

Visual Distraction Disrupts Category-tuned Attentional Filters in Ventral Visual Cortex

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Abstract

■ Our behavioral goals shape how we process information via attentional filters that prioritize goal-relevant information, dictating both where we attend and what we attend to. When something unexpected or salient appears in the environment, it captures our spatial attention. Extensive research has focused on the spatiotemporal aspects of attentional capture, but what happens to concurrent nonspatial filters during visual distraction? Here, we demonstrate a novel, broader consequence of distraction: widespread disruption to filters that regulate category-specific object processing. We recorded fMRI while participants viewed arrays of face/house hybrid images. On distractor-absent trials, we found robust evidence for the standard signature of category-tuned attentional filtering: greater BOLD activation in fusiform face area during attend-faces blocks and in parahippo-

campal place area during attend-houses blocks. However, on trials where a salient distractor (white rectangle) flashed abruptly around a nontarget location, not only was spatial attention captured, but the concurrent category-tuned attentional filter was disrupted, revealing a boost in activation for the to-be-ignored category. This disruption was robust, resulting in errant processing—and early on, prioritization—of goal-inconsistent information. These findings provide a direct test of the filter disruption theory: that in addition to disrupting spatial attention, distraction also disrupts nonspatial attentional filters tuned to goal-relevant information. Moreover, these results reveal that, under certain circumstances, the filter disruption may be so profound as to induce a full reversal of the attentional control settings, which carries novel implications for both theory and real-world perception. ■

INTRODUCTION

Our visual environments are too complex to process in their entirety. To compensate, we filter incoming visual information based on current behavioral goals, using attention to selectively process only the most relevant information (e.g., Desimone & Duncan, 1995; Bundesen, 1990). One way that we filter information is by prioritizing objects based on high-level attributes such as category: When searching for a friend on a busy street, for instance, we prioritize the faces in the scene at the expense of less relevant categories such as houses. Category-based attention ensures that important information is prioritized for attentional selection early (Nako, Wu, & Eimer, 2014; Zhang & Luck, 2009) and simultaneously throughout space (Liu & Hou, 2011; Liu & Mance, 2011; White & Carrasco, 2011; Sàenz, Buraças, & Boynton, 2003; Saenz, Buracas, & Boynton, 2002), increasing search efficiency (e.g., speed).

Such category-tuned filters are partially subserved by category-specific neural regions in ventral visual cortex, such as the fusiform face area (FFA; Kanwisher, McDermott, & Chun, 1997; Mccarthy, Puce, Gore, & Truett, 1997) and the parahippocampal place area (PPA; Epstein & Kanwisher, 1998). These regions respond preferentially to viewing images of faces and scene stimuli, respectively, and are sensitive to attentional manipulations. Neural evidence

of object-based attentional filtering has been demonstrated using categorically defined stimuli that overlap in space (i.e., “hybrid” stimuli of semitransparent superimposed images) as well as during binocular rivalry and mental imagery, with BOLD responses enhanced in FFA relative to PPA when observers attend to faces and in PPA relative to FFA when observers attend to houses (Baldauf & Desimone, 2014; Hsieh, Colas, & Kanwisher, 2012; O’Craven & Kanwisher, 2000; Serences, Schwarzbach, Courtney, Golay, & Yantis, 2004; Tong, Nakayama, Vaughan, & Kanwisher, 1998). This category-based attentional modulation has been linked to frontoparietal gamma synchrony (Baldauf & Desimone, 2014), attentional shift signals (Serences et al., 2004), and functional connectivity (Turk-Browne, Norman-Haignere, & Mccarthy, 2010).

At the same time, efficient goal-directed behavior also relies heavily on spatial attention (Nako et al., 2014; Liu & Mance, 2011; White & Carrasco, 2011; Zhang & Luck, 2009; Saenz et al., 2002, 2003; Hoffman & Nelson, 1981). Goal-directed spatial attention and feature- or category-based filters can coexist (Stein & Peelen, 2017), allowing us to tune attention to task-relevant objects in attended locations. However, many of these studies have overlooked a critical problem: Spatial attention is not static; in the real world, dynamic and distracting information also competes for selection. What are the consequences for category-based attention when distracting information appears in the search environment?

Most prior work on visual distraction has focused on disruptions to spatial attention: The presence of distractors increases search RTs (Theeuwes & Burger, 1998; Folk, Remington, & Johnston, 1992; Remington, Johnston, & Yantis, 1992; Yantis & Jonides, 1984; Jonides & Irwin, 1981), attracts eye movements (Liesefeld, Liesefeld, Töllner, & Müller, 2017; Henderson, 2003; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Theeuwes, Kramer, Hahn, & Irwin, 1998), and elicits electrophysiological markers of covert spatial attention (Bacigalupo & Luck, 2019; Wang, van Driel, Ort, & Theeuwes, 2019; Luck & Hillyard, 1994) during visual search. More recent work has started to evaluate broader consequences of visual distraction, for example, demonstrating that attentional capture can also distort feature perception (Chen, Leber, & Golomb, 2019). However, what about other types of concurrent nonspatial attentional control? Recently, Dube and Golomb (2021) proposed a filter disruption theory, suggesting that in addition to disrupting spatial attention filters, visual distraction also disrupts currently active nonspatial filters. Dube and Golomb (2021) used a behavioral memory-driven capture paradigm (Olivers, Meijer, & Theeuwes, 2006) to demonstrate that distraction disrupts the filter that prioritizes relevant information for visual working memory (VWM) encoding, resulting in irrelevant distractor features intruding into VWM. However, the most direct prediction of this theory remains untested: that distraction could even disrupt a prolonged, robust attentional control setting like a stable category-based filter, causing a temporary increase in neural processing of task-irrelevant information across the visual field.

In the current study, we use face–house hybrid stimuli and fMRI to directly evaluate this key prediction of the filter disruption theory: in addition to capturing spatial attention, visual distraction also momentarily disrupts a category-tuned attentional filter, causing the selection and processing of stimuli from a task-irrelevant category that would otherwise be ignored. We predicted that, on distractor-absent trials, we would observe the standard signature of attentional modulation: greater FFA activity on attend-faces blocks relative to attend-houses blocks and greater PPA activity on attend-houses blocks relative to attend-faces blocks. Critically, on trials where a salient distractor appears, we consider two competing hypotheses: (1) Spatial attention is captured, but the category filter remains intact, resulting in a behavioral capture effect (e.g., slower RTs), but preserved neural selectivity (e.g., greater FFA during attend-faces blocks), versus (2) spatial attention is captured and the category-tuned attentional filter is also broken, resulting in the errant processing of the irrelevant object category (i.e., houses during attend-faces blocks).

METHODS

Overview

On each trial, participants viewed an array of four face/house hybrid images, one of which was defined as

the target via a white border. Participants were instructed to attend to one stimulus category (i.e., attend-faces blocks and attend-houses blocks) and determine whether the identity of the target stimulus on the current trial matched that of the previous trial. On some trials, a salient distractor (a white dotted line) appeared briefly around one of the other three hybrid images. To examine category-tuned attentional filtering, we measured BOLD activation in the FFA and the PPA. Critically, here, we are not testing whether a distracting image is processed during attentional capture. Rather, we are evaluating whether attentional capture breaks a long-term (across-block) category filter, causing the incidental processing of the irrelevant object category within the hybrid images.

Participants

Fifteen participants participated in the study (eight women, seven men; mean age = 23.5 years, range = 19–31 years) for monetary compensation (\$10/hr for the behavioral prescreen, \$15/hr for the scanning session). One participant was an author but was scanned before their role in or knowledge of the study. All participants reported normal or corrected-to-normal vision, provided informed consent, and were prescreened for MRI eligibility. The study protocol was approved by the Ohio State University Biomedical Sciences institutional review board.

The sample size was selected with the goal of extensive within-participant sampling and was chosen to be sufficient to detect the characteristically large effect sizes for univariate comparisons of FFA/PPA activity, comparable to prior studies (Peters, Roelfsema, & Goebel, 2012; Yi, Kelley, Marois, & Chun, 2006; Wojciulik, Kanwisher, & Driver, 1998). The approach of collecting relatively smaller sample sizes, but with extensive numbers of trials for each participant, is an alternative way of increasing statistical power (Naselaris, Allen, & Kay, 2021) and carries certain benefits, including the ability to assess the robustness of effects at the individual participant level. In our design, each of our participants completed 576 experimental trials, and we show both group- and individual-level results in our data figures.

Stimuli and Task

Stimuli were generated and presented using MATLAB (Mathworks, Inc.) and the Psychophysics Toolbox (Brainard, 1997) and were presented on a gray background for both the experimental and localizer tasks. Participants viewed all stimuli from a distance of 74 cm via a mirror 45° above the head coil.

Experimental Task

See Figure 1 for a trial schematic. Experimental stimuli were grayscale face/house hybrid images, made by

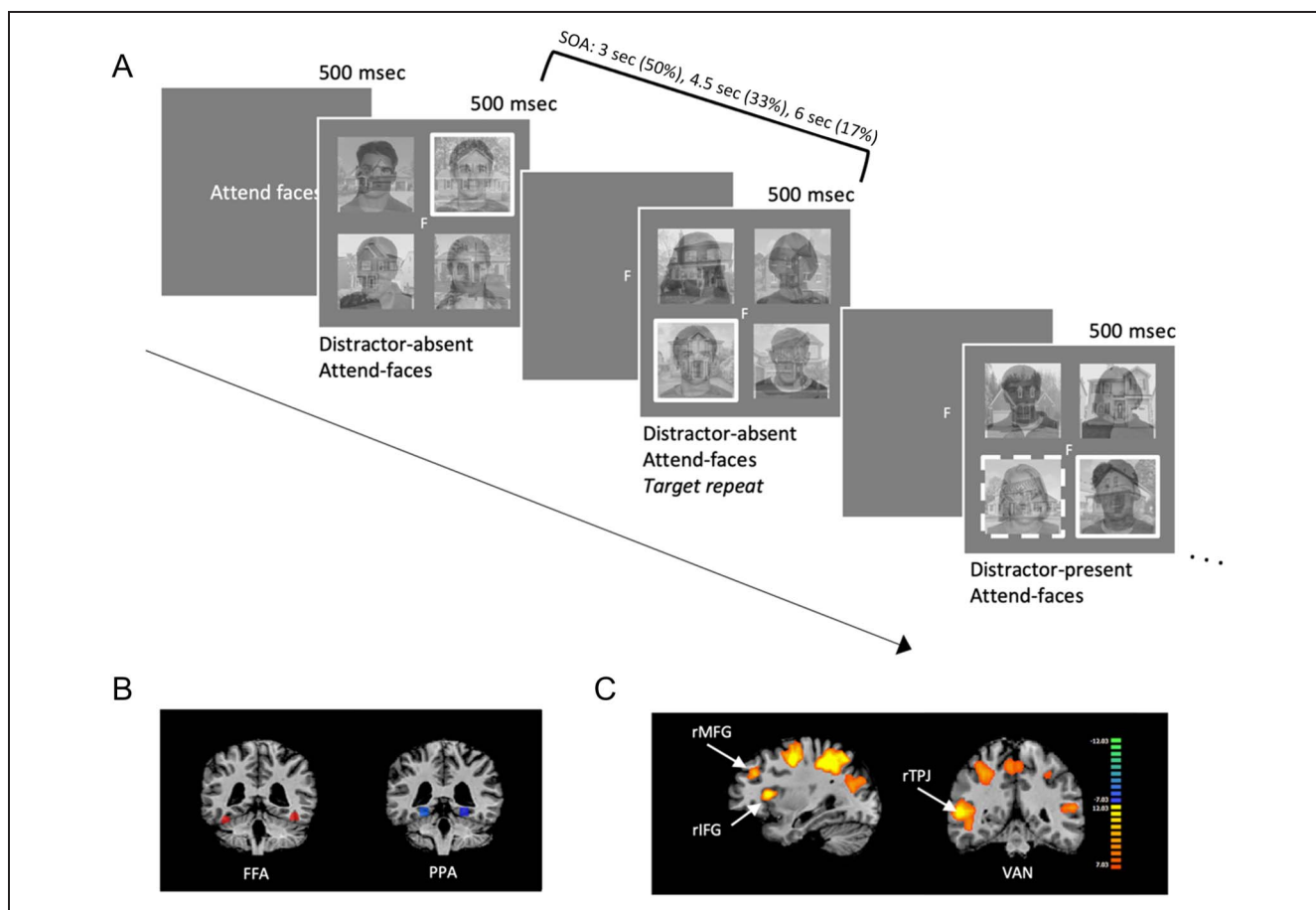


Figure 1. (A) The experimental trial sequence. In the scanner, participants performed a 1-back task based on the relevant category (here attend-faces), for the images appearing in the target box (white border). Participants responded with a “1” if the relevant image did not repeat and “2” if it did. On 25% of trials, a salient abrupt-onset distractor (dotted white border) appeared around one of the three nontarget hybrid images. The salient distractor appeared 50 msec after the onset of the stimulus display for that trial and remained on-screen for 100 msec. Participants were instructed to ignore this salient distractor when it appeared. (B) The a priori FFA and PPA ROIs for a sample participant. (C) A whole-brain contrast showing activation on salient-distractor-present contrasted with salient-distractor-absent trials, highlighting the VAN, with the rMFG, rIFG, and rTPJ ROIs labeled.

overlaying a 50% transparent face image over a 50% transparent house image. Hybrids were created from a bank of 160 total images (80 faces, as used in Golomb and Kanwisher [2012] and 80 houses retrieved from a Google image search and converted to grayscale), and face/house image pairs were generated randomly and separately for each participant (2304 unique hybrid images per participant: four per trial, 96 experimental trials per run, six runs). Each experimental run consisted of two blocks of 48 trials: an attend-faces block and an attend-houses block (order counterbalanced across runs; run order generated randomly across participants). Each block began with the 500-msec presentation of an instruction screen (“Attend faces” or “Attend houses”). The central fixation point on each subsequent trial was either a letter “F” or “H” (size = 1°) to indicate the current target category, and this remained on-screen for the duration of the block.

On each trial, four face/house hybrid images (size = 5° × 5°, eccentricity = 2.5°) were presented simultaneously in a 2 × 2 grid for 500 msec. One of the images

was framed with a white border, identifying it as the target for that trial. Participants were instructed to perform a 1-back task on the image inside this target box, based on the relevant category (the face or house); that is, is the current target face (or house) the same face (or house) as the previous trial’s target? Participants responded on the button box with a “2” if the target repeated and “1” if it did not. The target (relevant-category image inside the target box) repetition frequency was 20% per block. The nonrelevant category image inside the target box repeated independently with the same frequency, as did both the relevant and nonrelevant category images in the three nontarget locations. Participants performed 48 trials in a row for each block, with trials separated by an ISI of either 3 sec (50% of trials), 4.5 sec (33% of trials), or 6 sec (17% of trials). The target (F or H) remained on-screen for the duration of the block.

Our critical manipulation was that, on 25% of trials (12 trials per block, randomly intermixed but never back-to-back), a salient abrupt-onset distractor also appeared in

the display. The salient distractor was a thick dotted white border that flashed briefly around one of the three nontarget image locations (onset time = 50 msec after array onset, duration = 100 msec). Participants were instructed to ignore this dotted border when it appeared.

Participants completed six experimental runs (6.75 min each). This resulted in 216 attend-faces distractor-absent trials, 216 attend-houses distractor-absent trials, 72 attend-faces distractor-present trials, and 72 attend-houses distractor-present trials. The location of the target image, whether the salient distractor appeared, and the location of the salient distractor were all randomized across trials. We note that the task was intentionally difficult (the hybrid images substantially increase perceptual load, and the 1-back task requires working memory resources and a strong attentional control setting) to further incentivize attentional filtering.

Functional Localizer Task

Participants also completed two experimental runs of a standard functional localizer task to localize FFA and PPA ROIs. Participants viewed blocks of faces or houses (single images presented sequentially at screen center, sized 10°) and performed a 1-back task. Images were presented for 300 msec with a 500-msec ISI, and 1-back (repetition) frequency was 10%. There were 20 trials per block, and participants performed 13 blocks per run (five house blocks, five face blocks, and three fixation blocks during which only a fixation point appeared).

fMRI Acquisition

The study was carried out at the Ohio State University Center for Cognitive and Behavioral Brain Imaging with a Siemens Prisma 3-T MRI scanner using a 32-channel phase array receiver head coil. Functional data were acquired using a T2-weighted gradient-echo sequence (repetition time = 1500 msec, echo time = 28 msec, flip angle = 70°). We used multiband whole-brain coverage aligned to the anterior commissure–posterior commissure (48 slices, 3 × 3 × 3 mm voxel, 10% gap, multiband factor = 3). We also collected a high-resolution MPRAGE anatomic scan at 1-mm³ resolution for each participant. Each participant was scanned in one 2-hr session.

fMRI Preprocessing

The fMRI data were preprocessed with Brain Voyager QX (Brain Innovation). All functional data were corrected for slice acquisition time and head motion, temporally filtered (general linear model [GLM] Fourier; two cycles), and spatially smoothed with a Gaussian kernel of 4-mm FWHM. Runs with abrupt motion (>1 mm) were discarded from analyses, resulting in the removal of a single run from three separate participants and all six experimental runs for a single participant and leaving a final $n = 14$. Data

for each participant were normalized into Talairach space (Talairach & Tournoux, 1998).

ROIs

Our main analyses focused on two a priori functionally defined ROIs: the FFA and the PPA. We localized the FFA and PPA using standard procedures: Using data acquired from the independent localizer scan, for each participant, we defined a bilateral face-selective FFA in the mid-fusiform gyrus that responded more strongly to faces than houses and a bilateral house-selective PPA in the parahippocampal gyrus that responded more strongly to houses than faces. The resultant ROIs were contiguous voxels (cluster threshold = 10) that demonstrated categorical preference at a significance of $p < 10^{-3}$ (uncorrected). For two participants, we were unable to localize left FFA at this threshold, so we only included right FFA ROIs. For all other participants, we averaged across left and right ROIs for FFA and PPA analyses. The reported pattern of results is the same for left and right ROIs.

We performed additional exploratory analyses to evaluate the effects of the salient distractor in the ventral attention network (VAN). The VAN was identified based on a contrast of distractor-present trials relative to distractor-absent trials regardless of attended category. We localized ROIs in right TPJ (rTPJ), right middle frontal gyrus (rMFG), and right inferior frontal gyrus (rIFG), well-known regions of the VAN that detect salient events outside the current focus of attention (Shulman et al., 2009; Indovina & Macaluso, 2007; Serences et al., 2005; Downar, Crawley, Mikulis, & Davis, 2001; Corbetta, Kincade, Ollinger, Mcavoy, & Gordon, 2000). We defined these ROIs for each participant using a leave-one-subject-out procedure to avoid circularity concerns (Esterman, Tamber-Rosenau, Chiu, & Yantis, 2010). We iteratively left a single participant out of the group GLM and performed a whole-brain analysis on all trials on the group-level ($N - 1$) data to localize the relevant ROIs for the left-out participant, contrasting distractor-present trials relative to distractor-absent trials. From this contrast, we defined a set of contiguous voxels (cluster threshold = 30) in the rTPJ, rMFG, and rIFG for each participant that demonstrated substantially greater activation on distractor-present trials relative to distractor-absent trials at a significance of $p < 10^{-12}$ (uncorrected). These secondary ROIs were only analyzed for the final exploratory tests contrasting the first versus second half of trials: We report results from all three ROIs but focus our discussion on the rTPJ as a representative ROI from the VAN given its robust role in detecting unexpected events of potential behavioral relevance (i.e., a distractor that is visually similar/related to the target [Natale, Marzi, & Macaluso, 2010; Hu, Bu, Song, Zhen, & Liu, 2009; Hampshire, Duncan, & Owen, 2007; Serences et al., 2005]) and as a “reset” mechanism for reorienting (Corbetta, Patel, & Shulman, 2008). Figure 1B and C shows all ROIs.

Analyses

Behavior

Average RTs for the 1-back task were calculated per condition using only correct trials. We also calculated d' —a sensitivity metric based on signal detection theory—as a measure of accuracy for each condition. Here, d' measures sensitivity to a target (i.e., a repeat trial) based on the number of hits (correct recognition of a repeat trial) relative to false alarms (erroneously identifying a nonrepeat trial as a repeat; Stanislaw & Todorov, 1999). We also report the results of an exploratory analysis on behavioral data in which we compare RT results from the first half of a block to the second half of a block to evaluate for evidence of habituation to the salient onset distractor (i.e., Won & Geng, 2020) within a given control setting.

fMRI

Univariate fMRI analyses were carried out using Brain Voyager QX (Brain Innovation). Using the functionally defined FFA and PPA ROIs for each participant, we applied a GLM to evaluate the mean BOLD response (beta weights) for each experimental condition, ROI, and participant. Incorporated in the GLM were regressors for each of the four experimental conditions (attend-faces distractor-absent, attend-faces distractor-present, attend-houses distractor-absent, and attend-houses distractor-present) plus an instruction condition (“attend face” or “attend house” text before each block). “Distractor-present” and “distractor-absent” here and in the remainder of the text refer to the presence/absence, respectively, of the salient abrupt-onset distractor. The beta weights for the four experimental conditions were submitted to repeated-measures ANOVAs and paired t tests. We conducted analyses within each ROI separately and also combined across ROIs by averaging the BOLD responses for each ROI’s preferred and nonpreferred conditions.

We first performed planned paired-samples t tests to compare activation on attend-faces trials versus attend-houses trials in the distractor-absent conditions to establish baseline filtering in each ROI and then performed the same contrasts for the distractor-present conditions. We then conducted 2 (Target Category: attend-faces vs. attend-houses) \times 2 (Distractor Condition: absent vs. present) repeated-measures ANOVAs in FFA and PPA ROIs. Of particular importance in this analysis is the Target Category \times Distractor Condition interaction, which provides insight into whether attentional filtering patterns are substantially different on distractor-present relative to distractor-absent trials.

Next, we combined across FFA and PPA ROIs to evaluate activation reflecting the processing of the preferred stimulus category (FFA activity on attend-faces trials, PPA activity on attend-houses trials) relative to the nonpreferred stimulus category (PPA activity on attend-faces trials, FFA activity on attend-houses trials) across distractor

conditions. We performed an additional 2 (Target Category: attend-preferred vs. attend-nonpreferred) \times 2 (Distractor Condition: absent vs. present) \times 2 (ROI: FFA vs. PPA) repeated-measures ANOVA.

As a measure of filter strength, we also calculated an attentional filtering index for each ROI, participant, and distractor condition using the formula below, where higher positive values indicate stronger, more effective attentional filtering.

$$\text{Attentional Filtering Index} = \frac{(Att_{\text{preferred}} - Att_{\text{nonpreferred}})}{(Att_{\text{preferred}} + Att_{\text{nonpreferred}})}$$

We performed a 2 (ROI: FFA vs. PPA) \times 2 (Distractor Condition: absent vs. present) ANOVA on attentional filtering indices. We followed up with post hoc one sample t tests to evaluate whether attentional filtering was significantly nonzero in each distractor condition across ROIs.

Finally, we performed exploratory analyses to evaluate changes in the first half versus the second half of experimental blocks (block phase: first half vs. second half), for the FFA and PPA analyses described above, as well as the rTPJ ROI. For this, we applied a GLM with eight regressors (attend-faces distractor-absent block Phase 1, attend-faces distractor-absent block Phase 2; etc.), plus an instruction condition, to evaluate mean BOLD response for each of the original four experimental conditions by block phase (first half vs. second half), per participant.

Effect sizes (mean and 90% CI) are provided for all analyses.

RESULTS

Behavioral and Neural Confirmation of Attentional Capture

To confirm that the salient distractor captured spatial attention as intended, we compared mean RTs (Table 1) across conditions in the 1-back task. We subjected RTs to a 2 (Distractor Condition: absent vs. present) \times 2 (Target Category: attend-faces vs. attend-houses) repeated-measures ANOVA. We observed a significant main effect of Distractor Condition, $F(1, 13) = 41.75, p < .001, \eta_p^2 = .76$ (90% CI [0.97, 2.33]), such that RTs were slower on distractor-present trials relative to distractor-absent trials, demonstrating reliable attentional capture. There was also a significant main effect of Target Category, $F(1, 13) = 47.92, p < .001, \eta_p^2 = .79$ (90% CI [0.53, 0.86]), such that RTs were generally slower in the attend-houses conditions relative to the attend-faces conditions, although the lack of a significant interaction, $F(1, 13) = 0.01, p = .93, \eta_p^2 = .001$ (90% CI [0, 0.03]), suggests that the distractor costs were comparable across categories.

The response accuracy (Table 1) data trended in the same patterns as RT, suggesting no speed-accuracy trade-offs: here, a significant main effect of Distractor Condition, $F(1, 13) = 6.73, p = .02, \eta_p^2 = .34$ (90% CI [0.03, 0.56]), with a nonsignificant main effect of Target Category, $F(1,$

Table 1. Summary of Mean RT (sec), Hit Rate (HR), False Alarm (FA) Rate, and Accuracy (d')

	<i>Attend-faces, Distractor-absent</i>	<i>Attend-faces, Distractor-present</i>	<i>Attend-houses, Distractor-absent</i>	<i>Attend-houses, Distractor-present</i>
RT (<i>SD</i>)	0.99 (0.18)	1.12 (0.22)	1.11 (0.20)	1.24 (0.26)
HR (<i>SD</i>)	0.50 (0.17)	0.39 (0.17)	0.47 (0.15)	0.31 (0.24)
FA (<i>SD</i>)	0.10 (0.11)	0.11 (0.13)	0.13 (0.10)	0.11 (0.08)
d' (<i>SD</i>)	1.40 (0.63)	0.94 (0.85)	1.05 (0.51)	0.75 (0.87)

Data for all four experimental conditions. d' is calculated per participant from hit rate and false alarm rate using $d' = Z_{\text{HIT}} - Z_{\text{FA}}$ where z represents the respective z transformations (Macmillan & Creelman, 1990).

13) = 1.78, $p = .21$, $\eta_p^2 = .12$ (90% CI [0, 0.38]). Again, there was no significant interaction, $F(1, 13) = 0.22$, $p = .65$, $\eta_p^2 = .02$ (90% CI [0, 0.22]).

A whole-brain contrast of distractor-present versus distractor-absent trials also confirmed previously reported neural patterns associated with attentional capture, namely, increased activation in the VAN, including the rTPJ, rMFG, and rIFG (Figure 1C).

Neural Processing Via Category-tuned Attentional Filters in FFA and PPA

The key question this study was designed to address was whether the attentional capture effects were accompanied by changes to category-tuned filters. In both FFA and PPA (Figure 2A), we observed the expected pattern of standard category-based attentional modulation on distractor-absent trials: significantly greater FFA activation on attend-faces trials relative to attend-house trials, $t(13) = 5.70$, $p < .001$, $d = 1.52$ (90% CI [0.73, 2.29]) and significantly greater PPA activation on attend-houses trials relative to attend-faces trials, $t(13) = 13.6$, $p < .001$, $d = 3.64$ (90% CI [2.15, 5.10]). This baseline comparison confirms that, in the absence of a salient visual distractor, participants were effectively attending the target category and filtering out the irrelevant nontarget category in the hybrid images.

Strikingly, on distractor-present trials, this pattern was dramatically altered in both FFA and PPA. In fact, if anything, the filtering pattern was reversed: FFA activation to the hybrid images was numerically greater on attend-houses blocks relative to attend-faces blocks, $t(13) = -1.90$, $p = .08$, $d = -0.51$ (90% CI [-1.06, 0.06]), and PPA activation was significantly greater on attend-faces blocks relative to attend-houses blocks, $t(13) = 10.86$, $p < .001$, $d = 2.90$ (90% CI [1.67, 4.11]). This suggests that, under conditions of distraction, the filter that prioritized the to-be-attended category was not only disrupted but also reversed, causing the incidental prioritization of the faces in the hybrid face/house images on attend-houses trials and the incidental prioritization of the houses in the hybrid images on attend-faces trials. The Target Category \times Distractor Condition interactions were significant in both ROIs, FFA: $F(1, 13) = 9.21$, $p = .01$, $\eta_p^2 = .42$

(90% CI [0.07, 0.61]); PPA: $F(1, 13) = 178.34$, $p < .001$, $\eta_p^2 = .93$ (90% CI [0.83, 0.95]).

Figure 2B also shows the analysis combining across ROIs, with data sorted into preferred versus nonpreferred stimulus category (ANOVA statistics in Table 2). In addition to corroborating the significant effects above, there was a significant main effect of ROI, with ROI also modulating the other effects, such that overall BOLD activation was generally greater in FFA, but PPA showed greater differences between conditions.

To quantify attentional filter strength more directly, we calculated an attentional filtering index for each ROI and distractor condition for each participant (Figure 2C; combined ROI in Figure 2D). Consistent with the above results, we observed a significant main effect of distractor condition, $F(1, 13) = 112.71$, $p < .001$, $\eta_p^2 = .90$ (90% CI [0.75, 0.93]), with the filter disruption significant in both ROIs: FFA distractor absent versus present: $t(13) = 4.21$, $p = .001$, $d = 1.13$ (90% CI [0.54, 1.68]); PPA distractor absent versus present: $t(13) = 8.88$, $p < .001$, $d = 2.37$ (90% CI [1.47, 3.23]). Critically, we observed robust filter disruption in all 14 participants in both ROIs. Moreover, the attentional filtering index was significant (greater than zero) in both FFA and PPA on distractor-absent trials, $t(13) = 5.14$, $p < .001$, $d = 1.37$ (90% CI [0.62, 2.10]), and $t(13) = 9.22$, $p < .001$, $d = 2.46$ (90% CI [1.38, 3.52]), and significantly less than zero on distractor-present trials, $t(13) = -2.65$, $p = .02$, $d = -0.71$ (90% CI [-1.29, -0.11]), and $t(13) = -7.44$, $p < .001$, $d = -1.99$ (90% CI [-2.90, -1.06]).

To confirm the stability of the filter disruption in FFA and PPA, we ran two control analyses (Figure 2E). First, we equated for number of trials across conditions by randomly selecting an equal number of distractor-absent trials as distractor-present trials. The results were the same: Attentional filtering for the combined ROIs was significantly disrupted (i.e., weaker on distractor-absent relative to distractor-present trials), $t(13) = 6.52$, $p < .001$, $d = 1.74$ (90% CI [1.01, 2.43]), with the disruption present in 14 of 14 participants. Furthermore, attentional filtering was greater than zero on distractor-absent trials, $t(13) = 6.00$, $p < .001$, $d = 1.60$ (90% CI [1.05, 2.10]), and significantly less than zero on distractor-present trials, $t(13) = -5.40$, $p < .001$, $d = -1.44$ (90% CI [-1.91, -0.92]).

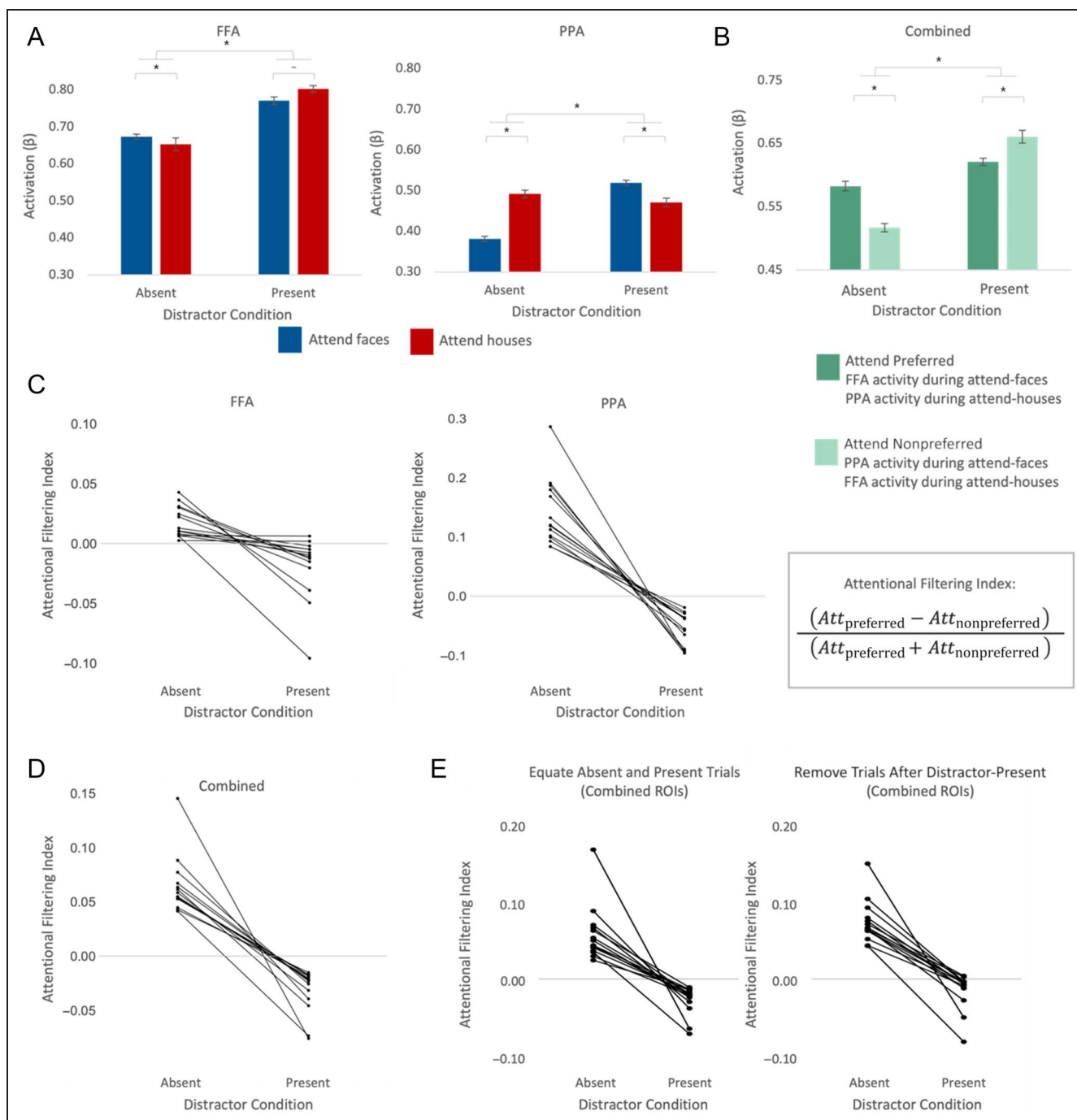


Figure 2. Summary of fMRI BOLD results. (A) Activation levels in the FFA and PPA across all experimental conditions and (B) activation in combined ROI across all experimental conditions. (C) Attentional filtering index (the proportion of total activation reflecting the processing of the preferred stimulus category) for the FFA and PPA and combined in (D) where each data point represents a single participant. This is a measure of filtering effectiveness—see box in the figure for calculation. A negative slope indicates filter disruption. Values below zero indicate filter reversal. (E) Results from two control analyses, plotting attentional filtering index for the combined ROI. Error bars are within-participant standard error (Morey, 2008).

Second, we removed trials immediately after distractor-present trials. Again, attentional filtering for the combined ROIs was significantly disrupted on distractor-present trials: $t(13) = 8.76, p < .001, d = 2.34$ (90% CI [1.45, 3.18]), with the disruption present in 14 of 14 participants, and attentional filtering was significantly greater than zero on distractor-absent trials, $t(13) = 10.00, p < .001, d = 2.68$ (90% CI [1.88, 3.38]), and significantly less than zero on

distractor-present trials, $t(13) = -2.37, p = .034, d = -0.63$ (90% CI [-1.00, -0.25]).

Exploratory Analysis: Distractor Habituation across a Block

As a final, exploratory analysis, we asked whether the observed filter disruption effect might decrease over time.

Table 2. Statistics for the 2 (Target Category: Attend-preferred vs. Attend-nonpreferred) \times 2 (Distractor Condition: Absent vs. Present) \times 2 (ROI: FFA vs. PPA) Repeated-Measures ANOVA Carried Out on BOLD Activation in FFA and PPA

	<i>df</i>	<i>F</i>	<i>p</i>	η_p^2 [90% CI]
ROI	1, 13	18.93	< .001	.59 [.23, .73]
Target category (preferred vs. nonpreferred)	1, 13	8.68	.011	.4 [.06, .61]
Distractor condition	1, 13	63.79	< .001	.83 [.61, .89]
ROI \times Target Category	1, 13	16.39	.001	.56 [.19, .71]
ROI \times Distractor Condition	1, 13	13.49	.003	.51 [.15, .68]
Target Category \times Distractor Condition	1, 13	105.05	< .001	.89 [.74, .93]
ROI \times Target Category \times Distractor Condition	1, 13	24.61	< .001	.65 [.31, .77]

There is prior evidence that the interference produced by a salient distractor—both with respect to RT costs (Won & Geng, 2020) and oculomotor responses (Bonetti & Turatto, 2019; Chelazzi, Marini, Pascucci, & Turatto, 2019; Turatto, Bonetti, & Pascucci, 2018)—can decrease after repeated or prolonged exposure. Such habituation

is typically studied over the course of an experiment when a salient onset distractor remains consistent. In the current task, whereas the salient onset distractor stimulus (dotted white border) remained consistent over the entire experiment, the attentional filter/control setting had to be updated at the start of each new block, such that the

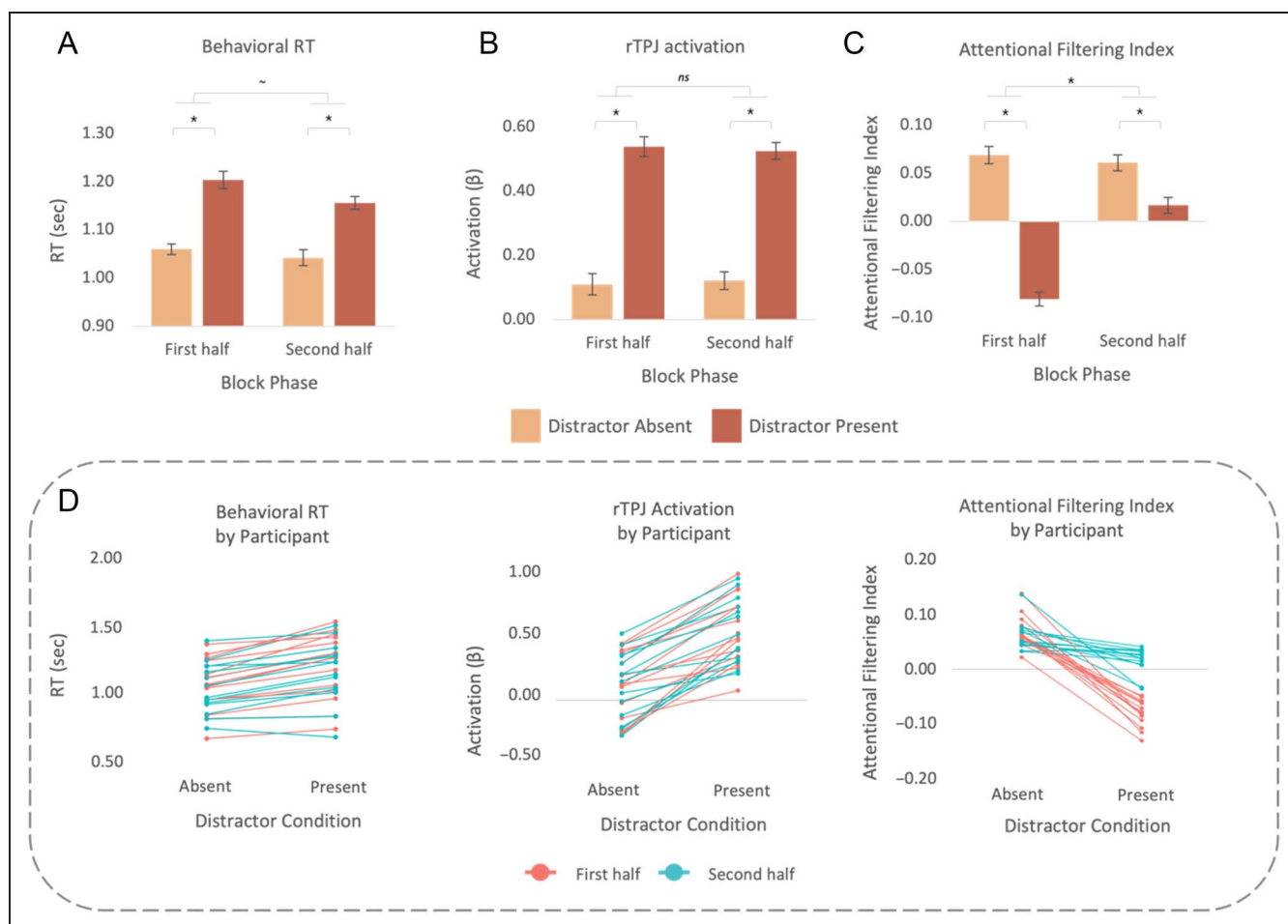


Figure 3. Summary of exploratory analyses of the first versus second halves of blocks. (A) Behavioral RT by distractor condition and block phase. (B) rTPJ activation by distractor condition and block phase. (C) Attentional filter strength (via the attentional filtering index) across distractor conditions and block phase, collapsed across ROI condition. (D) Participant-level RT, rTPJ activation, and the filtering index by block phase (where a negative slope indicates filter disruption and values below zero indicate filter reversal). Error bars are within-participant standard error (Morey, 2008).

to-be-filtered (nontarget) category reset accordingly. Thus, to explore if the consequences of attentional capture on category-tuned filtering (i.e., incidentally processing the nontarget category) might be mitigated over time, we separated our data into trials occurring in the first half versus last half of each block. We compared (1) the category-tuned attentional filtering index (combined across FFA and PPA), (2) a behavioral measure of attentional capture (RT for distractor-present vs. distractor-absent trials), and (3) a generic neural measure of attentional capture (rTPJ activation for distractor-present vs. distractor-absent trials). All three measures are shown across block phase at both the group and participant levels in Figure 3.

In brief, the filter disruption cost in FFA/PPA was reduced for the second half of the block relative to the first [Block Phase \times Distractor Condition interaction, $F(1, 13) = 74.95, p < .001, \eta_p^2 = .85$ (90% CI [0.57, 0.88])]. The behavioral capture cost (RT) was also reduced marginally (Phase \times Distractor interaction, $F(1, 13) = 3.48, p = .08, \eta_p^2 = .21$ (90% CI [0, 0.46])), but interestingly, the generic neural capture measure did not vary (Phase \times Distractor interaction, $F < 1.43, p > .25$).

In terms of the attentional filtering index (Figure 3C), on distractor-absent trials, attentional filtering was strong (significantly greater than zero) both early and later in the block, $t(13) = 9.09, p < .001, d = 2.43$ (90% CI [1.51, 3.3]), and $t(13) = 8.61, p < .001, d = 2.3$ (90% CI [1.42, 3.13]), respectively). On distractor-present trials, however, there was a notable difference over time: The attentional filter was disrupted and reversed (attentional filtering was significantly less than zero) early in the block, $t(13) = -12.15, p < .001, d = -3.25$ (90% CI [-4.34, -2.09]), but only more mildly disrupted (with no reversal) later in the block. In the second half of the block, there was still significant filter disruption, with the filtering index reduced on distractor-present compared to distractor-absent trials [paired-samples t test: $t(13) = 3.62, p = .003, d = 0.97$ (90% CI [0.42, 1.49])], but the filtering index remained positive [significantly greater than zero, $t(13) = 2.59, p = .02, d = 0.69$ (90% CI [0.19, 1.17])]. These results reveal that the distractor produced a significant cost to attentional filtering both early and later in a block, but this cost was substantially mitigated later in the block, where distraction disrupted but no longer reversed the filter.

Intriguingly, the same analysis carried out on rTPJ BOLD activation yielded a different result (Figure 3B): Activation in rTPJ was reliably greater on distractor-present trials relative to distractor-absent trials, $F(1, 13) = 74.82, p < .001, \eta_p^2 = .85$ (90% CI [0.66, 0.90]), but it was unaffected by block phase [in terms of both the lack of interaction and no significant main effect of block phase: $F(1, 13) = 0.01, p = .92, \eta_p^2 = .001$ (90% CI [0, 0.06])], suggesting that the neural response to the salient distractor itself remained equivalently strong over time (relative to the block onset), yet the impact of this distractor on attentional filtering and processing of the hybrid images was apparently reduced. The rTPJ pattern was consistent across the

other localized ROIs of the VAN (rMFG and rIFG Block Phase \times Distractor interaction, $ps > .69$).

DISCUSSION

We have long known that visual distraction disrupts spatial attention (Jonides & Irwin, 1981), but recently, the consequences are being understood to be broader (Dube & Golomb, 2021; Chen et al., 2019). The current findings reveal even more fundamental consequences for visual distraction. We show that distraction also disrupts a concurrently maintained category-tuned filter, interrupting the prioritization of goal-relevant information in the visual scene. This is particularly notable because the filter here reflected a prolonged, robust attentional control setting, and the disruption resulted in a temporary preference for task-irrelevant information. Moreover, the filter disruption was reliable enough to be seen at the individual participant level for all participants tested.

This study was designed to directly test the filter disruption theory proposed in Dube and Golomb (2021). Dube and Golomb (2021) demonstrated that visual distraction (by a similar abrupt onset distractor as the current study) causes the incidental encoding of distractor features, presumably by disrupting the filter that controls VWM encoding. When performing two sequential visual search tasks in which color was irrelevant, memory-driven capture (exacerbated attentional capture when visual information matches the contents of VWM; Olivers et al., 2006) was elicited in the second search when the color of a singleton matched the distractor color from the first search, suggesting that the irrelevant Search 1 distractor color intruded into memory and subsequently biased attention. However, although participants were told to ignore color, there was not an explicit instruction to filter irrelevant features from VWM encoding. Accordingly, we designed the current study to investigate a more robust attentional filter, such that the task required a long-term (i.e., sustained for a several minute block), explicit category-tuned filter. The results of this study extend the theoretical implications of Dube and Golomb (2021) in important ways, revealing that attentional capture not only disrupts spatial attention but also disrupts control over nonspatial filters that regulate behavior, such that activity in ventral visual cortex no longer reflects prioritization of goal-relevant information.

The results thus provide direct support for the filter disruption theory: During distraction, spatial attention is captured and the category-tuned attentional filter is also broken, resulting in the errant processing of the irrelevant object category. Is this boost in irrelevant category processing occurring primarily within the hybrid image at the distractor location, or is the category-tuned filter disrupted globally across the display? Although the current experiment was not designed to assess spatial selectivity (i.e., we did not control eye movements, and our localizer task used large, central stimuli), we conducted some

exploratory analyses capitalizing on the known contralateral organization of visual cortex—that in both FFA and PPA, neural activation is greater for stimuli presented on the contralateral side of the visual display (Hemond, Kanwisher, & Op de Beeck, 2007). We separately analyzed FFA/PPA activation by hemisphere for the subset of trials where the target and distractor were on opposite sides of the display and found the same pattern of category tuning and disruption in both hemispheres: A 2 (distractor-present vs. distractor-absent) \times 2 (preferred vs. nonpreferred target category) \times 2 (contra-target vs. contra-distractor hemisphere) ANOVA carried out on attentional filtering indices yielded a significant Distractor Condition \times Target Category interaction, $F(1, 13) = 80.4, p < .001, \eta_p^2 = .86$ (90% CI [0.67, 0.91]), but no three-way interaction, $F(1, 13) = 0.94, p = .35, \eta_p^2 = .07$ (90% CI [0, 0.31]), suggesting that the filter disruption effect did not interact with hemisphere. Given the already coarse contralateral organization of the FFA and PPA and limitations of the current experimental design, these hemisphere-based analyses do not allow us the resolution to inspect activation specific to the exact distractor or target locations and should be taken as exploratory, but these data suggest that the filter disruption is not limited solely to the distractor location. Such an effect would be consistent with the idea of a nonspatial category-tuned filter that operates globally across the visual field. It has been well established that feature-based attention operates quickly and globally in parallel across a visual scene, independently of spatial attention, allowing for a preliminary “scan” of the visual scene to help tune a spatial saliency map based on stimulus relevance (Liu & Mance, 2011; Serences & Boynton, 2007; Saenz et al., 2002; Treue & Martínez Trujillo, 1999). It is possible that nonspatial categorical filters may work in a similar way. If so, the current results suggest that, when the spatial attentional filter is broken, the category-tuned attentional filter may be similarly disrupted at both the location of the distractor and elsewhere, a conjecture that could be directly tested in future studies with more spatially sensitive methods.

In terms of neural mechanisms or signatures of distraction, many studies have focused on the role of the frontoparietal dorsal attention network and VAN, with the dorsal attention network (including the intraparietal sulcus and FEFs) active during voluntary, goal-based orienting of attention and the VAN (including the rTPJ and right ventral frontal cortex) acting as a circuit breaker to the dorsal network when attention is reoriented to salient events outside the current focus, as during attentional capture (Shulman et al., 2009; Indovina & Macaluso, 2007; Serences et al., 2005; Downar et al., 2001; Corbetta et al., 2000). Our whole-brain contrasts of distractor-present versus distractor-absent trials confirmed the involvement of the VAN in the current task. However, whereas prior studies have primarily focused analyses on these networks to assess questions related to spatial capture and recovery,

here we demonstrate that category-selective visual object processing areas are also influenced by this disruption to control. How, exactly, the VAN communicates with category-specific regions in ventral visual cortex to disrupt filtering is an open question: Regions such as the FFA and PPA may receive direct modulatory signals via feedback from parietal VAN regions, or the “circuit breaker” signal may instead be sent to earlier visual regions responsible for basic visuospatial processing and then fed forward to higher-level FFA and PPA.

Strikingly, we found that observers do not simply disengage from the current attentional filter setting during attentional capture; they appear to incidentally adopt an errant filter setting. Specifically, in both FFA and PPA, activation reflecting the processing of the current nontarget category (i.e., houses on attend-faces blocks) was temporarily greater than activation reflecting the current target category. In conceptualizing the current experiment and in the filter disruption theory framework more broadly, we predicted that the category-tuned filter might be disrupted under conditions of distraction. We did not predict the disruption would be so extreme as to cause filter reversal. The discovery that activity in ventral visual cortex instead prioritizes goal-inconsistent information immediately after distraction raises new and interesting theoretical consequences of distraction that would have been difficult to disentangle behaviorally. For example, behavioral accuracy in this task declined substantially on distractor-present compared to distractor-absent trials, which could be consistent with any of the following causes: spatial capture of attention away from the target (attentional capture), a disruption of attentional focus to the target category (filter disruption), and/or incidentally prioritizing the nontarget stimulus category over the target category (filter reversal). A unique appeal of this neuroimaging approach is that we are able to assess the processing of truly task-irrelevant information to reveal new potential consequences of distraction, both predicted and unpredicted, laying strong theoretical groundwork for future studies.

Although the filter reversal was an unexpected finding and not the main emphasis of this article, it was present in all of our participants, and such a robust finding begs speculation about why/how such a reversal could occur. One possibility is that the reversal effect may be a result of conditioning participants to switch between opposing control settings. Over the course of the experiment, participants alternated between only two goal states: attend-faces and attend-houses. Under these conditions, we speculate that when an observer loses control over the goal-consistent filter (i.e., attend-faces), they may automatically revert to the alternative goal (i.e., attend-houses). An intriguing question for future study would be to evaluate the nature of filter disruption in a task requiring more than a binary attend Category A/ignore Category B setting, for example, if more than two categories and/or possible attentional settings were involved.

Although the current data do not allow for more than speculation about what is causing the reversal, they do allow us to rule out at least one alternative explanation. Specifically, the reversal does not seem to be an incidental consequence of adaptation because of attending the same category over a several minute block of trials. Our exploratory block phase analysis argues strongly against this: If the filter reversal were because of adaptation, the reversal should be more evident in the second half of a block than the first half. This is the opposite of what we found: The filter was disrupted more severely (inducing the reversal) in the first half of a block.

Interestingly, this finding from the block phase analysis suggests that filter disruption is weaker in the second half of a block relative to the first half and that, over the course of a block, participants regain some control over the filter on distractor-present trials. Intriguingly, although the filter disruption in PPA and FFA was less severe in the second half of a block, our rTPJ analysis did not show the same reduction: rTPJ activation was significantly stronger on distractor-present relative to distractor-absent trials (as expected from prior studies; Downar et al., 2001), and the magnitude of this effect remained constant throughout the block. As such, it appears that spatial attentional capture was strong for the duration of the block, but its consequences—to both attentional filtering and, to a lesser extent, RTs—were mitigated over time. This is notable given recent interest in learned distractor suppression—more specifically, the finding that the effects of distractors can be attenuated with increased exposure (Won & Geng, 2020) and the debate over proactive versus reactive suppression (see Chelazzi et al., 2019, for a review). Given the ability to simultaneously measure rTPJ/VAN activation, a neural filtering index in object-processing areas, and behavioral RT, the paradigm introduced here may be a useful future tool in examining topics related to distractor habituation and other open questions about attentional capture, contributing to our growing knowledge of the broader consequences of attentional capture and distraction.

Open Practices Statement

The experiment reported here was not formally preregistered, but the design and analysis plan were proposed before data collection as part of a Natural Sciences and Engineering Research Council of Canada postdoctoral fellowship grant by B. D. Deidentified data are available on OSF via the link here.

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Blaire Dube: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Writing—Original draft; Writing—Review & editing. Lasyapriya Pidaparathi: Data curation; Formal analysis; Investigation; Project administration; Writing—Original draft; Writing—Review & editing. Julie D. Golomb: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Writing—Original draft; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were $M(\text{an})/M = .407$, $W(\text{oman})/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

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