

Involuntary capture of attention produces domain-specific activation

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In this study, we ask whether or not the involuntary capture of attention by a specific information type can produce domain-specific activation. Participants indicated the presence of a flicker in rapidly alternating letter-string masks presented in the periphery. Despite letters not being relevant to the task, we found, using functional MRI and a novel task that allowed us to contrast attended and

unattended processing of the same visual information, a robust modulation by attentional capture in a localized letter-processing region. This finding suggests that the involuntary capture of attention is sufficient to produce domain-specific activation in early visual processing. *NeuroReport* 18:975–979 © 2007 Lippincott Williams & Wilkins.

Keywords: attentional capture, domain-specific processing, visual word form area

Introduction

Visual attention can be directed voluntarily or it can be captured by salient events in the visual scene. Earlier research has revealed that voluntarily selecting stimuli of a particular type, such as a face, in an array of different stimulus types (e.g. faces and houses) can produce increased activation in brain regions that preferentially process the attended stimuli (i.e. domain-specific activity [1–3]). Such increases in activation are generally attributed to an interaction between stimulus-driven and ‘top-down’ attentional control factors [4–7]. In this study, we asked whether voluntarily directed attention is necessary to produce domain-specific activation.

In standard theories of information processing, early ‘automatic’ processes are autonomous and, importantly, independent of top-down cognitive mechanisms [8,9]. Thus, as has been demonstrated in studies in which participants voluntarily direct their attention, we hypothesized that the involuntary capture of attention [10–12] might also produce domain-specific activation. This has not been assessed before: (i) because domain-specific activity has generally been assumed to involve voluntary processes and (ii) because of the inherent difficulty in designing an experimental paradigm that allows the neural activity associated with stimuli that capture attention to be compared with the activity associated with stimuli that fail to capture attention (while holding the visual information constant in both conditions). In this study, we evaluated the hypothesis under investigation within the domain of letter processing using functional MRI (fMRI) and a novel paradigm that we recently developed to investigate behavioral manifestations of involuntary attentional capture [13].

It is well established that a specific brain region within the left fusiform gyrus, the so-called visual word form area (VWFA), is activated more strongly by letters than nonletter stimuli [14] and, importantly, that the VWFA processes letters at an abstract level, independent of case, font, or size ([15] also see Ref [16]). In contrast, the right hemisphere homologue of the VWFA is engaged by letters and non-letter stimuli equally [14] and fails to exhibit invariant processing of letter stimuli [15]. On the basis of these findings, it appears that the VWFA may be ‘tuned’ to process letters qua letters whereas the right hemisphere homologue is not and, consequently, processes letters as unexceptional shapes (Ref. [13]). Hence, we reasoned that if attentional capture (an involuntary process) can engage domain-specific mechanisms, then the VWFA should become selectively more active when participants’ attention is captured by a flicker that appears in a location containing letters. Importantly, because we were interested in the possibility that the involuntary capture of attention might produce domain-specific activation, our task did not require participants to voluntarily direct their attention to letters while ignoring other information. Participants simply had to indicate whether a flicker appeared on the left, right or both sides of the display. An important feature of our study was that it allowed us to contrast the processing of visual information under two conditions: when it captured attention versus when that same information failed to capture attention [13].

Methods

Participants

Twelve right-handed participants (four women) between 19 and 36 years old with normal or corrected-to-normal visual

acuity completed the study. The experimental protocol was approved by the Massachusetts General Hospital Institutional Review Board, and written informed consent was obtained from each participant before the study commenced. Participants were each paid \$100.

Stimuli and task

Letter strings (WZSPMRXQ and QRPZXMSW) appeared to the left and right of a central fixation cross (Fig. 1), and were rapidly alternated in presentation (167 ms), which gave the appearance of continuously ‘fluttering’ letter strings (each 5.4° × 0.7° visual angle, with nearest edge 3.7° visual angle from fixation). At unpredictable times, a target consisting of a lowercase letter pair (e.g. xk; 0.9° × 0.7° visual angle, with nearest edge 5.9° visual angle from fixation) replaced one of the letter strings for a brief period (33 ms). The letter strings served as masks for the targets and effectively eliminated target identification but did not eliminate target detection: [In a separate control experiment in which participants (N=5) performed a forced-choice task (Was the flicker caused by ‘mm’ or ‘pp’?), 84% of the targets were detected but target identification was at chance ($d' = 0.017$).] Detected targets appeared as a flicker in otherwise continuously fluttering letter strings.

Across the experiment, targets appeared with equal probability to the right and left sides of fixation and with or without lures in the opposite hemifield [with each of these four trial types occurring approximately 20 times, with a mean inter-stimulus interval (ISI) of 8 s]. Lures were identical to the targets but were presented for a longer duration (100 ms), beginning 33 ms before the onset of the target and persisting for 33 ms after the offset of the target. As such, the flicker produced by the lures was more

effective at capturing attention (i.e. more salient) than the flicker produced by the targets. Participants were not informed of the difference between lures and targets and thus simply responded via button press whenever they detected a flicker on the ‘left’, ‘right’, or ‘both sides’. Shortly after participants indicated the location of the flicker(s), the central fixation cross was replaced with a question mark (for 2000 ms), which cued participants to indicate their confidence regarding their preceding location judgment (‘sure’ or ‘unsure’); no targets or lures were presented during this time. This yielded a double judgment on every detected trial corresponding to perceived visual field(s) and confidence (‘right-sure’, RS; ‘right-unsure’, RU; ‘left-sure’, LS; ‘left-unsure’, LU; ‘bilateral-sure’, BS; and ‘bilateral-unsure’, BU).

Functional MRI

Imaging was conducted on a 3T Siemens Allegra scanner (Siemens, Erlangen, Germany). T1-weighted anatomic images were acquired using a multiplanar rapidly acquired gradient echo sequence (repeat time (TR)=30 ms, echo time (TE)=3.3 ms, flip angle=40°, field-of-view (FOV) =256 × 256 mm, matrix=256 × 256, slices=128, slice thickness=1.33 mm, and no gap). T2*-weighted functional images were acquired using an echo planar imaging sequence (TR=2000 ms, TE=30 ms, flip angle=90°, FOV=256 × 256, matrix=64 × 64, slices=35, slice thickness=4 mm, no gap; 4 mm isotropic resolution). There were two functional runs each lasting 9 min 18 s. Data preprocessing and analysis were conducted using BrainVoyager (Brain Innovation B.V., Maastricht, The Netherlands). Functional preprocessing included slice-time correction, motion correction, high-pass filtering (above three cycles per run), and transformation into Talairach space [17].

To conduct the functional analysis on an individual participant basis, each event’s protocol – a series of squarewaves defined by the associated event’s onsets and durations – was convolved with a canonical hemodynamic response function that incorporated the delay in hemodynamic response to yield the corresponding hemodynamic response model. Events included target type [unilateral target on the left (TUL) or right (TUR) or bilateral target on the left (TBL) or right (TBR); see Fig. 1] along with the corresponding response (RS, LS, BS, RU, LU, BU, and no response). On a voxel-by-voxel basis, a general linear model was used to determine each event’s hemodynamic response model amplitude/ β -weight [18]. Specifically, each model amplitude/ β -weight was scaled to provide the best fit to each voxel’s activation time course. Of particular relevance, a positive β -weight indicates that a given event type is correlated with activity in a given voxel. Contrasts between two event types were computed using the difference in β -weights. Conjunctions between two contrasts identified those voxels in which both contrasts were associated with positive β -weights [19]. These values were then entered into a true random effect (group) analysis to identify the voxels in which the β -weight differences or β -weights were consistently positive across participants, using one-tailed t -tests.

An individual voxel P -value of $P < 0.01$ was enforced for all contrasts and conjunctions. Furthermore, a cluster extent threshold [20] of 459 mm was enforced to ensure the results were corrected for multiple comparisons to $P < 0.05$. This

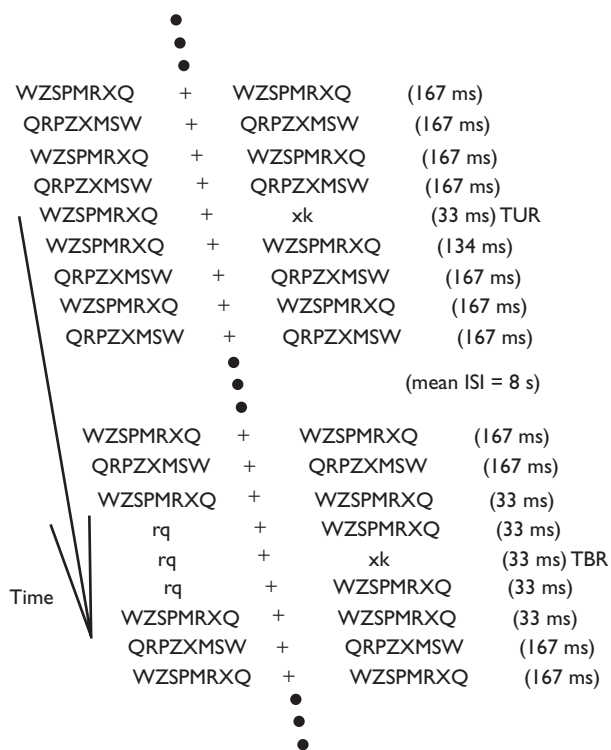


Fig. 1 Stimulus time sequence associated with two trial types, target unilateral right (TUR) and target bilateral right (TBR).

Table 1 Neural regions associated with cognitive contrasts and conjunction

Region	BA	x	y	z
TUR-RS > TBR-LS				
Left MOG	19	-29	-84	14
Left IOG	19	-42	-72	-1
Left fusiform gyrus	19	-28	-65	-12
Left fusiform gyrus	37	-33	-54	-13
Left fusiform gyrus	20	-32	-41	-13
TUL-LS > TBL-RS				
No activity				
(TBL-BS > TUL-LS) \cap (TBR-BS > TUR-RS)				
Left fusiform gyrus	37	-29	-53	-13
Right fusiform gyrus	37	30	-59	-15

Regions, Brodmann areas (BA) and Talairach coordinates (x, y, z) refer to the centers of each cluster of activity (within a given BA \times gyrus intersection). BS, 'bilateral-sure'; LS, 'left-sure'; RS, 'right-sure'; TBL, bilateral target on the left; TBR, bilateral target on the right; TUL, unilateral target on the left; TUR, unilateral target on the right. MOG, middle occipital gyrus; IOG, inferior occipital gyrus.

extent threshold was determined via 1000 Monte Carlo simulations using custom software written in MATLAB (The MathWorks, Natick, Massachusetts, USA), where the individual voxel type I error rate was set to $P=0.01$ and spatial autocorrelation was modeled via convolution with a 4.5 mm full-width half-maximum Gaussian smoothing kernel [21,22]. Given that the joint probability of observing two activations (each at $P<0.01$) yields an individual voxel joint probability of $P=0.001$ [22], enforcing the cluster extent threshold specified above for the conjunction yields correction for multiple comparisons to $P<0.01$.

Anatomic volumes were transformed into Talairach space and then averaged across participants, allowing for localization of functional activity. To aid in visualization, the group results were projected onto a cortical surface representation of a representative participant [18,23]. It is important to note that this activity is only reflective of the group results; for precise activation coordinates, see Table 1.

Hemispheric laterality in 'letter processing' areas was tested by extracting event-related activity timecourses from voxels within a 4 mm radius sphere centered at each coordinate/region of interest [24]. This sphere size was selected to balance signal strength and spatial resolution. Activity was corrected for linear drift and baseline-corrected to 0% signal change from 0 to 2 s before stimulus onset. The magnitude of activity was assessed at 6 s following stimulus onset (i.e., the expected maximum; see Refs [18,22]). For each region of interest (in the left or right hemisphere), a one-tailed paired *t*-test was used to determine whether the difference of activation between two event types – detected and undetected targets – was consistently positive across participants. Note that one-tailed *t*-tests were employed, as detected rather than undetected targets were hypothesized to produce an increase in contralateral activation *a priori*. For a region of interest and its homologue in the contralateral hemisphere, a within participant analysis of variance (ANOVA) was used to determine whether there was a significant condition \times hemisphere interaction.

Results

Participants detected 74% of the TUL and 73% of the TUR with confidence. Thus, participants were not biased to

detect targets in one hemifield over the other. Importantly, participants detected (with confidence) only 30.8% of the TBL targets (left hemifield target, right hemifield lure) and 32.9% of the TBR targets (right hemifield target, left hemifield lure). Furthermore, 43% of the TBL targets and 34% of the TBR targets were 'extinguished'. For example, on TBR trials, where the correct response is 'both sides – sure', participants responded 'left – sure' 34% of the time (i.e. TBR-LS), indicating that they detected the left hemifield lure and failed to detect the right hemifield target. [Note that the percentage of detected and extinguished trials does not add up to 100% because there were a number of targets that were either missed (no response given) or responded to without a confidence judgment.]

The lures, by virtue of their longer duration, captured attention most strongly and thus were most likely to produce activation in the regions responsive to letters. To isolate the regions associated with lure processing, the following conjunction analysis was used: (TBL-BS > TUL-LS) \cap (TBR-BS > TUR-RS). The first contrast in the conjunction isolated confident processing of lures in the right hemifield, whereas the second contrast in the conjunction isolated confident processing of lures in the left hemifield. The conjunction revealed that both the left and right fusiform gyri were activated by the processing of left and right hemifield lures (see Table 1). This pattern of bilateral activation is typically observed with attended processing of letter strings [14,15,25,26]. Critically, the regions of activation associated with lure processing in our paradigm corresponded closely to the VWFA coordinates reported in the literature (extending to within 5 mm, one SD, of the typical VWFA center of activation identified via a meta-analysis [25] and within 3 mm of the VWFA homologue center of activation [15]); this validates use of our conjunction analysis to identify VWFA and its right hemisphere homologue.

Having localized these 'letter-processing' regions, we wanted to determine if attentional capture modulated either or both. To investigate this possibility, we first contrasted targets that captured participants' attention in the right hemifield (TUR-RS) with targets that failed to capture attention in the right hemifield (TBR-LS). This analysis revealed a significant increase in activation in intermediate and late visual-processing regions within the left hemisphere, including an area in the left fusiform corresponding closely to the VWFA (Fig. 2; Table 1). Strikingly, the analogous comparison between left visual-hemifield targets (TUL-LS > TBL-RS) revealed no significant activity in either the left or right hemisphere. To investigate the possibility that the threshold we adopted was too conservative, we conducted hemispheric laterality tests by analyzing the event-related timecourses extracted from the left fusiform region corresponding to the VWFA (-33, -54, and -13) and the right fusiform homologue of this region (33, -54, and -13). Supporting our earlier results, the magnitude of event-related time-course activity was greater in the left fusiform for detected versus undetected targets in the right visual field ($P<0.05$). In contrast, this difference in activation in the right fusiform did not approach significance ($t<1$). Importantly, the condition \times hemisphere interaction was reliable ($P<0.05$). Furthermore, for stimuli presented in the left visual field, the time-course analysis confirmed that there were no significant differences in activity associated with detected versus undetected targets in either the left or

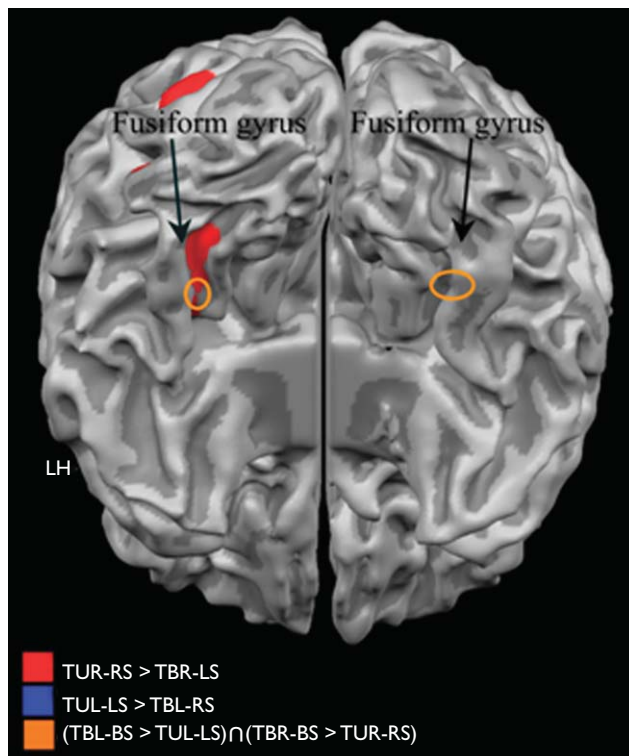


Fig. 2 Group neural activity projected onto the cortical surface of a representative participant (posterior–inferior view; left hemisphere is on the left). The neural regions associated with the highly salient lures are demarcated by orange ellipses. Depicted in red is the contrast between the greater neural activity associated with unilateral right targets that were detected correctly and confidently (target unilateral right – ‘right sure’ – TUR-RS) versus bilateral right targets that were missed with confidence (target bilateral right – ‘left sure’ – TBR-LS). In blue, the complementary contrast for left visual field targets is depicted (no differential activation between attended and unattended targets was observed).

right fusiform (both $t_s < 1$). These time-course analysis results demonstrate that attentional capture activates the VWFA in the left fusiform but not its right hemisphere homologue.

Discussion

These findings provide the first evidence that the involuntary capture of attention can produce domain-specific activation. In our experimental paradigm, participants maintained central fixation when monitoring for the presence of a flicker in one or both of two peripheral locations containing fluttering letter strings. Under these conditions, the localized letter-processing region in the left but not right fusiform gyrus exhibited a highly robust modulation by attentional capture. We suggest that the effect of attentional capture was restricted to this area because this region is tuned to process letters. This conclusion is consistent with earlier findings that have isolate letter-specific processing to this region [25–27]. Thus, our findings provide further support that the VWFA is selectively engaged by letters and additionally reveals that this domain-specific activation can be modulated by the involuntary capture of attention.

A possible objection to this conclusion is that attentional capture might always modulate the BOLD response in the

VWFA, meaning that the restriction of this effect to this region in our paradigm may not be informative with respect to domain-specific processing. Although this is logically possible, it is extremely unlikely and is undermined by what we already know about the neural correlates of attentional capture from studies that have used nonletter stimuli [28,29,30].

An issue for further research is whether or not the modulation by attentional capture that we have reported here depends upon participants adopting a particular task set. It could be, for example, that to observe domain-specific activity in the VWFA, participants would have to be aware that letters are important to the task at hand. In our task, participants were presumably aware that the flicker they were to report occurred in regions that contained letters and, hence, may have unintentionally adopted a letter-detection ‘set’. Future experiments will be needed to determine the extent to which the modulation of domain-specific activity is ‘contingent’ upon participants being aware of the informational content of the stimuli that capture their attention [10,31].

Conclusion

In support of the hypothesis under investigation, we observed robust modulation of the VWFA by attentional capture. This is the first demonstration – to our knowledge – that the involuntary capture of attention by a specific information type can produce domain-specific activation.

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