005). However, to understand the origins of these three effects, it is equally important to identify situations where they do not correspond (Sayres and Grill-Spector 2006). We observed several disjunctions between these effects in the current experiment.

First, there was a disjunction between behavioral priming effects and fMRI adaptation effects. The behavioral results from *experiment 1* and scans 1–6 of *experiment 2* suggest that subjects were able to use viewpoint-invariant representations to facilitate the matching of different views of the same familiar location. This facilitation was evidenced by greater accuracy

on viewpoint-change trials for familiar than for unfamiliar locations in both experiments and a larger viewpoint-invariant priming effect (i.e., faster RT for viewpoint changes than for place changes) in *experiment 2*. Yet little evidence was observed for larger viewpoint-invariant fMRI adaptation effects for familiar locations than for unfamiliar locations during scans 1–6 in either experiment, except for a small effect in right RSC in *experiment 1* which was not replicated in *experiment 2*. Nor did the whole-brain analysis reveal viewpoint-invariant adaptation effects outside of the targeted ROIs (although it is possible that extra-ROI effects simply failed to exceed the more stringent significance threshold used for whole-brain analyses.)

Second, and perhaps more importantly, there was a disjunction between the within- and between-trial fMRI adaptation effects in *experiment 2*. The within-trial adaptation effects observed in scans 1–6 were entirely viewpoint specific, consistent with previous reports (Epstein et al. 2003). In contrast, the between-trial adaptation effects observed in scans 7 and 8 were largely viewpoint invariant. In a previous study, we observed evidence that viewpoint-specific within-trial adaptation effects can become more viewpoint invariant over the course of a scan session (Epstein et al. 2005); however, no similar evolution of within-trial viewpoint invariance was observed here. The behavioral priming effects observed in scans 7 and 8 were consistent with the between-trial fMRI adaptation effects insofar as both were largely viewpoint invariant.

What can account for these apparently discrepant results? Intuitively, one might suppose that the within-trial repetition effects index representations that are more “perceptual,” whereas the between-trial repetition effects index representations that are more “mnemonic.” It is a general feature of declarative memory that stored representations of complex stimuli such as narratives, episodes, or scenes tend to abstract away perceptual details (e.g., Brewer and Treyns 1981). In the current study, this might correspond to loss of viewpoint specificity in the mnemonic representations. However, we are still left with the challenge of understanding how these different representations are encoded at the neural level. In particular, the whole-brain analyses found no evidence that the cross-trial repetition effects were driven by top-down modulation from areas associated with memory (such as the hippocampus or prefrontal cortex), nor did they find evidence that the within-trial repetition effects were driven by bottom-up-modulation from areas associated with perception (such as early visual cortex). Rather, both repetition effects appear to be coterminous within the same parahippocampal and retrosplenial regions.

One possibility is that within- and between-trial repetition effects may be modulated by different neural mechanisms that operate within the same cortical territory (Grill-Spector 2006). In particular, within-trial fMRI adaptation effects might reflect modulation of the *inputs* to a region, whereas between-trial adaptation effects might reflect modulation of neural processing *within* a region. In this account, the viewpoint specificity observed in the within-trial adaptation effects indicates that information about which view corresponds to which place is not present in the inputs to the PPA, RSC, and TOS. Processing within these regions leads to extraction of (partially) viewpoint-invariant place representations from viewpoint-specific

inputs, and this intraregional processing is reflected in the viewpoint invariance observed in the between-trial adaptation effects. The within-trial adaptation effect might be caused by synaptic depression (Abbott et al. 1997), which is believed to act on a relatively short time scale of < 2 s (Muller et al. 1999), whereas the between-trial adaptation effect might be caused by within-region changes of connectivity leading to more efficient processing (and faster reaction times). Although not observed in the current experiment, the fMRI correlates of a third adaptation mechanism, neuronal adaptation caused by tonic hyperpolarization (Carandini and Ferster 1997), might be observable when the adapting stimuli are shown for much longer presentation times of several seconds (Fang and He 2005; Fang et al. 2005).

Although admittedly speculative, this account is consistent with several results from neurophysiology. Li and colleagues (1993) recorded from neurons in inferior temporal (IT) cortex while monkeys viewed objects that were repeated within trials and between different trials. They observed separate, independent effects for within- and between-trial repetition that they referred to as matching (within-trial) and familiarity (between-trial) effects. They hypothesized that between-trial effects might be caused by a “sharpening” of object representations as neurons that encode nonessential features drop out of the representation, leading to reduced response (and faster reaction times) for repeated items (Desimone 1996; Wiggs and Martin 1998). Complementary to this, results from a recent study (Sawamura et al. 2006) suggest that within-trial repetition effects may reflect adaptation at the synaptic inputs rather than changes in neuronal selectivity. Recordings were made from IT neurons while either identical items or distinct items that elicit nearly identical responses (when presented in isolation) were repeated within a trial. Despite the fact that the neuronal response to each stimulus was equivalent when they were presented singly, more adaptation was observed within a two-item sequence when the second item was the same as the first than when it was different (but “equivalent”). This finding indicates that the adaptation effects caused by immediate repetition show greater selectivity than the neuron itself. One possible explanation of this result is that immediate repetition effects reflect adaptation at the synaptic inputs to the neuron (which could differ for the two different stimuli) rather than adaptation at the level of the neuron itself (which treats the two stimuli as equivalent).

Alternatively, the disjunction between the within- and between-trial adaptation effects might relate to the use of different behavioral tasks in runs 1–6 and 7 and 8. These tasks have different goals that may have led to the adoption of different performance strategies. In particular, during performance of the same/different place task in runs 1–6, subjects might have attended to image details such as the relationship between the observer and the scene to identify viewpoint changes and distinguish them from place changes. In contrast, during performance of the famous/nonfamous task in runs 7 and 8, subjects might have attended to more general place features that are likely to be somewhat invariant across views. As such, the same/different place task may have tapped representations that were more viewpoint specific than those used for the famous/nonfamous task. Consequently, the neural adaptation effects in runs 1–6 may have been primarily driven by view repetition while the neural adaptation effects in runs 7 and 8

may have been primarily driven by place repetition, leading to more viewpoint-specific adaptation in runs 1–6 than in runs 7 and 8. Note that this account assumes that viewpoint-invariant place representations were primed in runs 1–6 but did not cause fMRI repetition suppression effects until they were tapped for the behavioral task in runs 7 and 8. In other words, this account postulates that fMRI repetition suppression effects are driven not by repetition per se but by the speeded response that results when a repeated representation is employed in the service of a behavioral task.

This account is consistent with James and Gauthier’s “accumulator” model of fMRI repetition suppression, in which the reduced fMRI response observed after repetition is attributed to faster accumulation of information necessary to successfully perform a behavioral task (James and Gauthier 2006). Although not discussed by these authors, a prediction of their model is that fMRI repetition suppression effects should be at least somewhat task dependent because different forms of information are necessary to complete different tasks. Evidence for task-dependent repetition suppression has been obtained by Dobbins and colleagues (2004), although it is unclear how the response association phenomenon observed in these experiments can explain the current results.

Our present data do not allow us to decide between these two accounts of the discrepancy between within- and between-trial repetition effects. Future experiments might address this issue by measuring both effects while subjects perform a single behavioral task. In particular, the first hypothesis (distinct neural mechanisms) predicts that the within-trial/between-trial disjunction should still be obtained in this case, whereas the second hypothesis (distinct representations for each task) predicts that it will not be found. In any case, the current results suggest that fMRI repetition suppression effects might be driven by a variety of neural mechanisms that operate across different temporal scales (Fang et al. 2005; Grill-Spector et al. 2006). Elucidation of these mechanisms will require further experiments.

For our present purposes, however, the important point is that environmental familiarity modulates both within- and between-trial repetition effects in the same way. In neither case do we see greater viewpoint-invariance for images of the familiar campus.

Summary

The current study examined how both real-world and within-experimental-session familiarity affect the neural processing of visual scenes. The PPA, RSC, and TOS responded more strongly to images of familiar locations than to images of unfamiliar locations; however, there was no evidence that these regions processed familiar locations in a more viewpoint-invariant manner than unfamiliar locations. These results suggest that real-world experience with an environment may increase the richness of the neural representation of scenes drawn from that environment without changing their essential character. The PPA, RSC, and TOS may support a variety of scene representations with a range of viewpoint specificities, allowing them to mediate both the identification of places and the specification of one’s position and orientation within them.

ACKNOWLEDGMENTS

We thank W. Parker for assistance with these experiments.

GRANTS

This work was supported by Whitehall Foundation Grant 2004-05-99-APL and National Eye Institute Grant EY-016464 to R. Epstein.

REFERENCES

- Abbott LF, Varela JA, Sen K, Nelson SB. Synaptic depression and cortical gain control. *Science* 275: 220–224, 1997.
- Aguirre GK, D'Esposito M. Topographical disorientation: a synthesis and taxonomy. *Brain* 122: 1613–1628, 1999.
- Aguirre GK, Detre JA, Alsop DC, D'Esposito M. The parahippocampus subserves topographical learning in man. *Cereb Cortex* 6: 823–829, 1996.
- Bar M. Visual objects in context. *Nat Rev Neurosci* 5: 617–629, 2004.
- Biederman I. Recognition-by-components: a theory of human image understanding. *Psychol Rev* 94: 115–147, 1987.
- Bohbot VD, Kalina M, Stepankova K, Spackova N, Petrides M, Nadel L. Spatial memory deficits in patients with lesions to the right hippocampus and to the right parahippocampal cortex. *Neuropsychologia* 36: 1217–1238, 1998.
- Booth MC, Rolls ET. View-invariant representations of familiar objects by neurons in the inferior temporal visual cortex. *Cereb Cortex* 8: 510–523, 1998.
- Brewer WF, Treyns JC. Role of schemata in memory for places. *Cogn Psychol* 13: 207–230, 1981.
- Buckner RL, Goodman J, Burock M, Rotte M, Koutstaal W, Schacter D, Rosen B, Dale AM. Functional-anatomic correlates of object priming in humans revealed by rapid presentation event-related fMRI. *Neuron* 20: 285–296, 1998.
- Burgess N, Maguire EA, Spiers HJ, O'Keefe J. A temporoparietal and prefrontal network for retrieving the spatial context of lifelike events. *Neuroimage* 14: 439–453, 2001.
- Byrne P, Becker S, and Burgess N. Remembering the past and imagining the future: a neural model of spatial memory and imagery. *Psych Rev*. In press.
- Cabeza R, Prince SE, Daselaar SM, Greenberg DL, Budde M, Dolcos F, LaBar KS, Rubin DC. Brain activity during episodic retrieval of autobiographical and laboratory events: an fMRI study using a novel photo paradigm. *J Cogn Neurosci* 16: 1583–1594, 2004.
- Carandini M, Ferster D. A tonic hyperpolarization underlying contrast adaptation in cat visual cortex. *Science* 276: 949–952, 1997.
- Chua KP, Chun MM. Implicit scene learning is viewpoint dependent. *Percept Psychophys* 65: 72–80, 2003.
- Demb JB, Desmond JE, Wagner AD, Vaidya CJ, Glover GH, Gabrieli JD. Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. *J Neurosci* 15: 5870–5878, 1995.
- Desimone R. Neural mechanisms for visual memory and their role in attention. *Proc Natl Acad Sci USA* 93: 13494–13499, 1996.
- Dobbins IG, Schnyer DM, Verfaellie M, Schacter DL. Cortical activity reductions during repetition priming can result from rapid response learning. *Nature* 428: 316–319, 2004.
- Eger E, Schweinberger SR, Dolan RJ, Henson RN. Familiarity enhances invariance of face representations in human ventral visual cortex: fMRI evidence. *Neuroimage* 26: 1128–1139, 2005.
- Epstein RA. The cortical basis of visual scene processing. *Vis Cogn* 12: 954–978, 2005.
- Epstein R, DeYoe EA, Press DZ, Rosen AC, Kanwisher N. Neuropsychological evidence for a topographical learning mechanism in parahippocampal cortex. *Cogn Neuropsychol* 18: 481–508, 2001.
- Epstein R, Graham KS, Downing PE. Viewpoint-specific scene representations in human parahippocampal cortex. *Neuron* 37: 865–876, 2003.
- Epstein R, Harris A, Stanley D, Kanwisher N. The parahippocampal place area: recognition, navigation, or encoding? *Neuron* 23: 115–125, 1999.
- Epstein RA, Higgins JS. Differential parahippocampal and retrosplenial involvement in three types of visual scene recognition. *Cereb Cortex*, 2006. [doi:10.1093/cecor/bhl079].
- Epstein RA, Higgins JS, Thompson-Schill SL. Learning places from views: variation in scene processing as a function of experience and navigational ability. *J Cogn Neurosci* 17: 73–83, 2005.
- Epstein R, Kanwisher N. A cortical representation of the local visual environment. *Nature* 392: 598–601, 1998.
- Ewbank MP, Schluppeck D, Andrews TJ. fMR-adaptation reveals a distributed representation of inanimate objects and places in human visual cortex. *Neuroimage* 28: 268–279, 2005.
- Fang F, He S. Viewer-centered object representation in the human visual system revealed by viewpoint aftereffects. *Neuron* 45: 793–800, 2005.
- Fang F, Murray SO, Kersten D, He S. Orientation-tuned fMRI adaptation in human visual cortex. *J Neurophysiol* 94: 4188–4195, 2005.
- Ghaem O, Mellet E, Crivello F, Tzourio N, Mazoyer B, Berthoz A, Denis M. Mental navigation along memorized routes activates the hippocampus, precuneus, and insula. *Neuroreport* 8: 739–744, 1997.
- Grill-Spector K. The neural basis of object perception. *Curr Opin Neurobiol* 13: 159–166, 2003.
- Grill-Spector K. Selectivity of adaptation in single units: Implications for fMRI experiments. *Neuron* 49: 170–171, 2006.
- Grill-Spector K, Henson R, Martin A. Repetition and the brain: neural models of stimulus-specific effects. *Trends Cogn Sci* 10: 14–23, 2006.
- Grill-Spector K, Kushnir T, Edelman S, Avidan G, Itzhak Y, Malach R. Differential processing of objects under various viewing conditions in the human lateral occipital complex. *Neuron* 24: 187–203, 1999.
- Grill-Spector K, Malach R. fMR-adaptation: a tool for studying the functional properties of human cortical neurons. *Acta Psychol* 107: 293–321, 2001.
- Habib M, Sirigu A. Pure topographical disorientation—a definition and anatomical basis. *Cortex* 23: 73–85, 1987.
- Hasson U, Harel M, Levy I, Malach R. Large-scale mirror-symmetry organization of human occipito-temporal object areas. *Neuron* 37: 1027–1041, 2003.
- Henderson JM, Hollingworth A. High-level scene perception. *Annu Rev Psychol* 50: 243–271, 1999.
- Henson R, Shallice T, Dolan R. Neuroimaging evidence for dissociable forms of repetition priming. *Science* 287: 1269–1272, 2000.
- Ino T, Inoue Y, Kage M, Hirose S, Kimura T, Fukuyama H. Mental navigation in humans is processed in the anterior bank of the parieto-occipital sulcus. *Neurosci Lett* 322: 182–186, 2002.
- Intraub H. The representation of visual scenes. *Trends Cogn Sci* 1: 217–222, 1997.
- James TW, Gauthier I. Repetition-induced changes in BOLD response reflect accumulation of neural activity. *Hum Brain Mapp* 27: 37–46, 2006.
- James TW, Humphrey GK, Gati JS, Menon RS, Goodale MA. Differential effects of viewpoint on object-driven activation in dorsal and ventral streams. *Neuron* 35: 793–801, 2002.
- Janzen G, van Turenout M. Selective neural representation of objects relevant for navigation. *Nat Neurosci* 7: 673–677, 2004.
- Katayama K, Takahashi N, Ogawara K, Hattori T. Pure topographical disorientation due to right posterior cingulate lesion. *Cortex* 35: 279–282, 1999.
- Levy I, Hasson U, Avidan G, Hendler T, Malach R. Center-periphery organization of human object areas. *Nat Neurosci* 4: 533–539, 2001.
- Li L, Miller EK, Desimone R. The representation of stimulus-familiarity in anterior inferior temporal cortex. *J Neurophysiol* 69: 1918–1929, 1993.
- Maguire EA. The retrosplenial contribution to human navigation: a review of lesion and neuroimaging findings. *Scand J Psychol* 42: 225–238, 2001.
- Maguire EA, Burgess N, Donnett JG, Frackowiak RSJ, Frith CD, O'Keefe J. Knowing where and getting there: a human navigation network. *Science* 280: 921–924, 1998.
- Maguire EA, Frackowiak RSJ, Frith CD. Recalling routes around London: activation of the right hippocampus in taxi drivers. *J Neurosci* 17: 7103–7110, 1997.
- Marr D. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. New York: Freeman, 1982.
- Mendez MF, Cherrier MM. Agnosia for scenes in topographagnosia. *Neuropsychologia* 41: 1387–1395, 2003.
- Muller JR, Metha AB, Krauskopf J, Lennie P. Rapid adaptation in visual cortex to the structure of images. *Science* 285: 1405–1408, 1999.
- O'Craven KM, Kanwisher N. Mental imagery of faces and places activates corresponding stimulus-specific brain regions. *J Cognitive Neurosci* 12: 1013–1023, 2000.
- Park S, Intraub H, Widders D, Yi DJ, Chun MM. Boundary extension: filling-out scene layout information in human parahippocampal cortex (Abstract). *J Vision*: 802a, 2006.
- Rosenbaum RS, Ziegler M, Winocur G, Grady CL, Moscovitch M. "I have often walked down this street before": fMRI studies on the hippocampus and other structures during mental navigation of an old environment. *Hippocampus* 14: 826–835, 2004.

- Sawamura H, Orban GA, Vogels R.** Selectivity of neuronal adaptation does not match response selectivity: a single-cell study of the fMRI adaptation paradigm. *Neuron* 49: 307–318, 2006.
- Sayres R, Grill-Spector K.** Object-selective cortex exhibits performance-independent repetition suppression. *J Neurophysiol* 95: 995–1007, 2006.
- Schacter DL, Buckner RL.** Priming and the brain. *Neuron* 20: 185–195, 1998.
- Sugiura M, Shah NJ, Zilles K, Fink GR.** Cortical representations of personally familiar objects and places: functional organization of the human posterior cingulate cortex. *J Cogn Neurosci* 17: 183–198, 2005.
- Takahashi N, Kawamura M, Shiota J, Kasahata N, Hirayama K.** Pure topographic disorientation due to right retrosplenial lesion. *Neurology* 49: 464–469, 1997.
- Tarr MJ, Williams P, Hayward WG, Gauthier I.** Three-dimensional object recognition is viewpoint dependent. *Nat Neurosci* 1: 275–277, 1998.
- Vuilleumier P, Henson RN, Driver J, Dolan RJ.** Multiple levels of visual object constancy revealed by event-related fMRI of repetition priming. *Nat Neurosci* 5: 491–499, 2002.
- Wig GS, Grafton ST, Demos KE, Kelley WM.** Reductions in neural activity underlie behavioral components of repetition priming. *Nat Neurosci* 8: 1228–1233, 2005.
- Wiggs CL, Martin A.** Properties and mechanisms of perceptual priming. *Curr Opin Neurobiol* 8: 227–233, 1998.
- Wolbers T, Buchel C.** Dissociable retrosplenial and hippocampal contributions to successful formation of survey representations. *J Neurosci* 25: 3333–3340, 2005.