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Attentional modulation of background connectivity between ventral visual cortex and the medial temporal lobe

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Abstract

Attention prioritizes information that is most relevant to current behavioral goals. This prioritization can be accomplished by amplifying neural responses to goal-relevant information and by strengthening coupling between regions involved in processing this information. Such modulation occurs within and between areas of visual cortex, and relates to behavioral effects of attention on perception. However, attention also has powerful effects on learning and memory behavior, suggesting that similar modulation may occur for memory systems. We used fMRI to investigate this possibility, examining how visual information is prioritized for processing in the medial temporal lobe (MTL). We hypothesized that the way in which ventral visual cortex couples with MTL input structures will depend on the kind of information being attended. Indeed, visual cortex was more coupled with parahippocampal cortex when scenes were attended and more coupled with perirhinal cortex when faces were attended. This switching of MTL connectivity was more pronounced for visual voxels with weak selectivity, suggesting that connectivity might help disambiguate sensory signals. These findings provide an initial window into an attentional mechanism that could have consequences for learning and memory.

Introduction

Attention during encoding enhances subsequent recognition memory and can modulate activity in regions of the medial temporal lobe (MTL) that support such memory (Carr et al., 2013; Dudukovic et al., 2011; Uncapher and Rugg, 2009; Yi and Chun, 2005). The purpose of the current study was to investigate a particular way in which attention might enhance MTL processing, inspired by studies about how attention modulates the visual system. Specifically, top-down attention has been shown to modulate the coupling between visual areas, strengthening functional connectivity between areas that code for attended

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information (Al-Aidroos et al., 2012; Bosman et al., 2012). By establishing such functional pathways, attention may improve the transmission of task-relevant information (Fries, 2005).

If attention modulates coupling at the highest levels of the visual hierarchy, this mechanism could also prioritize which information is transmitted to the MTL and ultimately the hippocampus. Parahippocampal cortex (PHC) and perirhinal cortex (PRC) provide an interface between the visual system and the hippocampus and thus are good targets for evaluating attentional modulation of functional connectivity. PHC and PRC have different functional characteristics (Eichenbaum et al., 2007; Ranganath and Ritchey, 2012): for example, PHC processes spatial and contextual information such as scenes, whereas PRC processes items, such as objects and faces (Davachi, 2006; Lee et al., 2012).

We thus manipulated selective attention to scenes and faces in composite images (Al-Aidroos et al., 2012; O'Craven et al., 1999; Yi and Chun, 2005), predicting that this would influence functional connectivity with PHC and PRC. Much of ventral visual cortex processes low- and mid-level features that are common to both scenes and faces (e.g., contours, colors, textures) and these areas might couple with distinct MTL regions depending on attention. In particular, we hypothesized that ventral visual cortex would show stronger functional connectivity with PHC during scene attention and with PRC during face attention.

To measure functional connectivity, we examined the correlation of BOLD activity over time between regions or voxels. This approach has long been used to uncover the coupling between brain regions during rest (Fox and Raichle, 2007). However, such measures can be confounded during tasks because regions that respond synchronously to stimuli will be spuriously correlated over time even in the absence of any interaction. There are several approaches for dealing with this issue (Friston et al., 1997; Rissman et al., 2004). Here we adopt a “background connectivity” approach in which stimulus-evoked responses and noise sources are projected out of the data and correlations are calculated in the residuals during different experimental conditions (Al-Aidroos et al., 2012; Griffis et al., 2015; Norman-Haignere et al., 2012; Duncan et al., 2014; Tompary et al., 2015). The resulting connectivity reflects spontaneous, intrinsic interactions within the functional networks engaged by each condition.

By comparing background connectivity across epochs in which attention was oriented to scenes vs. faces, we identified patterns of PHC and PRC connectivity selective to each attentional state. We predicted that areas of ventral visual cortex would show higher background connectivity both with PHC during scene attention and with PRC during face attention. Moreover, we predicted that such switching would be most pronounced for voxels in ventral visual cortex that responded robustly to both scenes and faces, as connectivity is needed in such cases to determine how the information conveyed by this activity will be processed (Fries, 2005). That is, the influence of voxels with unselective evoked activity in broader networks might arise from selective functional connectivity.

Materials and Methods

Participants

Twelve participants (7 females, ages 18-26), with normal or corrected-to-normal vision, participated for monetary compensation. The study was approved by the Princeton University Institutional Review Board and all participants provided informed consent.

Attention runs

Functional runs followed an on-off block design with 18 s of stimulation interleaved with 18 s of fixation. Stimulation blocks contained 12 face/scene composite stimuli selected pseudorandomly, presented sequentially for 1 s each separated by a 500-ms interstimulus interval (Figure 1). Each run contained 12 blocks and lasted 7.2 minutes.

To create the composite stimuli, we drew from a set of 24 house photographs (from image searches on the Internet) and 24 face photographs (neutral expression, equal number of males and females, from www.macbrain.org/resources.htm). All photographs were equated in terms of mean luminance. For each run, 16 of the houses and 16 of the faces were selected randomly. Four of the photographs from each category were presented in a given block (three times each). The sequence of 12 photographs was determined separately for each category and included adjacent repetitions for the attention task (described below). The two streams were then combined by averaging the pair of house and face photographs at each serial position. This averaging involved simply taking the mean of the intensity values at each pixel. Because the two photographs had the same mean luminance, they made approximately equal contributions to the composite image. The photographs differed in other ways of course, which were preserved in the composite image, including: spatial frequency, central vs. peripheral information, number of objects, etc. Such differences were unavoidable to some extent, as they were what made the photographs depictions of houses and faces. Stimuli were presented on a projection screen at the back of the scanner bore ($6 \times 6^\circ$), viewed through a mirror attached to the head coil.

To manipulate attention, participants performed a one-back task on the photographs from one category for an entire run, while ignoring the photographs from the other category. During face-attention runs, for example, participants pressed a button with their right index finger when the face component of two successive composite images matched, irrespective of whether the house changed. Participants had 1 s to respond. One-back targets occurred once or twice per block (with equal probability) in both of the categories. During fixation periods, the only stimulus was a central fixation point.

There are two noteworthy properties of this task: First, bottom-up stimulation was identical across attentional states, allowing neural differences to be interpreted as reflective of top-down attention. Second, by holding attention on one category throughout each run, we encouraged participants to adopt strong attentional states that could modulate connectivity in a persisting manner. Although similar in design to one of our previous studies about retinotopic visual cortex (Al-Aidroos et al., 2012), a new dataset was collected for this study with high-resolution coverage of the MTL.

Rest runs

Additional rest runs of the same length as the attention runs were collected as a connectivity baseline, containing only the fixation point. Participants completed two rest runs first, followed by alternating face-attention and scene-attention runs (two each, order counterbalanced).

Localizer run

The localizer used the same stimuli, design, and task as the attention runs, but with house and face photographs presented individually in separate, alternating blocks (starting block counterbalanced).

Data acquisition

Data were acquired with a 3T Siemens Skyra scanner. Functional images were collected with a gradient-echo EPI sequence (TE = 28 ms; TR = 2000 ms; FA = 71°; matrix = 96×96). Each of 221 volumes contained 32 slices (2×2 mm in-plane, 3 mm thickness) perpendicular to the long axis of the hippocampus. A high-resolution 3D T1-weighted MPRAGE scan was collected for registration. A high-resolution T2-weighted TSE scan (32 slices; 0.4×0.4 mm in-plane; 3 mm thickness) was collected for manual MTL segmentation.

Preprocessing

Data were analyzed with FSL and MATLAB. The first 5 volumes of each run were discarded. All images were skull-stripped to improve registration. The images were preprocessed with motion correction (MCFLIRT), slice timing correction, spatial smoothing (4-mm FWHM), high-pass filtering (144-s cutoff), and FILM prewhitening. Functional images were registered to the MPRAGE and then the Montreal Neurological Institute (MNI) standard brain.

MTL segmentation

We manually segmented PRC and PHC on the TSE scan of each participant using published criteria (Insausti et al., 1998; Pruessner et al., 2002; see also Aly and Turk-Browne, 2016a). The anterior border of PRC was defined as the slice with the anterior-most tip of the collateral sulcus (CS). The posterior border of PRC was the last slice with the hippocampal head. The lateral border was at the base of the lateral bank of CS. The medial border coincided with the amygdala in slices with visible entorhinal cortex (ERC) and was halfway up the medial bank of the CS in slices where the ERC was not present. PHC was traced from the first slice of the hippocampal body to the last slice of the tail. The lateral border of PHC was perpendicular to the bend at the lateral bank of CS. The medial border was the subiculum, perpendicular to the dorsomedial edge of the temporal cortex. The resulting PRC and PHC ROIs of each participant were transformed to standard space.

Evoked activity in MTL ROIs

We estimated stimulus-evoked BOLD responses with a general linear model (GLM) containing finite impulse response (FIR) basis functions that captured the mean evoked

response across blocks. We used 17 FIR basis functions — one for every TR in a block, except the last TR (which served as the baseline for the next block). For each condition, we extracted the parameter estimates averaged over all voxels in an ROI, producing a timecourse of beta values. We converted them to percent signal change, combined across runs of the same type, and performed statistical analysis across participants. The peak response was averaged over TRs 3-11 in each block — the length of the block (TRs 1-9) shifted forward to account for hemodynamic lag (+ 2 TRs). Note that, because participants maintained the same attentional state for entire runs, we used only one set of FIR regressors per run. By fitting the evoked responses for scene- and face-attention in separate data, there was no collinearity or risk of shared variance ending up in the residual.

Background connectivity in ventral visual cortex

Background connectivity was estimated using a procedure detailed in Al-Aidroos et al. (2012). In brief, for each attention run, we first used a GLM to regress out nuisance variables (white matter and ventricle activity, and 6 motion parameters) from the preprocessed data. We applied a second GLM to the residuals of this nuisance model, to estimate stimulus-evoked BOLD responses with FIR basis functions, as for the evoked activity analysis above. This FIR approach precisely captured the timing and shape of the hemodynamic response in each voxel. The residuals of this task model were input into a third GLM, whose regressors were the mean residual timeseries in left and right PHC and PRC. The resulting parameter estimates provided a voxel-wise metric of correlation with PHC and PRC for each condition. The parameter estimates from runs of the same type were averaged within-subject at a second level using FSL, and then combined across left and right ROIs since we did not hypothesize hemispheric differences. We also examined differences between the first and second run of each attention condition, as a way of investigating whether attentional modulation increased when participants gained additional practice with the task (Figure S1).

Our key prediction was that voxels in ventral visual cortex would be more highly correlated with PHC during scene attention and PRC during face attention. To test this, we used *fslmaths* to contrast bilateral second-level parameter estimates for PHC in scene- and face-attention runs and for PRC in face- and scene-attention runs. We used FSL's *randomise* function to calculate the non-parametric, random-effects reliability of each contrast within an anatomical mask of the occipital and temporal lobes (defined using the MNI atlas), as well as to correct for multiple comparisons using cluster-mass correction (cluster-forming threshold, $p < 0.01$). The strongest version of our switching hypothesis was that some of the same voxels in ventral visual cortex would be more correlated with PHC in scene- vs. face-attention runs *and* more correlated with PRC in face- vs. scene-attention runs. To test this crossover interaction, we performed a conjunction analysis on the contrasts above by retaining only voxels that showed both effects at a corrected threshold.

Gradient analysis of MTL cortex

Until now, we treated PHC and PRC as distinct and internally homogeneous subregions of the parahippocampal gyrus, but there is evidence of a more continuous anterior-posterior gradient (Litman et al., 2009). To examine the profile of attentional switching more continuously, we merged PHC and PRC ROIs for each participant and repeated the analysis

above, slice-by-slice, from anterior to posterior along the parahippocampal gyrus. We only analyzed slices present in all participants in standard space, resulting in 20 parahippocampal gyrus slices per hemisphere (left hemisphere, $y = 42-61$; right hemisphere, $y = 44-63$). Each slice of the merged ROI served as the seed for analyzing background connectivity with ventral visual cortex.

We restricted analysis to voxels in ventral visual cortex that showed some interaction in background connectivity between MTL region (PHC, PRC) and attended category (scene, face). However, choosing an ROI because it shows the interaction in connectivity, and then examining the pattern of connectivity across slices in the same data would be plainly circular. We therefore adopted a leave-one-subject-out approach to help mitigate circularity: The interaction was calculated with the original PHC and PRC ROIs on $n-1$ participants; the largest cluster in ventral visual cortex was defined as an ROI ($ps < 0.05$ uncorrected); and then background connectivity with this ROI was calculated for every slice of parahippocampal gyrus in the n^{th} participant, for both scene- and face-attention runs. Every participant was left out once, resulting in a complete dataset. Note that this approach deals only with the most basic kind of statistical circularity, in which noise can bias results (e.g., overfitting). Specifically, noise contributing to the interaction in $n-1$ participants is no more likely than chance to be present in the n^{th} participant, and thus cannot benefit finding the interaction on average across iterations. However, we had reason to believe, from the main analysis, that the n^{th} participant would show an effect in the same general area, so were not blind to their data. We report results from these follow-up analyses to further visualize and characterize our main findings, but our key conclusions do not depend on them.

Note that we used the MTL region by attended category interaction to define the visual ROI in this analysis, rather than the conjunction reported earlier. This more liberal criterion — the crossover interaction revealed by the conjunction analysis is a subset of all possible interactions — ensured that we obtained a region in visual cortex for every partition of $n-1$ participants. The interaction ROI was also not subjected to the same multiple comparisons correction as before. Although these changes may have increased the likelihood of obtaining false positive voxels during ROI definition, the ROI on each $n-1$ iteration was used only to extract background connectivity from the independent n^{th} participant. Any false positive voxels in the ROI would only impair our ability to find effects in the held-out participant.

Relationship between evoked activity and background connectivity

We hypothesized that voxels responsive to scenes or faces but not selective for either category may show more attentional modulation of connectivity. To test this, we performed a voxel-wise analysis of ventral visual cortex. We first selected voxels based on their category selectivity in a group analysis of the functional localizer. We fit separate regressors for scene and face blocks, which modeled the evoked response with respect to an implicit baseline of the rest periods between blocks. Voxels that responded reliably to scenes and/or faces across participants (one or both parameter estimates > 0 , $p < 0.001$) were assigned a category-selectivity score — the absolute difference of the scene and face parameter estimates — which reflected the strength of their preference for one category over the other. We also assigned each of these voxels a connectivity-modulation score — background connectivity

with PHC for scene- minus face-attention runs *minus* background connectivity with PRC for scene- minus face-attention runs (the interaction term). We restricted analysis to voxels with the hypothesized switching effect (positive connectivity-modulation score). The relationship between scores was assessed by first averaging them over participants for each voxel and then calculating the Spearman's non-parametric rank correlation across voxels. We predicted a negative correlation, with weaker category selectivity linked to greater connectivity modulation. For random-effects hypothesis testing, we generated a bootstrapped confidence interval by resampling participants with replacement 1,000 times prior to the averaging and correlation computation, and calculated the p -value as the number of samples with positive correlations (Efron and Tibshirani, 1986).

Results

Behavioral performance

Participants were highly accurate on the one-back task, both when attending to scenes (mean $A' = 0.96$, $SD = 0.03$; vs. chance (0.50): $t(11) = 46.91$, $p < 0.0001$) and when attending to faces (mean $A' = 0.95$, $SD = 0.04$; $t(11) = 43.11$, $p < 0.0001$). Performance did not reliably differ between scene-attention and face-attention ($t(11) = 1.15$, $p = 0.28$). The hit rate across conditions was not at ceiling (mean = 0.84; $SD = 0.10$), suggesting that the task was demanding of attention.

Evoked activity in MTL ROIs

There was more activity in PHC (Figure 2A) for scene-attention compared to face-attention ($t(11) = 4.84$, $p = 0.0005$) and rest ($t(11) = 4.63$, $p = 0.0007$), but no difference between face-attention and rest ($t(11) = 0.54$, $p = 0.60$). There were no differences in PRC activity (Figure 2B) across conditions ($ps > 0.62$).

Background connectivity in ventral visual cortex

Two clusters of voxels in ventral visual cortex showed greater background connectivity with PHC in scene- vs. face-attention (Figure 3A): right posterior fusiform (PF) cortex (center-of-gravity MNI coordinates: 40, -58, -15; 896 voxels; corrected $p = 0.0005$) and left PF (-39, -66, -16; 750 voxels; corrected $p = 0.0008$). One cluster in ventral visual cortex emerged as showing greater background connectivity with PRC in face- vs. scene-attention (Figure 3D): right PF (42, -59, -18; 131 voxels; corrected $p = 0.04$). No clusters were obtained for the opposite contrasts of greater background connectivity with PRC for scene- vs. face-attention (Figure 3B) and with PHC for face- vs. scene-attention (Figure 3C).

The clusters in right PF with significant but opposite connectivity with PHC and PRC were overlapping (intersection: 39, -61, -17; 84 voxels; corrected $p < 0.05$). That is, this conjunction region (Figure 3E) showed the hypothesized switching effect — the same voxels were more coupled with PHC during scene-attention and PRC during face-attention. This attentional modulation was not reflected in evoked activity: peak responses in this PF region for scene-attention and face-attention were greater than rest ($t(11) = 9.75$, $p < 0.0001$ and $t(11) = 8.03$, $p < 0.0001$, respectively), but not different from each other ($t(11) = 0.36$, $p = 0.73$).

The remaining voxels outside of the conjunction region showed reliable background connectivity with only one of the seed ROIs. For PHC, these more selectively modulated voxels consisted of the entire left PF cluster and a large majority of the right PF cluster (812 voxels). For PRC, they were a small subset of the original right PF cluster (47 voxels).

Gradient analysis of MTL cortex

The profile of connectivity with ventral visual cortex changed gradually as we repeated the background connectivity analysis slice-by-slice throughout MTL cortex (Figure 4A), with greater connectivity for face-attention in mid-anterior slices and for scene-attention throughout posterior slices (Figure 4B). This pattern was reflected in a 2 (attention: scene, face) $\times$ 20 (slices) interaction ($F(19,209) = 3.50$, $p < 0.0001$).

Control analysis for residual evoked activity

We interpret background connectivity as reflecting idiosyncratic, spontaneous activity spreading over attentionally modulated functional networks. If true, then the residual timeseries in one scene-attention run should bear no relationship to the residual timeseries in the other scene-attention run (same for face-attention). If, on the other hand, residual evoked responses are sufficient for our effect, the same results should obtain if background connectivity is calculated across runs (because both runs used the same block timing). Consistent with our interpretation, the MTL region by attended category interaction that was significant within each run (Figure S1) was eliminated when background connectivity was calculated across runs — i.e., between PHC/PRC in one run and ventral visual cortex in the other run ($F(1,11) = 1.93$, $p = 0.19$).

Relationship between evoked activity and background connectivity

Across all visually-responsive voxels in ventral visual cortex that showed connectivity switching, there was a reliable negative correlation (Figure 5) between the strength of category selectivity and the amount of modulation of background connectivity with PHC and PRC (Spearman's $r(4054) = -0.43$, random-effects bootstrapped $p < 0.001$). That is, voxels with mixed category selectivity showed more attentional modulation of MTL connectivity. Consistent with this, the conjunction region — which showed the most robust switching effect — responded strongly to both scenes and faces in the localizer ($t(11) = 5.85$, $p = 0.0001$ and $t(11) = 7.54$, $p < 0.0001$, respectively) but was not selective for one category over the other ($t(11) = 0.47$, $p = 0.65$).

Discussion

There are at least two possible ways in which top-down attention could influence coupling between ventral visual cortex and MTL cortex, which are not mutually exclusive. The first way is that attention could operate on separate pathways that connect visual cortex to PHC and PRC, respectively. That is, attention to scenes may modulate PHC connectivity with certain visual regions and attention to faces may modulate PRC connectivity with other visual regions. This is consistent with the fact that different sets of cortical areas show resting connectivity with PHC and PRC (Kahn et al., 2008; Ranganath and Ritchey, 2012). In this account, these separate areas may themselves preferentially process scenes and faces,

respectively. When their preferred category is task-relevant, connectivity with the corresponding MTL area increases; when task-irrelevant, connectivity returns to baseline. Critically, these areas would not show increased connectivity with other MTL areas, no matter what category is task-relevant. The category-specific MTL connectivity of these areas may reflect attentional modulation of their local activity and synchronization, which would lead to increased impact on downstream regions (Womelsdorf and Fries, 2007). This impact can be reflected in long-range coherence in high-frequency oscillations (Saalmann et al., 2007; Gregoriou et al., 2009). BOLD correlations, as measured here, could reflect either this long-range coherence between regions or synchronized increases in their local coherence (Niessing et al., 2005; Koch et al., 2009; Harris and Gordon, 2015).

Some of our results were consistent with this separate-pathway account. Certain voxels in bilateral ventral visual cortex showed enhanced connectivity with PHC when scenes were attended, but attention did not modulate their connectivity with PRC. Likewise, other voxels in right ventral visual cortex showed enhanced connectivity with PRC when faces were attended, but attention did not modulate their connectivity with PHC. Overall, many fewer voxels showed category-specific connectivity with PRC than PHC. A possible reason for this is that PHC was more selective for scenes than PRC was for faces (Figure 2). Alternatively, the scene images may have been more complex than the face images in terms of low-level features, and thus recruited lower-level visual regions to a greater extent during task performance.

The second way that top-down attention could influence visual-MTL coupling is that the same area of visual cortex may be anatomically connected to both PHC and PRC, but which of these regions it is *functionally* connected to depends on what category is being attended. That is, attention to scenes may increase the area's background connectivity with PHC and attention to faces may increase its connectivity with PRC. Such doubly connected visual areas exist in non-human primates: TE and TEO in inferior temporal cortex project to both PHC and PRC (Suzuki and Amaral, 1994). In this account, a visual area need not be selective for either scenes or faces in terms of evoked activity. Rather, its involvement in processing the task-relevant category derives from its affiliation with the corresponding MTL area. In other words, attentional modulation does not entail strengthening a single pathway vs. not, but instead flexibly switching between two (or more) pathways. Given this potential lack of selectivity, however, enhancing local activity or synchronization (with fixed downstream consequences) may not be sufficient to selectively modulate connectivity. Instead, a separate top-down control signal may be needed. The thalamus and/or frontoparietal cortex can serve this role, for example by synchronizing oscillations or providing coordinated input between regions to induce long-range coherence (Noudoost et al., 2010; Saalmann et al., 2012).

Consistent with this branching-pathway account, our study revealed an area of right ventral visual cortex whose background connectivity with PHC and PRC depended on which category was task-relevant. This area responded equally to both scenes and faces in the localizer run and to both scene- and face-attention in the attention runs. Indeed, voxels in this area with a smaller difference in evoked activity between categories (less selectivity) showed the most switching in connectivity between PHC and PRC. We interpret this

negative relationship as reflecting a need for top-down control to disambiguate the evoked activity. Specifically, when a voxel or region has broad tuning — either for both scenes and faces, or for low-level features common to both categories — and is anatomically connected to regions with differing selectivity, attentional switching of connectivity may determine how the information is processed downstream. We were not well-positioned to identify the sources of this top-down control in the current study because we collected only a partial volume in order to obtain high-resolution coverage of the MTL.

Although we designed the study to test how MTL cortex interacts with visual cortex, our interest in MTL cortex derives from its role in providing input to the hippocampus. We thus also examined attentional modulation of the hippocampus. However, we did not observe modulation of evoked activity in hippocampal subregions (Figure S2), or modulation of background connectivity between the hippocampus and PHC/PRC (Figure S3). This lack of attentional modulation in the hippocampus mirrors prior findings (Dudukovic et al., 2011; Yamaguchi et al., 2004). However, recent evidence suggests that attentional signals in the hippocampus may be better reflected in distributed state representations (Aly and Turk-Browne, 2016a, 2016b). How the state of the hippocampus depends on connectivity between visual and MTL cortices, and between MTL cortex and the hippocampus remains an important question for future research.

Furthermore, because MTL connectivity might affect what information ends up in the hippocampus, attentional modulation of this connectivity could influence behavioral performance in learning and memory tasks that depend on the hippocampus. The current study had limitations with respect to measuring such relationships. The only behavioral measure of learning and memory we could have obtained, given the design, was subsequent memory for the images. However, we did not include a memory test at the end of the study. Our reasoning was that this would not be informative because the same scene and face images were repeated multiple times. Thus, it would be impossible to relate subsequent memory to any particular encoding event. This could be resolved by using trial-unique images. Even if we had done so, however, a more fundamental issue is that calculating connectivity requires several timepoints of data, making it hard to link connectivity and encoding on a trial-by-trial basis. In ongoing work, we are examining such mnemonic consequences using hippocampally dependent tasks in which learning plays out over a longer timescale (e.g., statistical learning).

These limitations also affected our ability to link connectivity to behavioral measures of attention. Namely, participants were only asked to respond when a target was present, but repetitions were infrequent. This low target probability means that false alarms were rare, and that there were only one or two opportunities to respond correctly per block. Thus, hit and miss rates were unstable at a block level, and again it would be hard to link connectivity calculated over runs (or even blocks) to these sparse events. In addition to requiring more frequent responses (e.g., to both present and absent trials), a more difficult task might be helpful in future work, as high performance (here $A' > 0.95$) also meant that there was not enough variation in accuracy to be explained.

The attentional modulation of connectivity between visual and memory systems that we report complements previous findings of switching within the visual system itself. Top-down attention enhances connectivity between visual areas selective for goal-relevant locations and features. When spatial attention is allocated to one of two locations in the receptive field of a population of V4 neurons, this population shows enhanced gamma coherence with the population of V1 neurons whose (much smaller) receptive field covers that location but not the V1 population coding for the other location (Bosman et al., 2012). When feature-based attention is allocated to a scene or a face in composite images (as in the current study), V4 shows enhanced background connectivity with PPA and FFA, respectively (Al-Aidroos et al., 2012). The present findings extend this form of attentional modulation outside of the visual system, providing a proof-of-concept for how top-down attention might influence other systems and cognitive processes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Attention increases coupling of visual areas that process task-relevant information
- May explain how information is prioritized for processing in medial temporal lobe
- Visual cortex connects to PHC when scenes attended and to PRC when faces attended
- Switching of background connectivity most pronounced for unselective visual voxels
- Candidate mechanism for how attention can influence learning and memory behavior

Figure 1. Stimulus design

(A) Example study timeline, including two rest runs, 4 attention runs (2 face- and 2 scene-attention runs, interleaved, order counterbalanced), and 2 localizer runs. (B) All runs followed an ON-OFF block design with 18 s of stimulation followed by 18 s of fixation. During the stimulation blocks in the attention runs, participants directed their selective attention to either the face or scene image in the composite stimuli and performed a 1-back task on that image (solid outline = target in task-relevant category; dashed outline = distractor in task-irrelevant category). The same category was relevant for an entire run. Stimuli were on screen for 1 s followed by 0.5 s of fixation. (C) In the localizer runs, blocks contained images and repetitions (solid outline) from either the face or scene category, but the category alternated within the same run (starting order counterbalanced).

Figure 2. Evoked activity

BOLD response in PHC (A) and PRC (B) for scene-attention, face-attention, and rest runs, averaged across participants. Stimulation lasted 18 s followed by 18 s of fixation, and we quantified the peak as 4-22 s to account for the hemodynamic lag. Error ribbons reflect ± 1 within-subject SEM.

Figure 3. Voxel-wise background connectivity

Voxels are colored in yellow when their residual activity was more highly correlated over time ($p < 0.05$ corrected) with the residual activity from (A) PHC during scene- vs. face-attention runs (bilateral PF) and (D) PRC during face- vs. scene-attention runs (right PF). Such modulation was specific to the type of information being attended, as no clusters were obtained for the opposite contrasts of higher correlation with (B) PRC during scene- vs. face-attention runs and (C) PHC during face- vs. scene-attention runs. (E) A subset of right PF voxels in (A) and (D) overlapped, with this conjunction cluster showing the hypothesized attentional switching of MTL background connectivity. Brains depicted in radiological convention (right on the left).

Figure 4. Slice-wise gradient

(A) Analysis was restricted to the 20 slices in MTL cortex obtained from all participants, each depicted in a different color. (B) Background connectivity between each slice and ventral visual cortex for scene-attention, face-attention, and rest runs, averaged across participants. Error ribbons reflect ± 1 within-subject SEM.

Figure 5. Selectivity-connectivity relationship

Voxel-wise relationship between category selectivity (absolute difference of scene minus face from localizer) and attentional modulation of background connectivity (interaction between MTL region and attended category in the hypothesized direction). The relationship was estimated using Spearman's rank correlation. Each voxel's value reflects the average across participants. Random-effects statistical analysis was performed by resampling participants with replacement and re-computing the correlation. To help visualize the trend,

the purple triangles indicate the average connectivity modulation across voxels in 15 equally spaced bins of category selectivity.