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Widespread frontoparietal fMRI activity is greatly affected by changes in criterion placement, not discriminability, during recognition memory and visual detection tests

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ABSTRACT

Widespread frontoparietal activity is consistently observed in recognition memory tests that compare studied ("target") versus unstudied ("nontarget") responses. However, there are conflicting accounts that ascribe various aspects of frontoparietal activity to mnemonic evidence versus decisional processes. According to Signal Detection Theory, recognition judgments require individuals to *decide* whether the memory strength of an item exceeds an evidence threshold—the decision criterion—for reporting previously studied items. Yet, most fMRI studies fail to manipulate both memory strength *and* decision criteria, making it difficult to appropriately identify frontoparietal activity associated with each process. In the current experiment, we manipulated both discriminability and decision criteria across recognition memory *and* visual detection tests during fMRI scanning to assess how frontoparietal activity is affected by each manipulation. Our findings revealed that maintaining a conservative versus liberal decision criterion drastically affects frontoparietal activity in target versus nontarget response contrasts for both recognition memory and visual detection tests. However, manipulations of discriminability showed virtually no differences in frontoparietal activity in target versus nontarget response *or* item contrasts. Comparing across task domains, we observed similar modulations of frontoparietal activity across criterion conditions, though the recognition memory task revealed larger activations in both magnitude and spatial extent in these contrasts. Nonetheless, there appears to be some domain specificity in frontoparietal activity associated with the maintenance of a conservative versus liberal criterion. We propose that widespread frontoparietal activity observed in target versus nontarget contrasts is largely attributable to response bias where increased activity may reflect inhibition of a prepotent response, which differs depending on whether a person maintains a conservative versus liberal decision criterion.

1. Introduction

Neuroimaging experiments of recognition memory consistently reveal widespread frontoparietal activity associated with contrasts comparing studied ("target") versus unstudied ("nontarget") responses (T > NT). Some attribute these patterns of activity to mnemonic evidence, given that "target" responses confer greater memory strength on average relative to "nontarget" responses (Wagner et al., 2005; Vilberg and Rugg, 2009; Criss et al., 2013; Gilmore et al., 2015; McDermott et al., 2017). Others argue that frontoparietal activity is associated with decisional processes since recognition judgments require individuals to *decide* whether items are "targets" versus "nontargets" (O'Connor et al., 2010; Jaeger et al., 2013; Aminoff et al., 2015; King and Miller, 2017; Kim, 2020). In a Signal Detection Theory (SDT) framework, recognition memory judgments encompass both evidential *and* decisional processes—participants must determine whether the memory strength elicited by an item is strong enough (i.e. exceeds the decision criterion) to warrant a "target" response (Macmillan and Creelman, 2005). However, most neuroimaging experiments of recognition memory fail to systematically manipulate both memory strength *and* decision criteria, making

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it difficult to determine which aspects of frontoparietal activity are associated with mnemonic evidence versus decisional processes.

One observation that is difficult to explain in the absence of both memory strength and criterion manipulations is that contrasts of correct “target” (hit) versus “nontarget” (correct rejection) responses (H > CR) appear very similar to contrasts of incorrect “target” (false alarm) responses versus correction rejections (Kahn et al., 2004; McDermott et al., 2017). SDT assumes that hit and false alarm trials carry greater memory strength *on average* relative to correct rejections, which could suggest these contrasts are associated with differences in memory strength or *the subjective experience of remembering* (Wagner et al., 2005). However, since these experiments did not manipulate decision criteria, it is difficult to rule out the possibility that decision biases favoring a tendency to respond “target” or “nontarget” contributed to these findings. Kantner and Lindsay (2012, 2014) found that almost all participants consistently respond with decision biases during recognition memory tests, even in the absence of any advantage or instructions to do so. Therefore, participants in the aforementioned fMRI experiments likely responded with decision biases, which means the reported T > NT contrasts are potentially confounded with non-memory related processes. For example, if a participant is biased to respond “nontarget” unless there is strong memory evidence that an item is a “target” (i.e. adopts a conservative criterion), then it is possible that “target” and “nontarget” responses encompass different *decisional* processes (e.g. by inhibiting versus providing prepotent “nontarget” responses). Conversely, some participants could be biased to respond “target” even when memory evidence is weak (i.e. adopts a liberal criterion), which may also lead to differences in decisional processes across response types, but in a different manner (e.g. inhibiting versus providing prepotent “*target*” responses). Thus, T > NT response contrasts likely reflect activity due to differences in memory strength *and* decisional processes underlying decision biases towards a particular response type (either “target” or “nontarget”). To avoid this potential confound, experimental designs must control for decision biases.

Aminoff et al. (2015) proposed that T > NT response contrasts might be affected by response biases where inhibiting versus providing prepotent responses increases frontoparietal activity. When a conservative criterion is maintained the prepotent response is “nontarget” whereas a “target” response is preponderant under a liberal criterion. Thus, a response bias account predicts greater frontoparietal activity for T > NT response contrasts under a conservative criterion, while the reverse should be true when a liberal criterion is utilized (i.e. greater activity in the NT > T response contrast). Aminoff et al. (2015) as well as King and Miller (2017) implemented recognition memory tests that included criterion manipulations during fMRI scanning in attempts to control for decision biases when examining H > CR contrasts (i.e. correct T > NT response contrasts). In these experiments, participants received explicit instructions prior to each test block informing them of the likelihood of encountering “target” items (either 30% or 70%). In this paradigm, participants could increase their correct response rates by strategically maintaining a conservative criterion when “target” items only appear 30% of the time (conservative criterion condition), and by shifting to a liberal criterion when the likelihood of encountering “target” items is 70% (liberal criterion condition). Participants who appropriately shifted between relatively more conservative versus liberal decision criteria during these recognition memory tests showed widespread frontoparietal activity in the H > CR contrast when maintaining a conservative criterion—but not a liberal criterion (Aminoff et al., 2015; King and Miller, 2017). This finding demonstrates that the decision criterion modulates the H > CR contrast, but a response bias account alone is insufficient for explaining these findings: maintaining a liberal criterion did *not* reveal significant differences in the reverse contrast (CR > H).

One limitation of the findings from Aminoff et al. (2015) and King and Miller (2017) is that these studies did not manipulate discriminability which means a mnemonic evidence explanation cannot be completely ruled out. By definition, adopting a conservative versus liberal criterion affects the mean memory strength of “target” and “nontarget” responses, even if there are no differences in discriminability. Specifically, adopting a conservative criterion implies that both “target” *and* “nontarget” responses will carry greater memory strength on average relative to these same response types under a liberal criterion. Since the decision criterion affects mean memory strength of “target” and “nontarget” responses in the same direction, it may seem that the *difference* in mean memory strength between response types is maintained regardless of criterion placement. However, memory strength distributions are nonlinear in an SDT framework, so the degree to which a conservative versus liberal criterion affects mean memory strength of “target” and “nontarget” responses is disproportionate (see Macmillan and Creelman, 2005). Therefore, it is necessary to implement both criterion *and* discriminability manipulations to circumvent this potential confound. Manipulating discriminability can alter the difference in mean memory strength between “target” and “nontarget” responses, regardless of the placement of a decision criterion. If frontoparietal activity is indeed modulated by differences in memory strength, then T > NT response contrasts should differ between discriminability conditions whether participants maintain a conservative or liberal criterion. Conversely, if decision biases are responsible for modulating T > NT response contrasts, then there should be differences across criterion conditions regardless of the level of discriminability. Thus, by combining criterion and discriminability manipulations, we can better disentangle the influences of memory strength and decision biases on frontoparietal activity.

Another approach to distinguish frontoparietal activity associated with mnemonic evidence versus decision criteria is to examine fMRI activity across different decision domains. Individual tendencies to shift criteria are consistent across decision domains whereas discriminability performance is virtually unrelated (Frithsen et al., 2018; Layher et al., 2020). This suggests that neural mechanisms underlying decision criteria may be conserved across decision domains whereas processes associated with task-specific performance may differ. One decision domain that may serve as a good comparison to recognition memory is visual detection given that frontoparietal activity in this domain is modulated by varying decision strategies and task difficulty (Guo et al., 2012). Such comparisons could reveal aspects of frontoparietal activity associated with decision criteria and task performance that are either domain-general or domain-specific. In the current experiment, we systematically manipulated both discriminability and decision criteria during recognition memory and visual detection tests during fMRI scanning. This approach allows us to differentiate frontoparietal activity associated with the strength of evidence versus decision criteria across memory and perceptual domains.

2. Material and methods

2.1. Participants

Thirty healthy adult participants (19 females; 11 males; ages 18–32, $M = 21$, $SD = 3.0$; 3 left-handed) from the University of California, Santa Barbara (UCSB) completed the fMRI experiment and earned $20/hour plus monetary bonuses based on task performance. Selection of the fMRI participants derived from a sample of one hundred and forty-four subjects (84 females; 60 males; ages 18–35, $M = 21$, $SD = 2.8$) who completed an initial prescreen computer task and earned $10/hour in addition to monetary bonuses. All procedures received approval from the UCSB Institutional Review Board, and participants provided written informed consent.

2.2. Task

2.2.1. Initial prescreen

Participants completed an initial prescreen computer task that consisted of shortened and modified versions of the recognition memory and visual detection tests used in the fMRI experiment. To be eligible for the fMRI experiment, participants (1) could not have MRI contraindications, (2) needed to adequately shift decision criteria ($\Delta c_a > 0.7$ in either the recognition memory or visual detection test, which is approximately the cutoff that Aminoff et al. (2015) implemented to designate the "High Shifters" group for fMRI analyses) and (3) perform above chance on both tasks ($d_a > 0$; see *2.3.1. Signal Detection Theory* subsection for Δc_a and d_a definitions and calculations). Eligible participants received an invitation to partake in the fMRI experiment on a first come first serve basis until a total of 30 eligible individuals agreed to participate. The procedures and results of the prescreen task are reported in the *Supplemental Materials*.

2.2.2. fMRI

The fMRI experiment included recognition memory and visual detection tests with manipulations intended to alter discriminability and criterion placement in a fully-crossed 2 (task domain: recognition memory vs. visual detection) x 2 (discriminability condition: low vs. moderate) x 2 (criterion condition: conservative vs. liberal) factorial design creating 8 test conditions (Fig. 1). The stimuli consisted of two nearly-identical sets of 512 unique scene images found on open source online databases and cropped to 500 × 500 pixels. One set contained the original scene image with a single person present (the visual detection target), while an edited set comprised of the same scene stimuli with the person cropped out (person absent) and background blended to maintain the naturalistic look of the scene.

Participants completed two cycles of a study block (for the recognition memory tests) followed by four test blocks during fMRI scanning. Each study block consisted of 256 unique scene images—half of which appeared once (for low discriminability at test) whereas the other half appeared six times (for moderate discriminability), yielding 896 total presentations. Participants passively viewed each study item sequentially and continuously for 720 ms (1 TR) in a randomized order for subsequent recognition tests. Half of the images contained a person whereas the other half did not (split evenly between images presented once vs. six times).

Each test block encompassed eight mini-blocks (one per test condition) of 16 trials (8 target and 8 nontarget images), generating a total of 64 test mini-blocks and 1024 test trials across the entire experiment. Every test trial began with a white crosshair displayed on a black

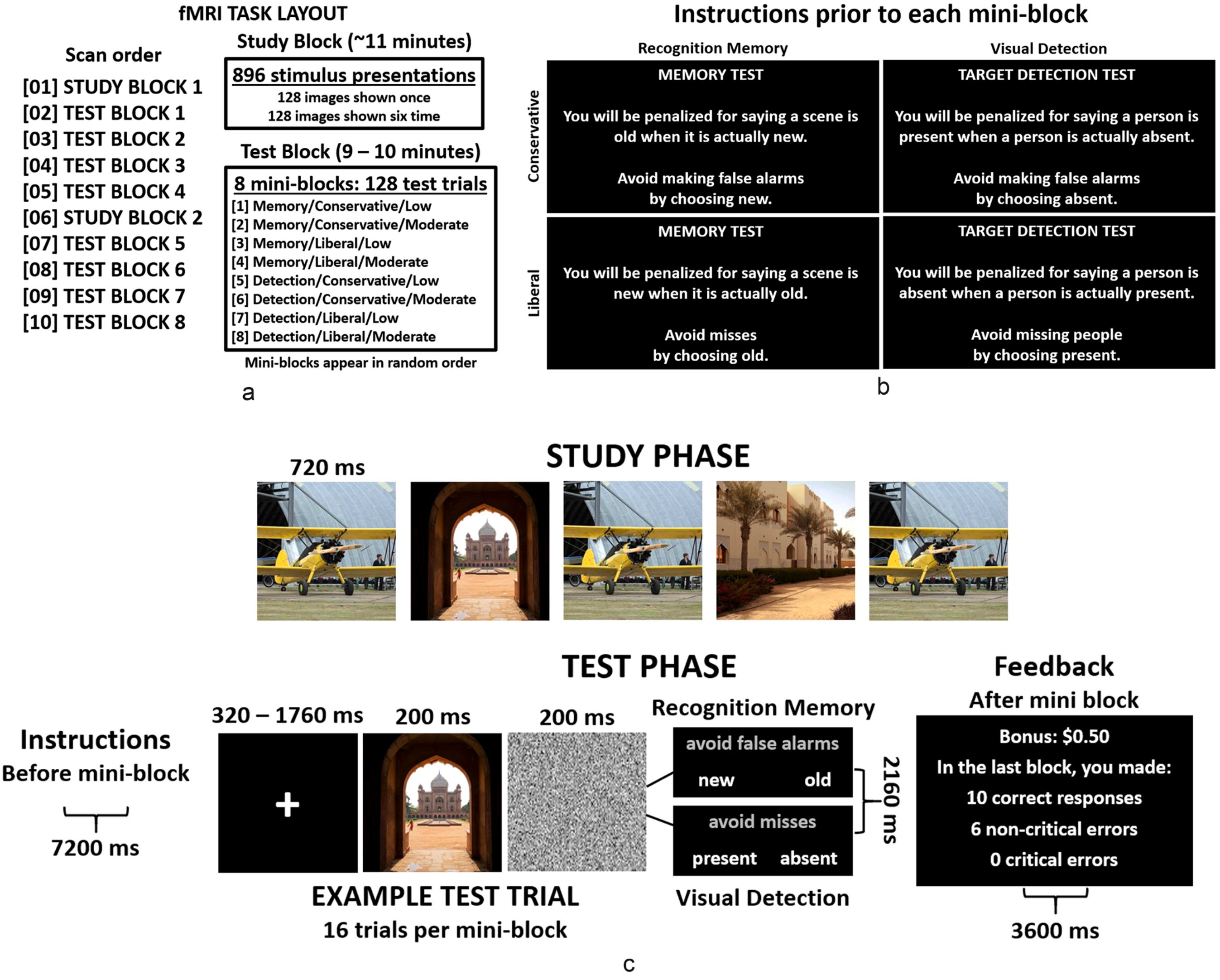

Fig. 1. Recognition memory and visual detection tasks that occurred during fMRI scanning. Panel (a) reveals the fMRI scanning order and details the contents of each study and test block. Panel (b) displays instruction screens shown to participants prior to each test mini-block, depending on the test condition (participants did *not receive* explicit instructions for the discriminability conditions). Panel (c) illustrates the study and test phase mini-block structure with an example test trial. After displaying the test image, the response option display included the phrase "avoid false alarms" (conservative criterion condition) or "avoid misses" (liberal criterion condition) in gray lettering to remind participants of the critical error for that test mini-block.

background for 320 ms, followed by the presentation of a scene image for 200 ms, then a noise mask appeared for 200 ms to eliminate the perceptual afterimage. Afterwards, participants viewed a screen displaying the two possible response types and needed to respond within 2,160 ms (3 TRs). Participants held MRI-compatible two-button response boxes in each hand and made responses with their left or right pointer finger. During recognition memory tests, participants decided whether an image appeared in the study phase ("old," target) or not ("new," nontarget); visual detection tests required participants to determine whether an image contained a person ("present," target) or not ("absent," nontarget). The response type corresponding to a left or right button press randomly changed on a trial-by-trial basis to prevent participants from knowing which button to press until *after* stimulus presentation. During low discriminability recognition test mini-blocks, "old" images only appeared once during the study phase whereas "old" images in the moderate discriminability condition appeared six times. To manipulate discriminability during visual detection tests, 15 researchers prior to the experiment independently rated the difficulty of finding a person in each scene image. Classification of scenes into the low or moderate discriminability condition occurred by taking a median-split of the mean difficulty ratings. A payment manipulation induced criterion shifts where participants earned five cents for each correct response, lost 10 cents for a critical error, but received no penalty for a noncritical error. In the conservative criterion condition, a critical error consisted of incorrectly responding "old" or "present" (false alarms) during recognition memory or visual detection tests, respectively, whereas incorrect "new" and "absent" responses (misses) served as critical errors in the liberal criterion condition. The assignment of images to each task type, criterion condition, and discriminability condition as well as the image version (person present or absent) occurred randomly across participants with the exception that images assigned to the low versus moderate discriminability conditions of the visual detection tests remained fixed.

Prior to each test mini-block, an instruction screen appeared for 7,200 ms (10 TRs) informing participants of the task type and monetary penalty of each incorrect response type for the upcoming trials. The top of the instruction screen displayed "MEMORY TEST" or "TARGET DETECTION TEST" to indicate the task type, while text in the middle of the screen informed participants of the criterion condition and urged participants to avoid critical errors (e.g. in the conservative criterion condition of visual detection tests: "You will be penalized for saying a person is present when a person is actually absent. Avoid making false alarms by choosing absent."). During each test trial, the top of the screen displayed the message "avoid false alarms" or "avoid misses" in gray font when presented with the two response options in the conservative and liberal conditions, respectively, to remind participants of the critical error. Participants did not receive explicit instructions as to whether a mini-block corresponded to the low or moderate discriminability conditions. Following each mini-block, a feedback screen appeared for 3,600 ms (5 TRs) displaying the number of correct responses, noncritical errors, and critical errors as well as money earned for that mini-block. Each functional test block scan included a white crosshair on a black screen for the first 7,200 ms (10 TRs) and the final 14,400 ms (20 TRs). A variable number of jitter trials (randomly determined) displayed a crosshair for 720 ms (1 TR) and appeared randomly after various instruction, test trial, and feedback displays throughout each test block, with a maximum of two consecutive jitter trials (i.e. a crosshair displayed for up to 1,440 ms or 2 TRs). The number of jitter trials displayed during each test block across all participants ranged from 82 to 135. Each study block lasted for about 11 min whereas each test block took between 9 and 10 min, depending on the number of jitter trials. The entire fMRI task lasted for approximately 100 min.

2.3. Behavioral analysis

2.3.1. Signal detection theory

An unequal-variance SDT model quantified discriminability (d_a), differences in discriminability across conditions ($\boldsymbol{\Delta} d_a$), criterion placement (c_a), and criterion shifting ($\boldsymbol{\Delta} c_a$) across all test conditions (see Macmillan and Creelman, 2005). Summation of the total hit (H), miss (M), correct rejection (CR), and false alarm (FA) trials within each test condition allowed for computations of hit rate (*HR*), false alarm rate (*FAR*) and SDT measures through the following equations:

$$HR = \frac{\mathrm{H}}{(\mathrm{H}+\mathrm{M})} \tag{1}$$

$$FAR = \frac{\mathrm{FA}}{(\mathrm{CR}+\mathrm{FA})} \tag{2}$$

$$d_a = \left(\frac{2}{1+s^2}\right)^{1/2}[z(HR) - sz(FAR)] \tag{3}$$

$$c_a = \frac{-\sqrt{2}s}{(1+s^2)^{1/2}(1+s)}[z(HR)+z(FAR)] \tag{4}$$

$$\boldsymbol{\Delta} c_a = c_a(conservative) - c_a(liberal) \tag{5}$$

$$\boldsymbol{\Delta} d_a = d_a(moderate) - d_a(low), \tag{6}$$

where z is the density of the standard normal distribution and s is the standard deviation ratio between nontarget and target distributions (Macmillan and Creelman, 2005). We set $s = 0.8$, which is considered an appropriate approximation for recognition memory tests (Ratcliff et al., 1992), since our tasks only produced two criterion thresholds and accurate estimations of s generally requires several thresholds (see Macmillan and Creelman, 2005). When a condition contained a *FAR* of 0% (1 instance) or *HR* of 100% (2 instances), an addition or subtraction, respectively, of one divided by the total number of trials within the condition occurred to prevent infinite normalized values (see Macmillan and Kaplan, 1985).

2.3.2. Statistics

Mean values are reported with *SD* measures that are adjusted for within-subject variables as described by Morey (2008). Pearson *r* correlations and mean differences (*M*Δ) across conditions are reported with 95% CIs and Cohen's *d* effect sizes. Any CI not containing zero is considered statistically significant. When summarizing results across multiple conditions in-text, the range and median (*Mdn*) across all values are reported. However, the values *within* each condition will appear separately in figures and/or tables.

2.4. MRI data acquisition

A 64-channel head and neck coil within a Siemens 3T PRISMA MRI scanner at UCSB acquired all imaging data. Functional image acquisition occurred via a T_2*-weighted multiband echo planar imaging sequence (72 oblique slices; TR = 720 ms; voxel size = 2 mm^3; FoV = 208 mm^2; TE = 37 ms; flip angle = 52°; multiband factor = 8). To correct for magnetic field inhomogeneities, we collected a T_2*-weighted gradient recall echo (GRE) fieldmap scan with the same slice count and dimensions as the functional scans (TE_1 = 4.92 ms; TE_2 = 7.38 ms). Structural images aided in functional image registration and included a T_1-weighted magnetization-prepared rapid gradient echo (MPRAGE) sequence (208 sagittal slices; TR = 2,500 ms; voxel size = 0.94 mm^3; FoV = 241 mm^3; TE = 2.22 ms; flip angle = 7°) and a T_2-weighted Sampling Perfection with Application optimized Contrasts using different flip angle Evolution (SPACE) sequence (208 sagittal slices; TR = 3,200 ms; voxel size = 0.94 mm3; FoV = 241 mm^3; TE = 566 ms; flip angle = 120°).

2.5. fMRI analysis

2.5.1. Preprocessing

Initial fMRI preprocessing occurred via the FMRI Brain Software Library (FSL), v6.0.4 (Jenkinson et al., 2012). Functional images underwent motion correction using the “MCFLIRT” function (Jenkinson et al., 2002) in FSL. B0 unwarping corrected for magnetic inhomogeneity in the functional images using each participants’ brain extracted fieldmap image. Functional images underwent temporal high pass filtering (0.01 Hz), prewhitening, and spatial smoothing using a 5 mm^3 full-width at half-maximum isotropic Gaussian kernel. Registration of functional images to subject-specific anatomical images occurred via the Advanced Normalization Tools (ANTs) software (Avants et al., 2011).

2.5.2. Whole-brain

The fMRI analyses aimed to investigate how frontoparietal activity in T > NT response (or item) contrasts is modulated across criterion, discriminability, and task manipulations. Event-related general linear models (GLM) implemented in FSL assessed T > NT response and item contrasts across the eight test conditions. First-level analyses for each functional test block included 16 regressors of interest: target and nontarget responses (or items) for each of the eight test conditions in the 2 × 2 × 2 design (e.g. one regressor for target responses in the conservative criterion/low discriminability/recognition memory condition, another for target responses in the conservative criterion/moderate discriminability/recognition memory condition, etc.). Regressors of noninterest included those for instructions, feedback, and rare instances of trials with no responses (0.43% of all trials). The default settings of FMRIB’s Linear Optimal Basis Sets (FLOBS) toolkit modeled the hemodynamic response function (HRF) convolution for each regressor in the GLM. The time window for HRF convolution on each test trial started at image onset and ended when the participant made a response, to control for differences in response time across trials. Additional nuisance regressors included six head motion parameters derived from motion correction realignment.

We initially conducted T > NT response contrasts collapsed across criterion and discriminability conditions within and between tasks to identify regions that are generally modulated by response type. To demonstrate how T > NT response (or item) contrasts differ across conditions, we defined 27 contrasts of interest in the first-level GLM for each test block, which consist of single (8), double (12), triple (6), and quadruple (1) subtractions. Single subtractions consist of T > NT contrasts within each of the eight test conditions (e.g. T > NT responses in the conservative criterion/low discriminability/recognition memory condition), which illustrate one-way interactions of response (or item) type separately for all test conditions. Double subtractions derive from subtracting T > NT contrasts across conservative (CON) and liberal (LIB) criterion conditions (T > NT * CON > LIB), moderate (MOD) and low (LOW) discriminability conditions (T > NT * MOD > LOW), or recognition memory (RM) and visual detection (VD) tasks (T > NT * RM > VD). Each double contrast is computed separately within the other four conditions (e.g. T > NT * CON > LIB responses in the low discriminability/recognition memory condition) to investigate two-way interactions between response (or item) types and each condition. Triple contrasts examine T > NT contrasts that are subtracted across two task conditions (e.g. T > NT * CON > LIB * MOD > LIB responses in the recognition memory task), which explore three-way interactions between response (or item) types and two of the three conditions. For completeness, a quadruple contrast examined subtractions across all conditions combined (i.e. T > NT * CON > LIB * MOD > LOW * RM > VD) to identify four-way interactions in the T > NT contrasts. Positive values obtained from T > NT contrasts represent greater activity for “target” relative to “nontarget” responses (or items), whereas negative values represent increased activity for the reverse contrast of “nontarget” versus “target” trials (i.e. NT > T contrasts). However, it is important to note that for higher order subtractions (i.e. double, triple, and quadruple contrasts), negative values can be conceptualized as a reverse subtraction of any particular factor not just NT > T. For example, negative values in a T > NT * MOD > LOW contrast reflects increased activity in contrasts of NT > T * MOD > LOW or T > NT * LOW > MOD, since reversing the subtraction for any particular factor will flip the sign of the original contrast.

For each subject, a higher-level analysis in FSL (level 2 analysis) computed a single group average with fixed effects across the eight first-level analyses (one for each test scanning block). These higher-level averages across the 30 subjects were then averaged together using mixed effects with the FLAME 1 function in FSL (level 3 analysis). Whole-brain group contrasts with voxel-wise thresholding at $Z = 3.1$ and cluster correction using Gaussian Random Field Theory ($p < .05$), implemented in the FMRI Expert Analysis Tool (FEAT), determined statistically significant activity related to the aforementioned 27 T > NT response (or item) contrasts. We implemented the Caret5 program to provide visualizations of whole-brain results (Van Essen et al., 2001).

2.5.3. ROI

Additional region of interest (ROI) analyses occurred for T > NT response and item contrasts based on ROI centroids derived from 12 peak cortical voxels reported by Aminoff et al. (2015): specifically, the H > CR contrast in the conservative condition of the recognition memory tests for words. These included regions in the insula, inferior frontal gyrus (IFG), middle frontal gyrus (MFG), medial frontal gyrus (MeFG), inferior parietal lobule (IPL), superior parietal lobule (SPL), precuneus (PC), and posterior cingulate gyrus (PoC). Using the MNI152 standard brain template in FSL, we created the 12 ROI centroids from spheres with 5 mm radii around each peak voxel (81 voxels per ROI). Mean parameter estimates from each ROI were extracted for every participant separately for the 16 event types of interest (e.g. target responses in the conservative criterion/low discriminability/recognition memory task). This generated a total of 5760 mean fMRI parameter estimates (30 subjects x 12 ROIs x 16 event types), separately for response and item types.

For ROI analyses, additive linear mixed models implemented with the lme4 package (Bates et al., 2015) in R, assessed the extent to which mean parameter estimates across the 12 ROIs, separately for response and item types, are affected by task type (RM > VD), criterion condition (CON > LIB), discriminability condition (MOD > LOW), and target type (T > NT). Deviation contrasts specified fixed effects and modeling of a four-way interaction occurred between task, criterion, discriminability, and target type contrasts, along with all marginal three-way and two-way interactions. The fixed effects models took the following form:

$$\begin{aligned}
\hat{y} = {} & b_0 + b_1(RM > VD) + b_2(CON > LIB) + b_3(MOD > LOW) + b_4(T > NT) \\
& + b_5(RM > VD * CON > LIB) + b_6(RM > VD * MOD > LOW) \\
& + b_7(CON > LIB * MOD > LOW) + b_8(RM > VD * T > NT) \\
& + b_9(CON > LIB * T > NT) + b_{10}(MOD > LOW * T > NT) \\
& + b_{11}(RM > VD * CON > LIB * MOD > LOW) \\
& + b_{12}(RM > VD * CON > LIB * \ T > NT) \\
& + b_{13}(RM > VD * MOD > LOW * \ T > NT) \\
& + b_{14}(CON > LIB * MOD > LOW * \ T > NT) \\
& + \ b_{15}(RM > VD * CON > LIB * MOD > LOW * \ T > NT) + \ \varepsilon.
\end{aligned}$$

Specification of crossed random effects on the model intercept accounted for baseline variation in mean parameter estimates across subjects and ROIs. We treated ROI as a random effect in the model because we wanted to assess whether this network of criterion-sensitive regions is *generally* affected by manipulations of discriminability and task as opposed to investigating how *each* ROI is affected by these manipulations. Using the restricted maximum likelihood approach to model estimation, 10,000 iterations of posterior simulation approximated empirical 95% CIs around each parameter. Effect size approximations of Cohen's *d* occurred by dividing contrast parameter estimates by the square root of the total random effects variance of the model (Westfall et al., 2014).

3. Results

3.1. Behavior

3.1.1. Discriminability

Discriminability manipulations in both tasks proved successful as mean d_a in the recognition memory tests remained significantly higher for the moderate ($M = 1.08$, $SD = 0.40$) versus low ($M = 0.31$, $SD = 0.36$) discriminability conditions ($M\Delta = 0.77$, 95% CI [0.67, 0.87], $d = 2.14$), as well as in the visual detection tests between the moderate ($M = 1.53$, $SD = 0.34$) and low ($M = 0.22$, $SD = 0.35$) discriminability conditions ($M\Delta = 1.31$, 95% CI [1.21, 1.41], $d = 4.69$). Mean d_a did not significantly differ between the recognition memory and visual detection tests in the low discriminability condition ($M\Delta = 0.10$, 95% CI [−0.00, 0.20], $d = 0.43$). However, mean d_a in the moderate discriminability condition remained higher for the visual detection versus recognition memory tests ($M\Delta = 0.44$, 95% CI [0.35, 0.54], $d = 1.19$), despite efforts to make levels of discriminability similar across decision domains.

Within the moderate discriminability condition, we found no significant differences in d_a between the conservative and liberal criterion conditions of the recognition memory task ($M\Delta = 0.05$, 95% CI [−0.12, 0.21], $d = 0.10$), but found a small significant difference in the visual detection task ($M\Delta = 0.18$, 95% CI [0.04, 0.32], $d = 0.48$). In the low discriminability condition, we observed significant differences in d_a between conservative and liberal criterion conditions in both the recognition memory ($M\Delta = -0.29$, 95% CI [−0.45, −0.12], $d = -0.86$) and visual detection ($M\Delta = -0.23$, 95% CI [−0.38, −0.08], $d = -0.84$) tasks, despite efforts to make discriminability equivalent across criterion conditions. However, it is important to note that differences in d_a *across* discriminability conditions were much larger than those between criterion conditions *within* each discriminability condition.

3.1.2. Criterion shifts

Mean Δc_a indicated that participants shifted decision criteria to large extents between criterion conditions in the recognition memory low ($M = 1.47$, $SD = 0.26$) and moderate ($M = 1.35$, $SD = 0.20$) discriminability conditions, as well as in the visual detection low ($M = 1.35$, $SD = 0.23$) and moderate ($M = 0.99$, $SD = 0.27$) discriminability conditions. Participants shifted criteria to a somewhat larger extent between the recognition memory and visual detection tests for both the low ($M\Delta = 0.12$, 95% CI [0.04, 0.21], $d = 0.18$) and moderate discriminability conditions ($M\Delta = 0.36$, 95% CI [0.28, 0.45], $d = 0.57$). Additionally, mean c_a across all conditions remained higher for visual detection ($M = 0.32$, $SD = 0.98$) versus recognition memory ($M = -0.06$, $SD = 1.14$) tests, especially in the liberal criterion conditions ($M\Delta = 0.50$, 95% CI [0.42, 0.57], $d = 1.21$) relative to the conservative conditions ($M\Delta = 0.26$, 95% CI [0.18, 0.34], $d = 0.64$). Thus, participants maintained a relatively more conservative criterion throughout all conditions of the visual detection versus recognition memory tests. A complete list of mean behavioral performance values across all conditions is shown in Table 1.

3.1.3. Behavioral correlations across task types

Very strong relationships existed between c_a in the recognition memory and visual detection tasks across the four criterion/discriminability conditions ($r_{(28)}$ range: 0.57-0.80, $Mdn = 0.74$) as well as Δc_a in the two discriminability conditions ($r_{(28)}$ range: 0.84-0.85, $Mdn = 0.85$; see Table 2, top). In contrast, relationships between d_a across tasks showed no significant relationships in three of the four criterion/discriminability conditions ($r_{(28)}$ range: −0.01-0.51, $Mdn = 0.12$) and no significant relationships existed between Δd_a in the two criterion conditions ($r_{(28)}$ range: −0.01-0.26, $Mdn = 0.13$; see Table 2, bottom). This indicates that behavioral similarities between the recognition memory and visual detection tests are largely specific to the decision criterion and *not* discriminability.

3.1.4. Reaction times

In the conservative criterion condition of the recognition memory task, mean RT remained higher for target ($M = 859$ ms, $SD = 289$) versus nontarget ($M = 817$ ms, $SD = 276$) responses across participants ($M\Delta = 49$ ms, 95% CI [11, 88], $d = 0.81$). However, in the liberal criterion condition, mean RT for target ($M = 770$ ms, $SD = 271$) responses remained *lower* relative to nontarget ($M = 904$ ms, $SD = 295$) responses ($M\Delta = -150$ ms, 95% CI [−188, −113], $d = 2.36$). These results support a response bias account of criterion shifting since maintaining a conservative criterion requires inhibiting prepotent "nontarget" responses to choose "target" (increasing "target" response RT), whereas the reverse is true when a liberal criterion is implemented (increasing

Table 2
Pearson correlations between c_a (top) and d_a (bottom) across criterion (conservative/liberal) and discriminability (low/moderate) conditions as well as differences between conditions (right). Each Pearson *r* value is accompanied by 95% CIs.

Cross task correlations: c_a			
	Conservative	Liberal	Δc_a
Low	0.72 [0.49, 0.86]	0.75 [0.53, 0.87]	0.84 [0.69, 0.92]
Moderate	0.57 [0.27, 0.77]	0.80 [0.62, 0.90]	0.85 [0.70, 0.92]
Cross task correlations: d_a			
	Moderate	Low	Δd_a
Conservative	0.51 [0.19, 0.74]	0.22 [−0.15, 0.54]	0.26 [−0.11, 0.57]
Liberal	-0.01 [−0.37, 0.35]	0.01 [−0.35, 0.37]	-0.01 [−0.37, 0.35]

Table 1
Mean and *SD* values (in parentheses) for hit rate (*HR*), false alarm rate (*FAR*), c_a, d_a, target (T), and nontarget (NT) reaction times across criterion, discriminability, and task conditions.

Condition		Recognition memory					
Discriminability	Criterion	*HR*	*FAR*	c_a	d_a	T (ms)	NT (ms)
Low	**Conservative**	0.27 (0.13)	0.17 (0.12)	0.82 (0.41)	0.17 (0.31)	891 (294)	814 (274)
	Liberal	0.78 (0.11)	0.68 (0.13)	−0.65 (0.36)	0.46 (0.29)	780 (266)	914 (287)
Moderate	**Conservative**	0.55 (0.15)	0.16 (0.13)	0.46 (0.40)	1.10 (0.35)	838 (268)	820 (257)
	Liberal	0.88 (0.09)	0.67 (0.10)	−0.88 (0.35)	1.06 (0.39)	760 (259)	891 (283)
		Visual Detection					
Low	**Conservative**	0.17 (0.09)	0.10 (0.09)	1.18 (0.35)	0.10 (0.30)	874 (277)	792 (243)
	Liberal	0.62 (0.13)	0.52 (0.15)	−0.17 (0.38)	0.33 (0.29)	866 (286)	892 (275)
Moderate	**Conservative**	0.59 (0.09)	0.08 (0.08)	0.62 (0.26)	1.61 (0.30)	776 (247)	804 (249)
	Liberal	0.83 (0.08)	0.39 (0.11)	−0.36 (0.32)	1.44 (0.31)	804 (273)	857 (261)

"nontarget" response RT).

In the conservative criterion condition of the visual detection task, mean RT did *not* significantly differ between target ($M = 804$ ms, $SD = 269$) versus nontarget ($M = 797$ ms, $SD = 254$) responses ($M\Delta = 12$ ms, 95% CI [−15, 39], $d = 0.24$). However, mean RT in the liberal criterion condition of the visual detection task remained lower for target ($M = 834$ ms, $SD = 291$) versus nontarget ($M = 876$ ms, $SD = 278$) responses ($M\Delta = -58$ ms, 95% CI [−84, −32], $d = 1.02$); similar to findings in the recognition memory tests. A complete list of mean RT values across all conditions is reported in Table 1. To account for RT variability in the fMRI analyses, HRF convolution for each trial occurred from stimulus onset until the participant made a response.

3.2. fMRI: Whole-brain

3.2.1. Target > nontarget response contrast

To demonstrate a general effect of response type on frontoparietal activity, we conducted an initial examination of T > NT response contrasts collapsed across criterion and discriminability conditions within the recognition memory and visual detection tasks, as well as the difference between tasks. The recognition memory T > NT response contrast revealed widespread frontoparietal activity, especially in the left hemisphere (Fig. 2, left). This included regions that are commonly implicated in previous assessments of various old > new response contrasts, such as areas within the IFG, IPL, and PoC (see Wagner et al., 2005; Gilmore et al., 2015). The visual detection T > NT response contrast revealed spatially sparser frontoparietal activity, such as areas in the fusiform gyrus, middle temporal gyrus, and IPL (Fig. 2, middle). When comparing the T > NT response contrast between recognition memory and visual detection tasks, activity in some predominantly left hemisphere parietal areas remained higher in the recognition memory task, such as the PC, PoC, and angular gyrus (Fig. 2, right). These parietal areas may represent memory-specific regions that exhibit differential activity between target and nontarget responses. The fMRI local maxima from the whole-brain statistical Z-maps in the T > NT response contrasts collapsed across criterion and discriminability conditions are presented in Table 3.

When comparing within each condition, whole-brain GLM analyses in the recognition memory task revealed widespread frontoparietal activity in T > NT response contrasts when participants maintained a conservative criterion, but not when maintaining a liberal criterion, in both the low and moderate discriminability conditions (Fig. 3, four panels in top left corner). In fact, under a liberal criterion, the *reverse* contrast (NT > T responses) in both discriminability conditions revealed significant activity in frontal regions including the right anterior insula, IFG, and MeFG, suggesting that recruitment of these areas is particularly well-described by a response bias account. Comparisons of the T > NT response contrasts between conservative and liberal criterion conditions (T > NT * CON > LIB) revealed widespread frontoparietal activity including bilateral regions in the insula, anterior cingulate cortex (ACC), IFG, MFG, MeFG, SPL, and PC in both discriminability conditions (Fig. 3, two-panel column in top right corner). This indicates a very strong two-way interaction between response type and criterion condition on frontoparietal activity. However, comparisons of T > NT response contrasts across moderate and low discriminability conditions (T > NT * MOD > LOW) in the recognition memory task showed no significant differences in whole-brain activity regardless of whether participants maintained a conservative or liberal criterion (represented in Fig. 3 as blank panels with "N.S." in white lettering). The T > NT response contrast between criterion and discriminability conditions (T > NT * CON > LIB * MOD > LOW), also revealed no significant differences in whole-brain activity (i.e. no three-way interaction). These results strikingly reveal that changes in decision criterion placement during recognition memory tests drastically affect the T > NT response contrast, whereas changes in discriminability do not.

In the visual detection task, whole-brain analyses of T > NT response contrasts also revealed greater frontoparietal activity when participants maintained a conservative, but not a liberal criterion—though to a much lesser spatial extent relative to the recognition memory tests (Fig. 4, four panels in top left corner). Comparing T > NT response contrasts across criterion conditions (T > NT * CON > LIB) revealed increased frontoparietal activity in both the low and moderate discriminability conditions of the visual detection tasks, including bilateral regions of ACC, IFG, and insula (Fig. 4, two-panel column in top right corner). However, we did not observe differences in T > NT response contrasts across discriminability conditions (T > NT * MOD > LOW) in either criterion condition, except for sparse differences within the visual cortex specifically in the conservative criterion condition. A three-way interaction between criterion and discriminability conditions in the T > NT response contrast (T > NT * CON > LIB * MOD > LOW) revealed sparse differences in the visual cortex, but no differences in frontoparietal activity. These findings indicate that frontoparietal activity in T > NT response contrasts of visual detection tasks are also affected by criterion placement but *not* changes in discriminability.

When comparing T > NT response contrasts between recognition memory and visual detection tasks (T > NT * RM > VD), only sparse differences in activity were observed, but no consistent patterns existed across criterion or discriminability conditions (e.g. greater activity in the

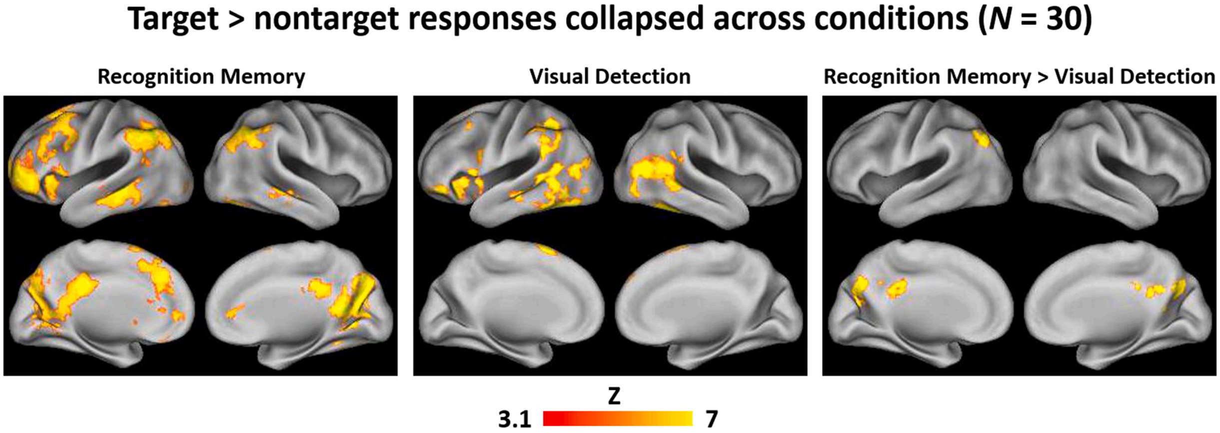

Fig. 2. Whole-brain statistical Z-maps of T > NT response contrasts collapsed across criterion and discriminability conditions in the recognition memory (left) and visual detection (middle) tasks as well as the subtraction between the two tasks (right) displayed on the inflated caret brain (Caret5). Statistically significant activity with thresholding at $Z > 3.1$ and cluster correction at $p < .05$, are displayed in orange. No significant activity appeared in any of the reverse contrasts (i.e. NT > T responses).

Table 3
Local maxima from whole-brain statistical Z-maps of T > NT response contrasts collapsed across criterion and discriminability conditions within the recognition memory (top) and visual detection (middle) tasks, as well as differences between tasks (bottom; see also Fig. 2). Peak intensity coordinates, brain locations, and Broadmann Areas (BA) are derived from the MNI152 standard template brain in FSL. *Indicates local maxima that do *not* overlap with criterion-sensitive regions as determined by whole-brain (T > NT * CON > LIB) response contrasts within the respective task (see Figs. 3& 4).

fMRI local maxima T > NT responses collapsed across conditions

Recognition Memory

Cluster	Z-value	X	Y	Z	Location	BA
1*	6.07	−50	−60	44	Left Angular Gyrus	39
1*	5.72	10	−58	14	Right Calcarine Fissure	23
1	5.49	−2	−34	34	Left Posterior Cingulate Gyrus	23
1	5.32	−36	−58	46	Left Inferior Parietal Lobule	39
1*	5.28	−52	−50	38	Left Inferior Parietal Lobule	39
1	5.22	20	−62	24	Right Precuneus	31
2	5.87	−44	44	−6	Left Inferior Frontal Gyrus	10
2*	5.73	−40	52	4	Left Middle Frontal Gyrus	10
2*	5.49	−24	14	54	Left Middle Frontal Gyrus	6
2	5.4	−30	20	2	Left Insula	13
2*	5.2	−22	64	10	Left Superior Frontal Gyrus	10
2*	5.18	−24	10	62	Left Middle Frontal Gyrus	6
3	5.49	8	−78	−30	Right Cerebellum	18
3	5.16	40	−64	−48	Right Cerebellum	37
3	4.87	6	−54	−50	Right Cerebellum	37
3*	4.85	−6	−58	−52	Left Cerebellum	37
3	4.84	38	−66	−32	Right Cerebellum	37
3	4.76	16	−76	−32	Right Cerebellum	19
4*	4.92	−64	−34	−8	Left Middle Temporal Gyrus	21
4*	4.91	−64	−38	−6	Left Middle Temporal Gyrus	21
4*	4.89	−62	−24	−20	Left Inferior Temporal Gyrus	21
4*	4.86	−64	−40	−2	Left Middle Temporal Gyrus	21
4*	4.85	−68	−20	−16	Left Middle Temporal Gyrus	21
4*	4.82	−62	−26	−8	Left Middle Temporal Gyrus	21
5	5.14	−6	34	36	Left Medial Superior Frontal Gyrus	8
5	5.14	−4	34	32	Left Anterior Cingulate Gyrus	8
5	4.72	−6	18	44	Left Medial Superior Frontal Gyrus	8
5	4.03	−2	32	52	Left Medial Superior Frontal Gyrus	8
5*	3.99	0	40	6	Left Anterior Cingulate Gyrus	24
5	3.89	−6	42	22	Left Anterior Cingulate Gyrus	32
6	4.5	44	−60	42	Right Angular Gyrus	39
6*	4.25	52	−54	42	Right Inferior Parietal Lobule	39
6*	4.18	64	−58	14	Right Middle Temporal Gyrus	37
6	4.18	36	−58	40	Right Angular Gyrus	39
6	4.12	42	−50	36	Right Angular Gyrus	39
6*	4.1	54	−52	36	Right Angular Gyrus	39
7	4.28	−8	−74	−28	Left Cerebellum	18
7	4.27	−42	−70	−18	Left Cerebellum	37
7	3.99	−42	−64	−30	Left Cerebellum	37
7	3.89	−48	−66	−18	Left Cerebellum	37
7	3.88	−32	−68	−30	Left Cerebellum	19
7	3.72	−16	−74	−30	Left Cerebellum	18
8	4.75	−16	12	10	Left Caudate	48
8	4.69	−8	12	0	Left Caudate	48
8	4.59	−14	4	14	Left Caudate	48
8	4.14	−10	0	4	Left Pallidum	50
8	3.27	−16	−8	18	Left Caudate	48
8	3.24	−14	−4	16	Left Caudate	48
9*	4.39	62	−36	−4	Right Middle Temporal Gyrus	21
9	4.16	62	−32	−8	Right Middle Temporal Gyrus	21
9*	3.89	66	−36	−2	Right Middle Temporal Gyrus	21
9*	3.88	54	−24	−10	Right Middle Temporal Gyrus	21
9*	3.75	64	−22	−8	Right Middle Temporal Gyrus	22
9	3.64	58	−30	−14	Right Inferior Temporal Gyrus	21
Visual Detection						
1*	5.64	52	−74	0	Right Middle Temporal Gyrus	19
1*	5.35	62	−62	−4	Right Inferior Temporal Gyrus	37
1*	5.06	52	−76	8	Right Middle Temporal Gyrus	19
1*	4.96	46	−66	14	Right Middle Temporal Gyrus	19
1*	4.85	52	−58	−22	Right Inferior Temporal Gyrus	37
1*	4.81	40	−66	−24	Right Cerebellum	37
2*	5.04	−46	−56	−22	Left Fusiform Gyrus	37
2*	5	−52	−62	−20	Left Inferior Temporal Gyrus	37
2*	4.67	−52	−52	−24	Left Inferior Temporal Gyrus	37
2*	4.62	−44	−54	14	Left Middle Temporal Gyrus	39
2*	4.54	−44	−66	−20	Left Cerebellum	37
2*	4.38	−54	−44	−2	Left Middle Temporal Gyrus	21
3*	4.85	−48	46	−12	Left Inferior Frontal Gyrus	47
3*	4.78	−48	24	42	Left Middle Frontal Gyrus	8
3*	4.72	−50	48	0	Left Inferior Frontal Gyrus	46
3*	4.71	−48	20	42	Left Middle Frontal Gyrus	8
3	4.66	−38	20	0	Left Insula	13
3*	4.63	−48	50	4	Left Inferior Frontal Gyrus	46
4*	4.78	−36	−52	48	Left Inferior Parietal Lobule	40
4*	4.42	−44	−54	56	Left Inferior Parietal Lobule	39
4*	4.28	−44	−42	46	Left Inferior Parietal Lobule	40
4*	4.27	−46	−42	50	Left Inferior Parietal Lobule	40
4*	4.26	−38	−52	54	Left Inferior Parietal Lobule	40
4*	4.23	−50	−44	34	Left Supramarginal Gyrus	39
5*	4.73	4	56	40	Right Medial Superior Frontal Gyrus	9
5*	4.38	−16	28	62	Left Superior Frontal Gyrus	6
5*	4.37	−12	14	68	Left Supplementary Motor Area	6
5*	4.35	−18	14	68	Left Superior Frontal Gyrus	6
5*	4.34	−20	26	62	Left Superior Frontal Gyrus	6
5*	4.27	−6	12	64	Left Supplementary Motor Area	6
Recognition Memory > Visual Detection						
1	4.77	−10	−68	32	Left Precuneus	7
1	4.45	−4	−72	34	Left Cuneus	7
1	4.19	0	−44	28	Left Posterior Cingulate Gyrus	23
1	4.12	10	−62	30	Right Precuneus	31
1	4.04	12	−66	30	Right Precuneus	7
1	3.94	10	−58	12	Right Calcarine Fissure	23
2	4.54	−42	−72	40	Left Angular Gyrus	39
2	4.19	−38	−76	44	Left Inferior Parietal Lobule	39
2	3.95	−44	−64	46	Left Angular Gyrus	39
2	3.94	−44	−64	42	Left Angular Gyrus	39
2	3.19	−40	−68	50	Left Angular Gyrus	39

right PC within the low discriminability/conservative criterion condition and less activity in the right IFG in the moderate discriminability/liberal criterion condition, see *Supplemental Materials*). These results suggest that the hallmark frontoparietal activity in T > NT response contrasts may represent domain-general neural mechanisms associated with criterion placement, at least to a certain extent. The fMRI local maxima from the whole-brain statistical *Z*-maps in the T > NT response contrast between criterion conditions (T > NT * CON > LIB) for both discriminability conditions and tasks are presented in Table 4. The recognition memory local maxima listed in Table 4 that overlap with (T > NT * CON > LIB) response contrasts in the visual detection task are marked with an asterisk, indicating regions that appear domain-general in terms of being criterion-sensitive. Virtually all local maxima listed for the visual detection (T > NT * CON > LIB) response contrasts overlap with the respective recognition memory contrasts. Local maxima from whole-brain statistical *Z*-maps in other T > NT response contrasts are reported in the *Supplemental Materials*.

Although we did not observe any frontoparietal differences in T > NT response contrasts across discriminability conditions at the whole-brain level, we do note in Table 3 non-overlapping local maxima between T > NT response contrasts collapsed across criterion and discriminability conditions and the (T > NT * CON > LIB) response contrasts within each task. These are regions that demonstrate a general effect of response type, but cannot necessarily be considered criterion-sensitive since there are no significant differences in activity across criterion manipulations.

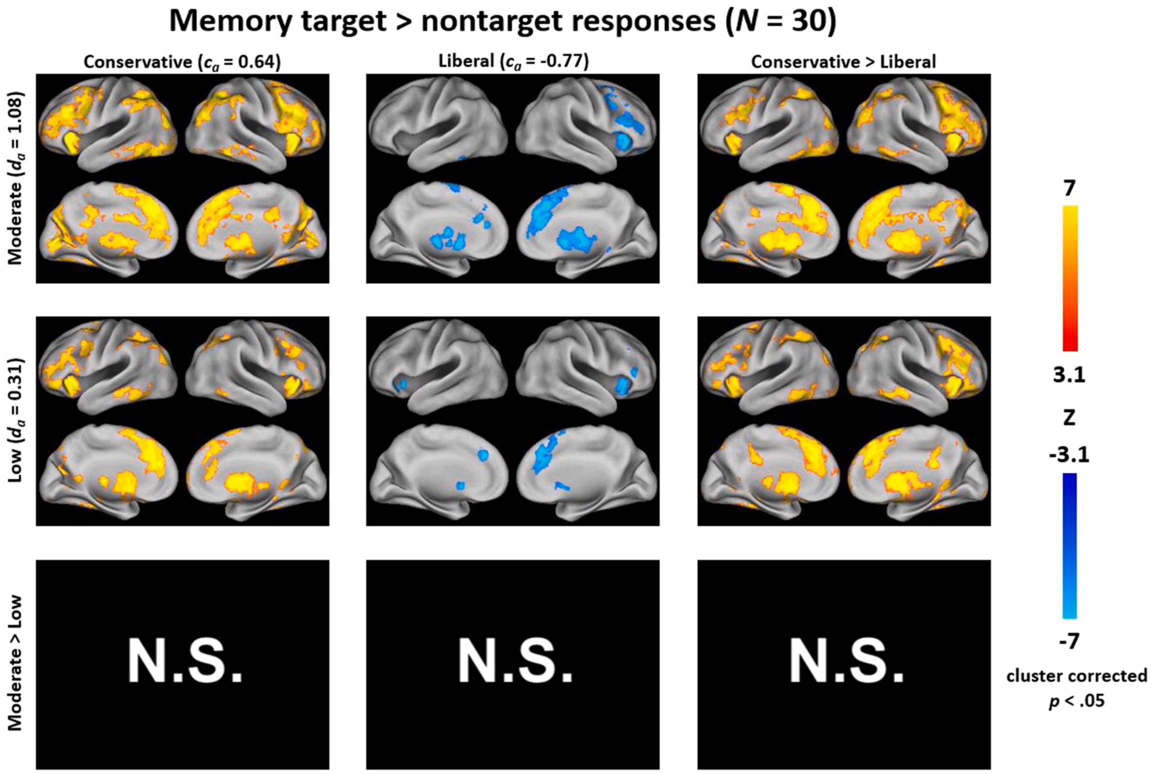

Fig. 3. Whole-brain statistical Z-maps of T > NT response contrasts in the recognition memory task across criterion and discriminability conditions displayed on the inflated caret brain (Caret5). Each row represents a different discriminability condition or contrast between the two conditions (MOD > LOW; bottom), whereas each column represents a different criterion condition or contrast between the two conditions (CON > LIB; right). Statistically significant activity with thresholding at $Z > 3.1$ or $Z < -3.1$ and cluster correction at $p < .05$, are displayed in orange (T > NT) and blue (NT > T). Images containing "N.S." represent conditions in which no significant activity occurred at the whole-brain level.

We posit these regions as potential candidates for future investigations of strength-based effects between target and nontarget response types across recognition memory or visual detection tests.

3.2.2. *Target > nontarget item contrast*

Given the striking finding that changes in decision criteria robustly affected frontoparietal activity in the T > NT response contrasts—but *not* changes in discriminability—analyses of T > NT *item* contrasts sought to assess the sensitivity of the discriminability manipulations regardless of response type. Since target and nontarget items appeared randomly and evenly across conditions, mean target strength should be equivalent between the conservative and liberal conditions. If frontoparietal activity is associated with target evidence strength, then greater activity should be observed in the moderate versus low discriminability conditions regardless of the criterion condition. The T > NT item contrasts in both tasks revealed spatially sparse activations (e.g. in the right insula and MeFG), but only when participants maintained a conservative criterion within the moderate discriminability condition. Since differences in activity between T > NT item contrasts across discriminability conditions remained specific to the conservative condition, this again supports the notion that criterion placement plays a major role in frontoparietal differences between target and nontarget items. However, an interaction may exist where greater discriminability enhances frontoparietal activity, specifically when maintaining a conservative criterion, though virtually no significant differences appeared when assessing three-way interactions (T > NT * CON > LIB * MOD > LOW) at the whole-brain level in either task. The fMRI local maxima from the whole-brain statistical Z-map in the T > NT item contrasts across criterion conditions (T > NT * CON > LIB) for the moderate discriminability condition in both the recognition memory and visual detection tasks are presented in Table 5 (the low discriminability contrasts showed no significant activations). Local maxima from whole-brain statistical Z-maps in other T > NT item contrasts are reported in the *Supplemental Materials*.

3.3. *fMRI: ROI*

3.3.1. *Target > nontarget response contrasts across tasks*

Whole-brain analyses of T > NT response contrasts revealed much more widespread frontoparietal activity in the recognition memory versus visual detection tests. However, virtually no differences existed at the whole-brain level when comparing across decision domains. One possibility is that these comparisons are underpowered, given the high-dimensionality of the data and the need for strict multiple comparisons correction at the whole-brain level. Therefore, more focal analyses were conducted based on 12 ROIs identified as criterion-sensitive regions during recognition memory tests for words (Aminoff et al., 2015). Comparing across mean parameter estimates for each ROI individually, all 12 ROIs revealed greater activity in T > NT response contrasts across criterion conditions (T > NT * CON > LIB) for both discriminability conditions in the recognition memory task. In the visual detection task, 9 out of 12 ROIs showed greater activity in the T > NT response contrast across criterion conditions (T > NT * CON > LIB) within the moderate discriminability condition, while 6 out 12 ROIs revealed greater activity within the low discriminability condition. Fig. 5 displays mean fMRI parameter estimates in the T > NT response contrast for each ROI across the eight test conditions (see *Supplemental Materials* to view these values in a table). Table 6 includes mean fMRI parameter estimates in T > NT response (and item) contrasts across criterion conditions (T > NT * CON > LIB) in both discriminability conditions and tasks.

When considering all ROIs together, the linear mixed model revealed that the T > NT response contrasts between criterion conditions (T > NT

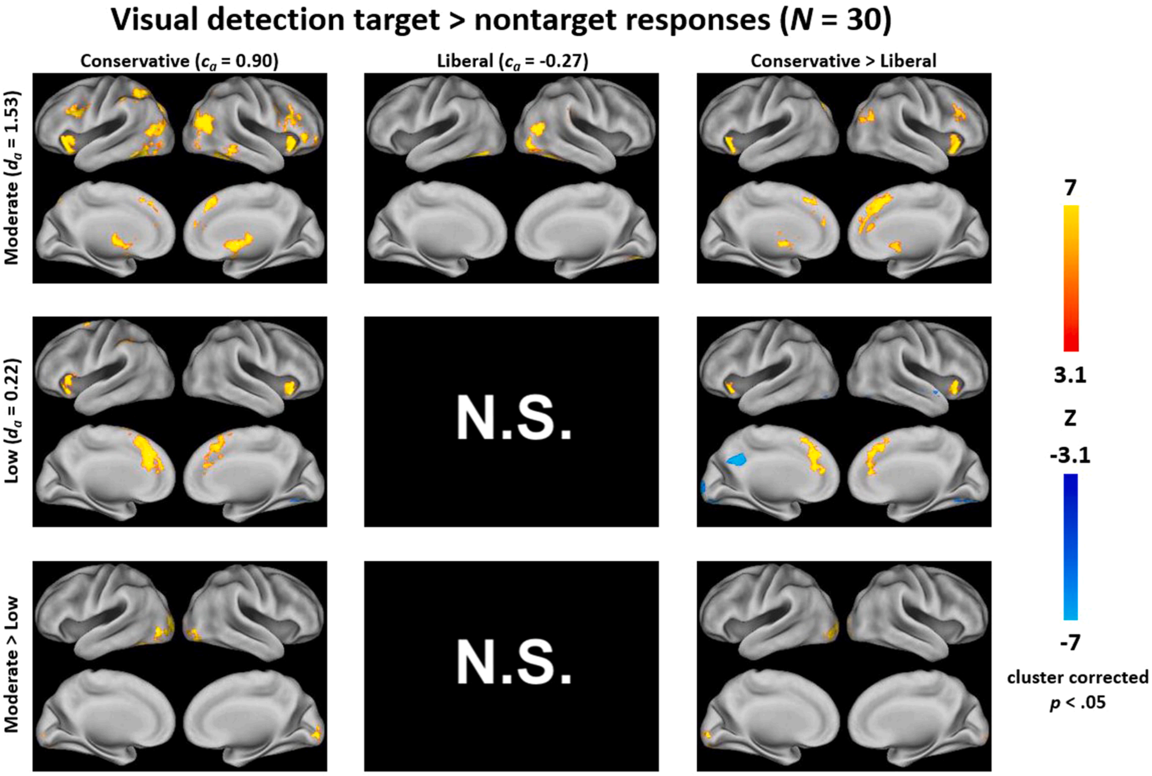

Fig. 4. Whole-brain statistical Z-maps of T > NT response contrasts in the visual detection task across criterion and discriminability conditions displayed on the inflated caret brain (Caret5). Each row represents a different discriminability condition or contrast between the two conditions (MOD > LOW; bottom), whereas each column represents a different criterion condition or contrast between the two conditions (CON > LIB; right). Statistically significant activity with thresholding at $Z > 3.1$ or $Z < -3.1$ and cluster correction at $p < .05$, are displayed in orange (T > NT) and blue (NT > T). Images containing "N.S." represent conditions in which no significant activity occurred at the whole-brain level.

* CON > LIB * RM > VD) showed greater activity in the recognition memory versus visual detection task ($b = 5.89$, 95% CI [3.65, 8.16], $SD = 1.16$, $t = 5.09$, $d = 0.64$). This suggests that the T > NT response contrast in these criterion-sensitive regions are modulated to a greater degree by changes in decision criteria when performing recognition memory versus visual detection tasks (a finding *not* observed in the whole-brain analyses). One potential caveat to this finding is that specific ROI locations derived from findings in a prior *recognition memory* task and it is possible that criterion-sensitive regions for visual detection tasks evoke similar responses, but in slightly different areas within these brain structures (i.e. the maximally active criterion-sensitive voxels for visual detection tests might be spatially different than those for recognition memory). Despite this potential caveat, there still *are* common criterion-sensitive frontoparietal regions across task domains including areas within MeFG, MFG, insula, and IPL (Fig. 5; Table 6). However, regions that might only be criterion-sensitive during recognition memory tests include PC and PoC.

The linear mixed model revealed no significant differences between response types and discriminability condition (T > NT * MOD > LOW; $b = -1.38$, 95% CI [−3.00, 0.24], $SD = 0.82$, $t = -1.69$, $d = 0.15$). In fact, no interactions involving contrasts between discriminability conditions (MOD > LOW) proved significant (see Table 7 and Fig. 7). This suggest that this network of criterion-sensitive regions is not significantly affected by changes in discriminability regardless if comparisons are made across response type (T > NT), criterion condition (CON > LIB), and/or task type (RM > VD).

3.3.2. Target > nontarget item contrasts across tasks

None of the 12 ROIs in the low discriminability condition showed significant differences in the T > NT item contrast between criterion conditions (T > NT * CON > LIB) in either task. However, 4 out of 12 ROIs in the recognition memory task and 8 out of 12 ROIs in the visual detection task showed significant differences across the moderate discriminability condition for the T > NT item contrast across conditions (T > NT * CON > LIB; see Fig. 6 and Table 6). Considering all 12 ROIs together, the linear mixed model did not reveal a significant cross-task interaction in the T > NT item contrast across criterion conditions (T > NT * CON > LIB * RM > VD; $b = -1.24$, 95% CI [−3.55, 1.06], $SD = 1.17$, $t = -1.06$, $d = 0.12$). However, the linear mixed model did reveal an interaction between criterion and discriminability conditions in the T > NT item contrast (T > NT * CON > LIB * MOD > LOW; $b = 3.60$, 95% CI [1.30, 5.92], $SD = 1.17$, $t = 3.08$, $d = 0.37$), regardless of task type. This again suggests that greater discriminability in both tasks increases frontoparietal activity when comparing across target and nontarget items, *specifically* when individuals maintain a conservative criterion. Mean posterior values from all contrasts in the linear mixed model for item types are shown in Fig. 7 (right) and Table 7 (bottom).

4. Discussion

Despite decades of research unequivocally and reliably associating widespread frontoparietal activity with T > NT response contrasts during recognition memory, the debate remains as to whether activity in these regions can best be ascribed to memory versus decisional processes. Some theories predict that activity in T > NT response contrasts is associated with the subjective experience of familiarity (Gilmore et al., 2015; McDermott et al., 2017), including processes such as mnemonic evidence accumulation (Wheeler and Buckner, 2003; Kahn et al., 2004; Wagner et al., 2005), the buffering of retrieved content (Wagner et al., 2005; Vilberg and Rugg, 2009), or memory-related attentional processes (Cabeza et al., 2008; Ciaramelli et al., 2008, 2020), which should be affected by changes in discriminability regardless of the decision

Table 4
Local maxima from whole-brain statistical *Z*-maps of T > NT response contrasts across criterion conditions (T > NT * CON > LIB) within each discriminability and task condition (see also Figs. 3 and 4, two-panel column in top right corner). Peak intensity coordinates, brain locations, and Broadmann Areas (BA) are derived from the MNI152 standard template brain in FSL. Negative *Z*-values represent the reverse contrast (NT > T * CON > LIB). *Indicates local maxima within the recognition memory task that overlap with whole-brain (T > NT * CON > LIB) response contrasts in the visual detection task. Virtually all whole-brain activity observed in the visual detection (T > NT * CON > LIB) response contrasts appears in the same recognition memory contrasts.

fMRI local maxima (T > NT * CON > LIB) response contrasts						
Recognition Memory Moderate Discriminability						
Cluster	*Z*-value	X	Y	Z	Location	BA
1*	6.74	0	20	44	Left Medial Superior Frontal Gyrus	8
1*	6.55	4	36	24	Right Anterior Cingulate Gyrus	9
1*	6.45	4	38	20	Right Anterior Cingulate Gyrus	9
1*	6.31	34	22	−6	Right Insula	13
1*	6.31	−10	2	2	Left Thalamus	48
1*	6.26	−14	6	14	Left Caudate	48
Recognition Memory Low Discriminability						
1	5.26	6	−34	26	Right Posterior Cingulate Gyrus	23
1	4.12	−4	−30	28	Left Posterior Cingulate Gyrus	23
1	4.06	10	−38	44	Right Median Cingulate Gyrus	31
1	3.95	8	−32	38	Right Median Cingulate Gyrus	31
1	3.93	0	−34	40	Left Median Cingulate Gyrus	31
1	3.79	−12	−40	44	Left Median Cingulate Gyrus	31
2	5.09	34	−50	44	Right Inferior Parietal Lobule	39
2	4.80	10	−76	50	Right Precuneus	7
2	4.59	30	−86	40	Right Superior Occipital Gyrus	19
2	4.43	30	−74	44	Right Superior Occipital Gyrus	7
2	4.37	52	−54	54	Right Inferior Parietal Lobule	39
2	4.31	20	−70	64	Right Superior Parietal Lobule	7
3*	6.58	−36	18	−4	Left Insula	13
3*	6.49	40	24	−8	Right Insula	47
3	6.41	56	14	34	Right Precentral Gyrus	44
3*	6.20	−6	6	−2	Left Caudate	48
3*	6.18	−10	0	4	Left Thalamus	50
3	6.17	10	16	2	Right Caudate	48
Visual Detection Moderate Discriminability						
1	4.56	−28	24	−8	Left Insula	47
1	4.51	−30	28	−2	Left Insula	13
1	4.25	−26	22	−14	Left Insula	47
2	4.14	44	−64	26	Right Middle Occipital Gyrus	39
2	4.12	38	−74	30	Right Middle Occipital Gyrus	39
2	4.00	38	−80	38	Right Middle Occipital Gyrus	39
2	3.86	46	−76	36	Right Angular Gyrus	39
2	3.58	46	−72	24	Right Middle Temporal Gyrus	19
2	3.57	46	−76	24	Right Middle Occipital Gyrus	19
3	4.35	48	24	26	Right Inferior Frontal Gyrus	9
3	3.96	54	34	16	Right Inferior Frontal Gyrus	46
3	3.68	48	40	16	Right Inferior Frontal Gyrus	46
3	3.65	52	26	18	Right Inferior Frontal Gyrus	9
3	3.54	42	26	24	Right Inferior Frontal Gyrus	9
3	3.34	44	28	16	Right Inferior Frontal Gyrus	9
4	5.17	28	18	−14	Right Insula	13
4	4.93	30	20	−10	Right Insula	13
4	4.63	34	18	2	Right Insula	13
4	4.53	42	20	−8	Right Insula	13
4	3.54	44	24	2	Right Inferior Frontal Gyrus	45
4	3.53	46	28	−14	Right Inferior Frontal Gyrus	47
5	4.73	10	8	−6	Right Caudate	48
5	4.50	−16	−2	18	Left Caudate	48
5	4.17	−4	0	2	Left Thalamus	50
5	4.10	−10	6	6	Left Caudate	48
5	3.96	10	6	2	Right Thalamus	48
5	3.90	−8	−4	14	Left Thalamus	50
6	4.60	−12	−72	56	Left Precuneus	7
6	4.33	−24	−70	36	Left Superior Occipital Gyrus	7
6	4.01	−34	−86	30	Left Middle Occipital Gyrus	19
6	3.95	−6	−70	60	Left Precuneus	7
6	3.88	−40	−84	28	Left Middle Occipital Gyrus	19
6	3.82	−28	−76	32	Left Middle Occipital Gyrus	39
7	5.34	6	26	44	Right Medial Superior Frontal Gyrus	8
7	4.76	8	30	36	Right Median Cingulate Gyrus	8
7	4.69	8	44	16	Right Anterior Cingulate Gyrus	10
7	4.58	0	34	36	Left Medial Superior Frontal Gyrus	8
7	4.54	4	36	42	Right Medial Superior Frontal Gyrus	8
7	4.37	2	40	34	Left Medial Superior Frontal Gyrus	8
8	5.09	−14	−50	−44	Left Cerebellum	37
8	4.77	12	−78	−26	Right Cerebellum	18
8	4.75	20	−44	−46	Right Cerebellum	37
8	4.71	−8	−74	−32	Left Cerebellum	18
8	4.54	18	−60	−26	Right Cerebellum	37
8	4.51	8	−74	−46	Right Cerebellum	18
Visual Detection Low Discriminability						
1	4.09	−32	26	−4	Left Insula	13
1	4.07	−30	22	−10	Left Insula	47
1	4.05	−32	28	−8	Left Inferior Frontal Gyrus	47
1	3.98	−40	20	−2	Left Insula	13
1	3.44	−44	14	−12	Left Insula	47
1	3.37	−38	18	−12	Left Insula	47
2	4.67	38	22	−8	Right Insula	13
2	4.63	36	22	−2	Right Insula	13
2	4.48	30	24	−12	Right Inferior Frontal Gyrus	47
3	4.81	0	32	38	Left Medial Superior Frontal Gyrus	8
3	4.62	2	38	36	Left Medial Superior Frontal Gyrus	8
3	4.60	−4	44	14	Left Anterior Cingulate Gyrus	32
3	4.56	−4	30	30	Left Anterior Cingulate Gyrus	32
3	4.48	0	20	50	Left Supplementary Motor Area	8
3	4.43	6	40	16	Right Anterior Cingulate Gyrus	32
4	−4.28	42	−6	−10	Right Superior Temporal Gyrus	13
4	−3.98	52	6	−10	Right Superior Temporal Gyrus	22
4	−3.30	56	−14	−12	Right Middle Temporal Gyrus	22
4	−3.29	52	−8	−4	Right Superior Temporal Gyrus	22
5	−4.17	−6	−56	30	Left Precuneus	31
5	−3.96	−8	−48	32	Left Posterior Cingulate Gyrus	23
6	−4.62	−8	−98	2	Left Calcarine Fissure	18
6	−4.35	−26	−80	−14	Left Lingual Gyrus	19
6	−4.18	−18	−90	−16	Left Lingual Gyrus	18
6	−3.87	−12	−94	−2	Left Calcarine Fissure	18
6	−3.66	−12	−100	−6	Left Inferior Occipital Gyrus	18
6	−3.19	−36	−82	−4	Left Inferior Occipital Gyrus	18
7	−4.66	20	−84	−10	Right Lingual Gyrus	18
7	−4.56	24	−78	−4	Right Fusiform Gyrus	18
7	−4.55	26	−80	−12	Right Fusiform Gyrus	19
7	−4.47	34	−64	−8	Right Inferior Occipital Gyrus	37
7	−4.34	26	−72	−4	Right Fusiform Gyrus	19
7	−3.67	40	−70	−14	Right Inferior Occipital Gyrus	19

Table 5
Local maxima from whole-brain statistical *Z*-maps of T > NT items contrasts across criterion conditions (T > NT * CON > LIB) within the moderate discriminability condition of both tasks (no significant differences occurred in the low discriminability conditions). Peak intensity coordinates, brain locations, and Broadmann Areas (BA) are derived from the MNI152 standard template brain in FSL.

fMRI local maxima (T > NT * CON > LIB) item contrasts						
Recognition Memory Moderate Discriminability						
Cluster	Z-value	X	Y	Z	Location	BA
1	4.60	10	4	6	Right Caudate	48
1	4.39	12	0	12	Right Caudate	48
1	4.33	10	4	0	Right Pallidum	51
2	4.35	32	24	−8	Right Inferior Frontal Gyrus	13
2	4.34	34	26	−4	Right Insula	13
2	4.31	34	18	−10	Right Insula	13
2	4.01	50	12	12	Right Inferior Frontal Gyrus	44
2	4.00	40	32	−10	Right Inferior Frontal Gyrus	47
2	3.79	38	42	10	Right Middle Frontal Gyrus	10
3	4.74	0	30	34	Left Median Cingulate Gyrus	8
3	4.51	−4	28	34	Left Median Cingulate Gyrus	32
3	4.31	14	46	8	Right Anterior Cingulate Gyrus	10
3	4.02	8	38	18	Right Anterior Cingulate Gyrus	32
3	4.02	0	48	10	Left Anterior Cingulate Gyrus	32
3	4.01	2	24	44	Right Medial Superior Frontal Gyrus	8
Visual Detection Moderate Discriminability						
1	4.67	38	20	−2	Right Insula	13
1	4.62	32	22	−12	Right Insula	47
1	4.51	42	20	−16	Right Inferior Frontal Gyrus	47
2	4.56	−4	−86	−24	Left Cerebellum	18
2	4.31	−6	−78	−32	Left Cerebellum	18
2	4.13	−42	−60	−44	Left Cerebellum	37
2	4.05	−38	−72	−54	Left Cerebellum	37
2	3.89	−44	−68	−44	Left Cerebellum	37
2	3.84	16	−82	−28	Right Cerebellum	18
3	5.10	−2	44	28	Left Medial Superior Frontal Gyrus	9
3	4.59	2	34	52	Left Medial Superior Frontal Gyrus	8
3	4.53	2	32	56	Right Medial Superior Frontal Gyrus	8
3	4.41	4	22	64	Right Supplementary Motor Area	6
3	4.31	8	22	64	Right Supplementary Motor Area	6
3	4.27	10	40	22	Right Anterior Cingulate Gyrus	9

criterion. Others suggest that expectations of an item to be old versus new (O'Connor et al., 2010; Jaeger et al., 2013) or the placement of a decision criterion (Aminoff et al., 2015; King and Miller 2017) is linked to activity in these contrasts, which should be affected by decision strategies independently of memory strength. Here we directly manipulated discriminability, criterion placement, and decision domains to better assess which aspects of frontoparietal activity are associated with each manipulation when comparing between responses that exceed the decision criterion (target) versus those that do not (nontarget).

Both evidence strength and response bias accounts predict greater frontoparietal activity in T > NT response contrasts when a conservative criterion is maintained. According to SDT principles, target responses confer greater memory strength on average *and* require inhibiting prepotent nontarget responses (Macmillan and Creelman, 2005). These accounts diverge when a liberal criterion is maintained because target responses still carry greater evidence strength; however, prepotent *target* responses must be inhibited to make a nontarget response. One challenge in studying the neural mechanisms underpinning a conservative versus liberal criterion is that some individuals will not shift criteria despite being explicitly aware of the advantages for doing so (Aminoff et al., 2012, 2015; Kantner et al., 2015; Frithsen et al., 2018; Layher et al., 2018; Miller and Kantner, 2019; Layher et al., 2020). Failing to strategically shift precludes the ability to investigate differential activity related to multiple criterion placements within-subjects. Aminoff et al. (2015) revealed no significant differences in the H > CR contrast across criterion conditions when participants failed to shift during recognition memory tests, demonstrating that a criterion manipulation alone does not significantly impact frontoparietal activity. We therefore carefully prescreened participants to exclude those who did not adequately shift criteria, ensuring that criterion-related contrasts reflected changes in decision-making behavior.

4.1. *Frontoparietal activity is heavily modulated by criterion placement*

Whole-brain GLM analyses revealed that the adaptation of conservative versus liberal criteria drastically altered frontoparietal activity in T > NT response contrasts, both during recognition memory and visual detection tasks. Most notably, we did not find any regions in whole-brain T > NT response contrasts that appeared in *both* the conservative and liberal criterion condition for either discriminability or task condition (except for a subset of regions that appeared in both, but in opposing directions). This suggests that maintaining a conservative versus liberal criterion modulates the activity of all regions sensitive to target versus nontarget response types, at least to some extent.

Previous studies revealed robust frontoparietal activity in the H > CR contrast (correct T > NT response contrast) during recognition memory tests *specifically* when participants maintained a conservative criterion when the likelihood of encountering "old" items decreased (Aminoff et al., 2015; King and Miller 2017). Our results extend these findings by revealing that this pattern of widespread frontoparietal activity is also observed (1) when a reward manipulation is implemented (with equal probability of encountering target vs. nontarget items), (2) with variations in discriminability, and (3) across recognition memory *and* visual detection tasks. Additionally, our results revealed significant activations in the right insula, MFG, and MeFG in the NT > T response contrast when participants maintained a liberal criterion during recognition memory, which supports a response bias account. Herron et al. (2004) reported a similar phenomenon in recognition memory tests for words where the ratio of old to new items varied across test blocks. In their assessment of old versus new items, some frontal regions showed greater activity when old items only appeared 25% of the time, but activity became greater for new versus old items when old items appeared on 75% of trials. Although the manipulation of target ratios did not induce meaningful criterion shifts, their findings demonstrated that many frontal regions are sensitive to features of recognition memory tests (e.g. target saliency) that are unrelated to processes directly involved in the retrieval of memory evidence.

However, in the visual detection task, whole-brain models revealed no significant frontoparietal activity in the NT > T response contrasts when participants maintained a liberal criterion—despite the strong relationships in criterion placement and shifting performance between decision domains. Additionally, T > NT response contrasts across criterion conditions (T > NT * CON > LIB) revealed more widespread frontoparietal activity for recognition memory versus visual detection tests, though whole-brain analyses revealed virtually no significant differences. However, ROI analyses revealed significantly greater activity in the T > NT response contrast across criterion conditions in frontoparietal regions between the recognition memory versus visual detection tests (T > NT * CON > LIB * RM > VD), suggesting that the task domain may modulate frontoparietal activity. It is possible that the added demands of recognizing images versus visual detection alone, engages these criterion-sensitive regions to greater extents when a conservative versus liberal criterion is maintained. Nonetheless, the T > NT response contrasts across criterion conditions elicited similar frontoparietal networks across task domains, particularly regions in the insula and IFG, even though activity tended to be greater and more widespread for recognition memory versus visual detection tests.

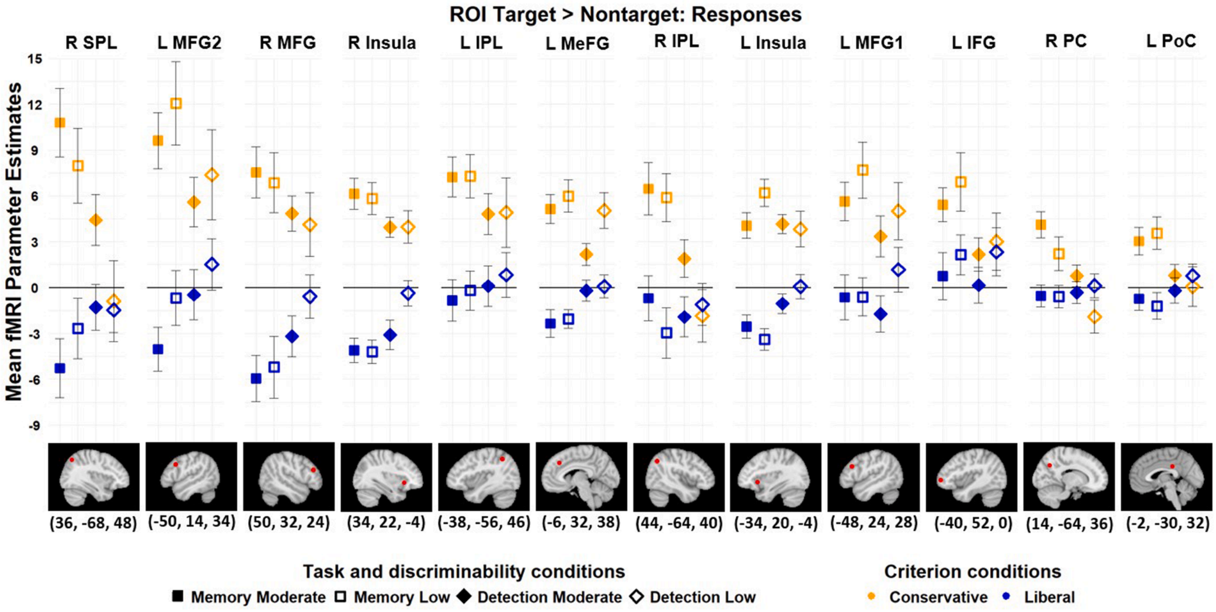

Fig. 5. ROI mean fMRI parameter estimates across T > NT response contrasts within the conservative (orange) and liberal (blue) criterion conditions, low (open shapes) and moderate (filled shapes) discriminability conditions, and recognition memory (square) and visual detection (diamond) tasks. ROIs are ordered left to right based on the highest to lowest values in the moderate discriminability condition of the recognition memory task. The MNI152 brain template coordinates of each ROI centroid are listed at the bottom of the figure along with illustrations depicting the ROI location with a red dot. Each point is fitted with standard error bars. L = left; R = right; IFG = inferior frontal gyrus; IPL = inferior parietal lobules; MFG = middle frontal gyrus; MeFG = medial frontal gyrus; PC = precuneus; PoC = posterior cingulate.

4.2. Frontoparietal activity is largely unaffected by changes in discriminability

In stark contrast to the robust differences in frontoparietal activity associated with changes in criterion placement, varying levels of discriminability revealed virtually no significant differences in activity across T > NT response contrasts in either the recognition memory or visual detection tasks. Broader assessments of T > NT *item* contrasts revealed sparse activity in the right anterior insula and MeFG in the moderate discriminability conditions of both decision domains, but this *only* occurred when participants maintained a conservative criterion. ROI analyses revealed a significant interaction in the T > NT item contrast between criterion and discriminability conditions (T > NT * CON > LIB * MOD > LOW) regardless of decision domain. While frontoparietal activity in T > NT item contrasts might be modulated by an interaction between criterion placement and discriminability levels, this effect is small-to-moderate at best and inconsistent with findings from whole-brain analyses between discriminability conditions (T > NT * MOD > LOW) and T > NT *response* contrasts. Other than this potential interaction between criterion and discriminability conditions across *item* types, these results suggest that the frontoparietal network classically observed in T > NT contrasts is rather insensitive to changes in discriminability (when controlling for the decision criterion) in both recognition memory and visual detection tasks.

While some studies report greater frontoparietal activity in memory tests at higher versus lower levels of discriminability (Wheeler and Buckner 2003; Criss et al., 2013; Ciaramelli et al., 2020), these studies generally do not include a criterion manipulation, making it difficult to rule out a response bias explanation. Furthermore, when studies attempt to manipulate both discriminability and decision criteria (e.g. Ciaramelli et al., 2020), there is no prescreen procedure to identify individuals who adequately shift criteria, nor is there a large enough sample size to exclude individuals who fail to shift criteria from fMRI analyses, which detrimentally impacts accurate assessment of frontoparietal activity associated with criterion placement. Thus, the biggest hurdles for dissociating task-related activity due to strength of evidence versus criterion placement in T > NT response (or item) contrasts are prescreening out participants who do not adequately shift criteria and obtaining a large enough sample to overcome the apparent insensitivities of fMRI for detecting activity related to changes in discriminability. Our results clearly reveal that T > NT response contrasts are robustly modulated by appropriately adopting a conservative versus liberal criterion—but *not* when target strength is modulated between near-chance versus moderate levels of discriminability.

4.3. Modeling recognition memory and visual detection behavior

To demonstrate that the criterion and discriminability manipulations successfully induced criterion shifts and modulated task difficulty, we implemented an unequal-variance SDT model.

Unequal-variance SDT models where the target distribution variance is 1.25 times greater than the nontarget distribution variance is considered a better fit for recognition memory data relative to equal-variance SDT models (Ratcliff et al., 1992). For consistency, we implemented the same unequal-variance model to assess the recognition memory and visual detection data. However, it is possible that the best fitting model differs across task domains. In particular, the assumptions of the unequal-variance SDT model may not fully capture the underlying processes that go into a recognition versus visual detection judgment. For instance, the dual-process SDT model suggests that recognition memory tasks encompass processes related to target strength *and* recollection that need to be modeled separately (Yonelinas, 2007). Yonelinas and Parks (2007) review datasets where recollected items are separately modeled as a threshold process and find that an equal-variance SDT model is oftentimes a good fit for recognition memory data that is *not* based on recollection, though others argue against this (see Wixted, 2007). It is possible that recollection processes cause recognition memory data to be better fit by unequal-variance SDT models whereas the visual detection task, which is presumably devoid of recollection, might be better fit by an equal-variance SDT model.

While the best fitting model may differ between recognition memory and visual detection tasks, we mainly wanted to demonstrate that our

Table 6
Mean fMRI parameter estimates with 95% CIs (in parentheses) in the T > NT response (left) and item (right) contrasts between the conservative versus liberal criterion conditions (T > NT * CON > LIB) for the low and moderate discriminability conditions in both the recognition memory (RM) and visual detection (VD) tasks. Values in bold with a gray background represent mean parameter estimates that are statistically greater than zero (see also Figs. 5 and 6). IFG = inferior frontal gyrus; IPL = inferior parietal lobules; MFG = middle frontal gyrus; MeFG = medial frontal gyrus; PC = precuneus; PoC = posterior cingulate.

ROI (T > NT * CON > LIB) Mean fMRI Parameter Estimates

			Response		Item	
	ROI	Task	Low	Moderate	Low	Moderate
Left	**IFG**	**RM**	**4.77 (1.01, 8.52)**	**4.66 (1.01, 8.31)**	−1.33 (−4.44, 1.78)	1.89 (−1.34, 5.12)
		VD	0.69 (−2.92, 4.30)	2.01 (−1.21, 5.23)	−0.04 (−3.02, 2.93)	2.39 (−0.64, 5.43)
	Insula	**RM**	**9.57 (7.23, 11.92)**	**6.61 (4.55, 8.68)**	−0.05 (−1.69, 1.59)	**3.26 (1.15, 5.37)**
		VD	**3.76 (1.52, 6.01)**	**5.22 (2.95, 7.49)**	0.27 (−1.56, 2.10)	**3.63 (1.47, 5.79)**
	IPL	**RM**	**7.48 (3.98, 10.97)**	**8.07 (5.07, 11.06)**	−0.70 (−3.32, 1.83)	2.68 (−0.06, 5.42)
		VD	4.09 (−0.36, 8.54)	**4.71 (1.09, 8.33)**	−0.14 (−2.75, 2.48)	**5.15 (2.38, 7.91)**
	MeFG	**RM**	**8.03 (5.73, 10.33)**	**7.50 (4.87, 10.12)**	−1.45 (−3.37, 0.47)	**3.12 (1.36, 4.89)**
		VD	**4.97 (2.75, 7.19)**	**2.39 (0.49, 4.29)**	0.11 (−1.41, 1.64)	**3.66 (1.37, 5.96)**
	MFG 1	**RM**	**8.29 (3.98, 12.59)**	**6.28 (2.94, 9.62)**	−1.44 (−4.43, 1.55)	0.03 (−4.63, 4.69)
		VD	**3.83 (0.32, 7.34)**	**5.08 (1.09, 8.33)**	−0.59 (−3.77, 2.60)	**4.86 (0.50, 9.23)**
	MFG 2	**RM**	**12.74 (7.59, 17.88)**	**13.64 (9.29, 17.99)**	−4.75 (−11.00, 1.51)	2.60 (−1.75, 6.96)
		VD	**5.85 (0.08, 11.63)**	**6.05 (1.37, 10.73)**	−0.61 (−3.97, 2.75)	**5.16 (1.52, 8.80)**
	PoC	**RM**	**4.77 (2.59, 6.95)**	**3.77 (1.39, 6.15)**	−0.97 (−2.74, 0.81)	1.52 (−0.59, 3.63)
		VD	−0.70 (−3.51, 2.12)	0.98 (−1.08, 3.03)	0.30 (−1.68, 2.29)	**1.85 (0.19, 3.50)**
Right	**Insula**	**RM**	**10.02 (7.86, 12.18)**	**10.25 (7.94, 12.55)**	−0.14 (−2.18, 1.90)	**4.47 (2.17, 6.77)**
		VD	**4.34 (2.24, 6.44)**	**7.03 (4.10, 9.96)**	0.87 (−0.73, 2.46)	**4.27 (1.65, 6.90)**
	IPL	**RM**	**8.85 (4.67, 13.02)**	**7.17 (3.22, 11.12)**	0.13 (−3.42, 3.69)	2.45 (−0.84, 5.74)
		VD	−0.73 (−5.23, 3.77)	**3.82 (0.45, 7.19)**	0.56 (−2.48, 3.61)	2.58 (−0.28, 5.43)
	MFG	**RM**	**12.06 (6.98, 17.14)**	**13.47 (9.32, 17.62)**	−0.18 (−4.24, 3.88)	3.81 (−0.81, 8.42)
		VD	**4.71 (0.90, 8.52)**	**8.03 (4.64, 11.43)**	0.71 (−2.35, 3.77)	**5.17 (1.47, 8.86)**
	PC	**RM**	**2.80 (0.29, 5.31)**	**4.64 (2.48, 6.81)**	−0.44 (−2.02, 1.14)	1.32 (−0.74, 3.38)
		VD	−2.02 (−4.81, 0.76)	1.09 (−1.06, 3.25)	−0.15 (−2.08, 1.78)	0.72 (−1.12, 2.56)
	SPL	**RM**	**10.64 (5.29, 16.00)**	**16.07 (10.33, 21.80)**	−1.16 (−5.43, 3.10)	**5.49 (1.17, 9.81)**
		VD	0.58 (−5.67, 6.84)	**5.70 (2.53, 8.87)**	1.04 (−2.45, 4.54)	**6.09 (1.97, 10.22)**

criterion and discriminability manipulations successfully induced criterion shifts and altered task difficulty across decision domains. In both tasks, our manipulations altered decision biases and discriminability to large degrees and is readily apparent regardless of the implemented SDT model or even when assessing the hit and false alarm rates alone (see Table 1). Although there are some differences in performance that may confound cross-task comparisons within a particular condition (e.g. greater discriminability in the moderate discriminability condition between the visual detection versus recognition memory tasks), there is considerable separation of criterion placement and discriminability within each task. While the unequal-variance SDT model may not fully account for all underlying processes of response types across tasks, such as recollection, it is one of the most commonly implemented models for assessing recognition memory data (Macmillan and Creelman, 2005).

4.4. Potential limitations

One limitation of our findings is that the discriminability manipulations only allowed comparisons between low and moderate levels of discriminability. It is possible that at higher levels of discriminability the observed frontoparietal network becomes more active and possibly more detectable via fMRI. We intentionally made the low discriminability conditions very difficult in order to make differences in mean signal strength between target and nontarget items close to zero. However, we ensured above-chance performance to demonstrate that participants are indeed performing the tasks as instructed. Therefore, T > NT contrasts in the low discriminability conditions should be relatively void of differences in signal strength. By comparing between low and moderate discriminability conditions we hoped to capture differences in frontoparietal activity driven by greater differences in signal strength.

Another limitation of our results is that participants tended to shift criteria to large degrees, which may have caused individuals to be more attuned to the decision strategy rather than evidence strength, relative to tests that do not include a criterion manipulation. However, there are trait-like individual differences in how people place a decision criterion in recognition memory tests that do not include a criterion manipulation (Kantner and Linsday, 2012, 2014). Some people will regularly establish a conservative criterion, whereas others consistently maintain a liberal criterion, even when there is no advantage or instructions to do so. Thus, participants almost always exhibit some inherent bias in their decision strategies that must be accounted for when comparing across response types.

4.5. Implications for response-based fMRI tasks

Our findings illustrate the importance of controlling for decision biases during response-based fMRI tasks since frontoparietal activity can be drastically affected by whether an individual maintains a conservative or liberal decision criterion. Even with a carefully controlled paradigm, decision biases might create unexpected confounds across conditions or task domains that may impact fMRI findings. For example,

Table 7
Model-level statistics for mean fMRI parameters estimates across the 12 ROIs for target (T) and nontarget (NT) response (top) or item (bottom) types across recognition memory (RM) and visual detection (VD) tasks in the conservative (CON) and liberal (LIB) conditions as well as the low (LOW) and moderate (MOD) discriminability conditions (see also Fig. 7).

Model-Level Statistics: ROI Mean Parameter Estimates (response types)

Term	Estimate (95 CI)	*SE*	*t*	Effect Size (*d*)
Intercept	3.71 (1.25, 6.17)	1.25	2.96	0.41
RM > VD	2.09 (0.98, 3.22)	0.58	3.62	0.23
CON > LIB	−1.66 (−2.80, −0.51)	0.58	−2.87	0.18
MOD > LOW	0.96 (−0.18, 2.11)	0.58	1.66	0.11
T > NT	0.28 (−0.87, 1.42)	0.58	0.48	0.03
(RM > VD) * (CON > LIB)	−3.42 (−5.04, −1.81)	0.82	−4.17	0.37
(RM > VD) * (MOD > LOW)	−0.56 (−2.16, 1.02)	0.82	−0.68	0.06
(CON > LIB) * (MOD > LOW)	−1.33 (−2.95, 0.27)	0.82	−1.62	0.14
(RM > VD) * (T > NT)	−2.08 (−3.69 −0.49)	0.82	−2.54	0.23
(CON > LIB) * (T > NT)	2.45 (0.84, 4.06)	0.82	2.99	0.27
(MOD > LOW) * (T > NT)	−1.38 (−3.00, 0.24)	0.82	−1.69	0.15
(RM > VD) * (CON > LIB) * (MOD > LOW)	0.72 (−1.52, 3.00)	1.16	0.62	0.08
(RM > VD) * (CON > LIB) * (T > NT)	5.89 (3.65, 8.16)	1.16	5.09	0.64
(RM > VD) * (MOD > LOW) * (T > NT)	0.94 (−1.31, 3.24)	1.16	0.81	0.10
(CON > LIB) * (MOD > LOW) * (T > NT)	1.90 (−0.36, 4.16)	1.16	1.64	0.21
(RM > VD) * (CON > LIB) * (MOD > LOW) * (T > NT)	−1.72 (−4.95, 1.44)	1.64	−1.05	0.19
Random Effect: (Intercept | Subject) + (Intercept | ROI)				
Subjects	30			
ROIs	12			
(Intercept | Subject) (*SD)*	3.33			
(Intercept | ROI) (*SD)*	3.52			
N	5760			

Model-Level Statistics: ROI Mean Parameter Estimates (item types)

Term	Estimate (95 CI)	*SE*	*t*	Effect Size (*d*)
Intercept	5.02 (2.18, 7.87)	1.45	3.45	0.51
RM > VD	−0.83 (−1.98, 0.33)	0.58	−1.41	0.08
CON > LIB	−2.22 (−3.37, −1.07)	0.58	−3.79	0.23
MOD > LOW	0.76 (−0.38, 1.92)	0.58	1.30	0.08
T > NT	0.14 (−1.01, 1.29)	0.58	0.24	0.02
(RM > VD) * (CON > LIB)	1.47 (−0.15, 3.11)	0.83	1.78	0.15
(RM > VD * (MOD > LOW)	−0.40 (−2.02, 1.21)	0.83	−0.48	0.04
(CON > LIB) * (MOD > LOW)	−0.41 (−2.06, 1.20)	0.83	−0.50	0.04
(RM > VD) * (T > NT)	2.20 (0.56, 3.83)	0.83	2.66	0.22
(CON > LIB) * (T > NT)	0.20 (−1.43, 1.83)	0.83	0.24	0.02
(MOD > LOW) * (T > NT)	−1.02 (−2.66, 0.61)	0.83	−1.24	0.11
(RM > VD) * (CON > LIB) * (MOD > LOW)	−0.67 (−2.95, 1.62)	1.17	−0.58	0.07
(RM > VD) * (CON > LIB) * (T > NT)	−1.24 (−3.55, 1.06)	1.17	−1.06	0.12
(RM > VD) * (MOD > LOW) * (T > NT)	−0.61	1.17	−0.52	0.06

(*continued on next page*)

Table 7 (*continued*)

Model-Level Statistics: ROI Mean Parameter Estimates (item types)				
Term	Estimate (95 CI)	*SE*	*t*	Effect Size (*d*)
	(−2.91, 1.70)			
(CON > LIB) * (MOD > LOW) * (T > NT)	3.60 (1.30, 5.92)	1.17	3.08	0.37
(RM > VD) * (CON > LIB) * (MOD > LOW) * (T > NT)	0.16 (−3.09, 3.41)	1.65	0.10	0.01
Random Effect: (Intercept | Subject) + (Intercept | ROI)				
Subjects	30			
ROIs	12			
(Intercept | Subject) (*SD*)	4.43			
(Intercept | ROI) (*SD*)	3.93			
N	5760			

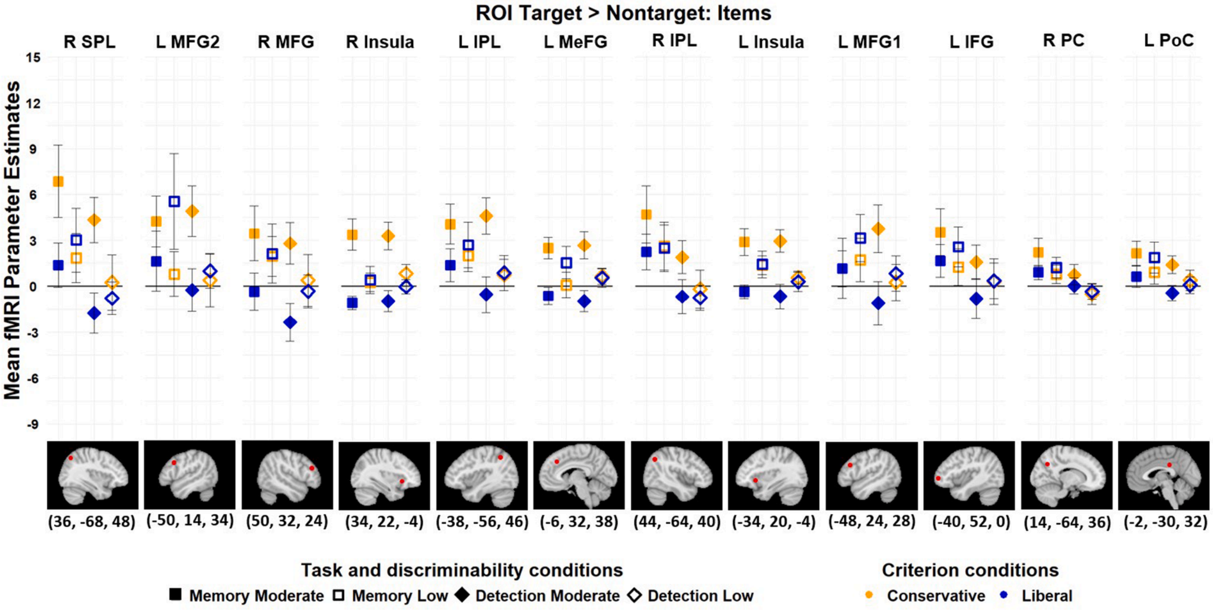

Fig. 6. ROI mean fMRI parameter estimates across T > NT response contrasts within the conservative (orange) and liberal (blue) criterion conditions, low (open shapes) and moderate (filled shapes) discriminability conditions, and recognition memory (square) and visual detection (diamond) tasks. ROIs are ordered left to right based on the highest to lowest values in the moderate discriminability condition of the recognition memory task (specifically for T > NT responses to match the order of Fig. 5). The MNI152 brain template coordinates of each ROI centroid are listed at the bottom of the figure along with illustrations depicting the ROI location. Each point is fitted with standard error bars. L = left; R = right; IFG = inferior frontal gyrus; IPL = inferior parietal lobules; MFG = middle frontal gyrus; MeFG = medial frontal gyrus; PC = precuneus; PoC = posterior cingulate.

Westphal et al. (2017) examined functional connectivity across task domains in a paradigm where cross-domain test trials remained exactly the same except for whether subjects made decisions based on memory, perception, or reasoning. One of the authors' main findings revealed reduced functional modularity during the memory task relative to the other two task domains. Due to the scrupulously controlled paradigm that made the test trial structure perceptually the same across decision domains, it is reasonable to assume that this observed difference is attributable to memory-specific processes. However, the authors also reported an unexpected strong relationship between modularity and false alarm rates in the memory task. This finding surprised the authors who concluded that further investigations are needed to understand this relationship. Since decision biases affect false alarm rates, one possible explanation for the observed relationship is that functional modularity might be affected by individual differences in decision biases. Future experiments will need to control for decision biases to more conclusively determine whether the observed fMRI findings by Westphal et al. (2017) are truly a memory-specific phenomenon or are attributable to decisional processes. Any task that requires a response is susceptible to decision biases and must be controlled for in fMRI experiments to appropriately attribute activity to decision strategies versus task performance.

Additionally, it is possible that our findings have implications that extend beyond simple response-based tasks. For example, there is debate as to whether memory recall is influenced by criterion shifts (Miller and Wolford, 1999) or not (Gallo et al., 2001). Some evidence suggests that memory recall involves complex metacognitive decision processes where people need to decide whether to report or withhold uncertain memory evidence (Koriat and Goldsmith, 1996). Greater inhibition of reporting uncertain memory evidence might be akin to adopting a conservative criterion whereas a willingness to report vague memories could be consistent with establishing a liberal criterion. If this is the case, then criterion-sensitive regions observed in recognition memory might also be involved in inhibiting versus reporting uncertain memory evidence during recall. Thus, fMRI experiments investigating memory recall should consider controlling for decisional processes related to reporting versus withholding memory information. Future studies must establish a link between decisional processes involved in recognition memory and recall, but our findings provide a potential starting point for investigating the neural underpinnings associated with such processes.

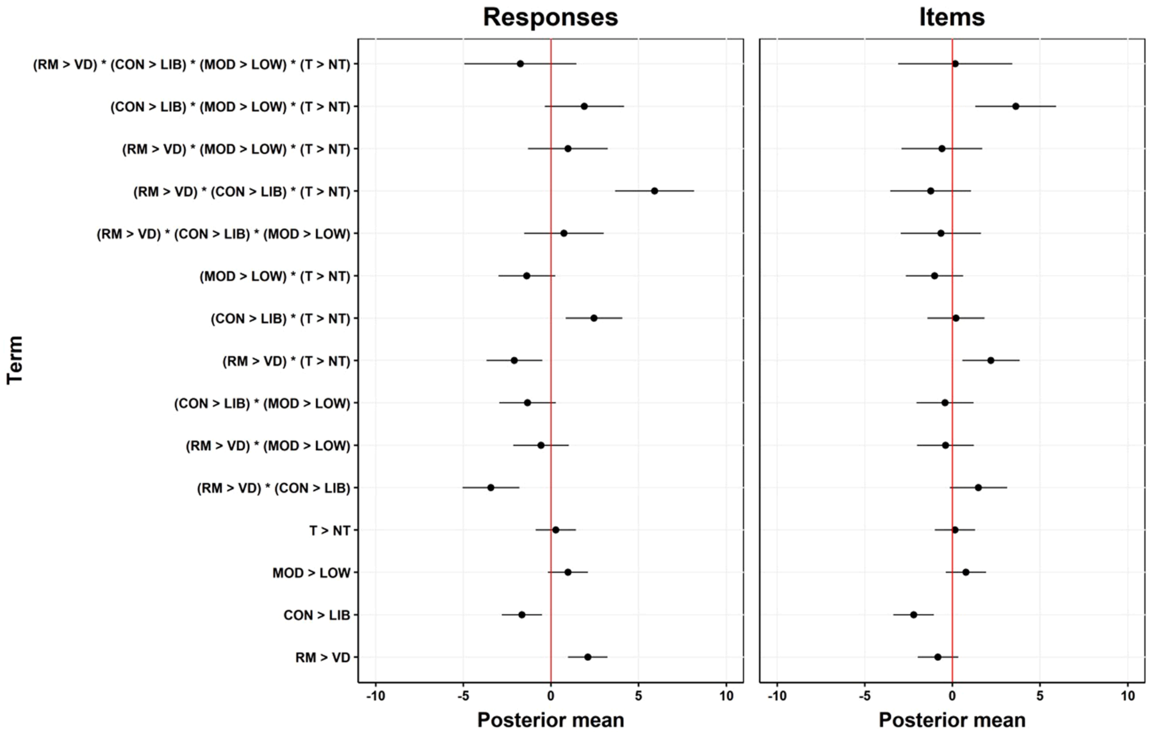

Fig. 7. Posterior mean across fixed effects of mean fMRI parameter estimates in the 12 ROIs. Each parameter estimate is fitted with 95% CIs for response (left) and item (right) types. Estimates not intersecting zero are statistically significant.

4.6. Confidence ratings cannot dissociate activity related to memory versus decisional processes

Many recognition memory experiments assess differences in familiarity strength and decision criteria through confidence ratings instead of directly manipulating discriminability and criteria. In these paradigms, participants provide a confidence rating (e.g. low, medium, or high confidence) with an old/new judgment, which represents a participant's subjective level of familiarity strength *and* their decision criterion for a particular test item (see Yonelinas and Parks, 2007). High confident "old" responses carry greater familiarity strength than "new" and low/medium confidence "old" responses, but they also encompass a more conservative criterion since participants should only make such responses when familiarity strength is very high. Conversely, high confidence "new" responses represent the weakest levels of familiarity as well as the most liberal criterion relative to "old" and low/medium "new" responses since such responses should be reserved for items with the lowest levels of familiarity strength. Since confidence ratings incorporate the familiarity strength of items *and* an individual's decision criterion, it is not possible to differentiate fMRI activity related to each process without direct manipulations of discriminability and decision criteria. For example, Yonelinas et al. (2005) found widespread frontoparietal activity that gradually increased with increasing familiarity strength (i.e. from high confident "new" to high confident "old" responses) and concluded that these regions are associated with varying levels of familiarity strength. However, the decision criterion also becomes increasingly more conservative when examining response types from high confident "new" to high confident "old," which means that the observed frontoparietal activity might simply be attributable to the conservativeness of a decision criterion. Since confidence ratings directly tie greater familiarity strength with a more conservative decision criterion and vice versa, activity related to memory versus decisional processes are not distinguishable. It is therefore necessary to implement discriminability *and* criterion manipulations to distinguish between fMRI activity related to familiarity strength versus the decision criterion.

4.7. Frontoparietal activity is not entirely attributable to decision criterion

Importantly, we are *not* proposing that frontoparietal activity observed in T > NT response contrasts of recognition memory and visual detection tests is entirely attributable to the decision criterion. A response bias account alone is insufficient: widespread frontoparietal activity is more robust when comparing T > NT responses under a conservative criterion relative to NT > T responses when a liberal criterion is maintained. Maintaining a conservative criterion may require greater cognitive control for discerning relatively stronger versus weaker target evidence, whereas responding "target" under a liberal criterion may be less cognitively demanding since the decision may be a simpler assessment of whether an item elicits *any* decisional evidence or not. Additionally, changes in discriminability appear to modulate the strength of frontoparietal activity in T > NT item contrasts across decision domains to some degree, but only when participants maintain a conservative—but not a liberal—criterion.

Herron et al. (2004) identified regions that proved to be insensitive to test manipulations of target ratios, though criterion placement remained virtually unaffected across conditions. This included parietal regions that are classically implicated in old > new response contrasts, such as areas in the PC and IPL, indicating that these areas might be good candidate regions for future investigations of strength-based effects, at least in recognition memory. Although we did not identify any regions that could be definitively considered criterion insensitive since whole-brain T > NT response contrasts revealed no region that appeared in both the conservative and liberal criterion conditions, it is possible that these parietal areas are implicated in strength-based effects. For instance, certain regions in IPL appeared in the recognition memory T > NT response contrast collapsed across criterion and discriminability conditions, but did *not* appear in (T > NT * CON > LIB) response contrasts suggesting that these same regions cannot be completely attributable to criterion effects. Although we failed to find any regions in T >

NT response contrasts that are modulated by task difficulty, we believe future experiments investigating strength-based effects of recognition memory should consider parietal regions in IPL and posterior cingulate cortex since these regions appeared in the recognition memory T > NT response contrast collapsed across conditions, but did not appear in (T > NT * CON > LIB) response contrasts. However, investigating strength-based fMRI effects may prove challenging since it appears fMRI is relatively insensitive for detecting spatial differences in activity across varying levels of discriminability and may require larger sample sizes and/or increased trial counts to do so.

5. Conclusion

Our results unambiguously demonstrate that frontoparietal activity in T > NT response contrasts is predominantly sensitive to changes in criterion placement rather than changes in discriminability, which future experiments must account for. Recruitment of this frontoparietal network is dependent on the decision criterion in a seemingly domain-general manner, though recognition memory appears to modulate frontoparietal regions to a greater degree and larger spatial extent, relative to visual detection tests. It will be critical for future experiments to systematically assess the effects of decision evidence *and* criteria at many levels of discriminability (from near-chance to near-perfect performance) and criterion placement (from very conservative to very liberal) to better dissociate the neural substrates associated with these intertwining cognitive processes.

Data availability

Code and datasets from analyses in this manuscript are accessible through the Open Science Framework using the following link: https://osf.io/nt4jk/.

CRediT authorship contribution statement

Evan Layher: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft. **Tyler Santander:** Formal analysis, Writing – review & editing. **Puneeth Chakravarthula:** Conceptualization, Investigation, Resources, Writing – review & editing. **Nicole Marinsek:** Conceptualization, Investigation, Software. **Benjamin O. Turner:** Conceptualization, Investigation. **Miguel P. Eckstein:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Michael B. Miller:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare no financial interests or conflicts of interest.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2023.120307.

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