Anxiety and the neurobiology of temporally uncertain threat anticipation

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AUTHOR CONTRIBUTIONS

A.J.S., K.A.D., and J.F.S. designed the study. J.F.S. developed and optimized the imaging paradigm. K.A.D. managed data collection and study administration. K.A.D., J.F.S., A.S.A, J.K., and R.M.T. collected data. K.A.D., J.H., and A.J.S. processed and analyzed phenotypic data. J.F.S. developed data processing and analytic software. J.H., J.F.S., H.C.K., and R.M.T. processed imaging data. J.F.S., J.H., A.J.S., and A.S.F. developed the analytic strategy. J.F.S., J.H., and A.J.S. analyzed data. J.H., A.J.S., J.F.S., and A.S.F. interpreted data. J.H., J.F.S., A.S.F., and A.J.S. wrote the paper. J.H., M.K., and A.J.S. created figures. J.H., H.C.K., and A.J.S. created tables. A.J.S. funded and supervised all aspects of the study. All authors contributed to reviewing and revising the paper and approved the final version.

RESOURCE SHARING

Raw data are available at the National Institute of Mental Health's Data Archive. Key statistical maps are or will be publicly available at NeuroVault.org.

ABSTRACT

When extreme, anxiety—a state of distress and arousal prototypically evoked by uncertain danger—can be debilitating. Uncertain anticipation is a shared feature of situations that elicit signs of anxiety across disorders, species, and assays. Despite the significance of anxiety for human health and wellbeing, the neurobiology of uncertain threat anticipation remains remarkably unsettled. Leveraging a paradigm adapted from animal research and optimized for functional MRI, we examined the neural circuits engaged during the anticipation of temporally uncertain and certain threat in 99 men and women. Results revealed that uncertain and certain threat are anatomically co-localized in fronto-cortical regions and the extended amygdala (EA). Comparison of the two threat conditions demonstrated that this core network can be fractionated, with fronto-cortical regions showing relatively stronger engagement during the anticipation of uncertain threat, and the EA showing the reverse pattern. Although there is widespread agreement that the bed nucleus of the stria terminalis and dorsal amygdala—the two major subdivisions of the EA—play a critical role in orchestrating adaptive responses to potential danger, their precise contributions to human anxiety have remained contentious. Follow-up analyses demonstrated that these regions show statistically indistinguishable responses to temporally uncertain and certain threat. These observations provide a framework for conceptualizing anxiety and fear, for understanding the functional neuroanatomy of threat anticipation in humans, and for guiding the development of more effective intervention strategies for extreme anxiety.

SIGNIFICANCE STATEMENT

Anxiety—an emotion prototypically associated with the anticipation of uncertain harm—has profound significance for public health and wellbeing, yet it is unclear how the human brain responds to uncertain threat. Leveraging a novel neuroimaging paradigm in a large sample, we identify a core network responsive to both uncertain and certain threat anticipation, and show that this network bifurcates into regions with a bias for one kind of threat over the other. The extended-amygdala occupies center-stage in neuroscientific models of anxiety, but its functional architecture has remained contentious. Here we demonstrate that its major subdivisions show statistically indistinguishable responses to temporally uncertain and certain threat. Collectively, these observations indicate the need to revise how we think about anxiety and fear.

INTRODUCTION

When extreme, anxiety—a state of distress and arousal elicited by the anticipation of uncertain danger—can be debilitating (Hur et al., 2019). Anxiety disorders are common and existing treatments are inconsistently effective, underscoring the urgency of developing a clearer understanding of the underlying neurobiology (McNaughton, 2019).

Studies in mice have begun to reveal the specific molecules and cellular ensembles that underlie defensive responses to uncertain threat, but the relevance of these discoveries to human anxiety is unclear (Fox and Shackman, 2019). The role of neocortical regions that are especially well-developed in humans—including the midcingulate cortex (MCC), anterior insula (AI), and dorsolateral prefrontal cortex (dlPFC)—remains particularly opaque.

In human research, anxiety has received less attention than other aspects of emotion. The vast majority of neuroimaging studies have relied on static photographs of emotion-expressing faces, aversive scenes, or Pavlovian threat cues. None of these approaches is suitable for understanding *sustained states* of distress and arousal elicited by *the anticipation of uncertain threat*. Work using various uncertain-threat tasks has begun to reveal the broad contours of the neural systems underlying human anxiety (e.g. Klumpers et al., 2017). Yet progress has been slowed by paradigms confound variation in threat certainty with differences in perception (e.g. anticipation vs. presentation of threat). These concerns are magnified in fMRI studies, where samples are typically small, hampering reproducibility; technical limitations abound (e.g. regressor collinearity), making it difficult to disambiguate signals associated with the anticipation and presentation of threat; reinforcers are mild, threatening validity; and reinforcer delivery is inconsistent. For example, in one prominent study, the probability of shock delivery in the 'certain' threat condition was only 54%, thwarting decisive inferences (Alvarez et al., 2011). In short—with some

important exceptions—we know remarkably little about the distributed circuitry underlying anxious states in humans.

The role of the central extended amygdala—including the dorsal amygdala in the region of the central nucleus (Ce) and the bed nucleus of the stria terminalis (BST)—remains particularly contentious (Fox and Shackman, 2019). Inspired by an earlier-generation of lesion studies in rodents, it is widely believed that these regions are functionally dissociable, with the amygdala mediating phasic responses to clear-and-immediate danger ('acute threat') and the BST mediating sustained responses to uncertain-or-remote danger ('potential threat'). This 'strict-segregation' hypothesis has even been enshrined in the National Institute of Mental Health's (NIMH) Research Domain Criteria (RDoC) framework. RDoC emphasizes the importance of the Ce to acute threat (while omitting the BST) and the importance of the BST to uncertain threat (while omitting the Ce), implying a double dissociation (National Institute of Mental Health, 2020b, a). Yet, a growing body of new mechanistic evidence suggests that defensive responses to uncertain threat are assembled by microcircuits encompassing both regions (Fox and Shackman, 2019), motivating the competing hypothesis that the dorsal amygdala and BST are both important substrates for human anxiety (Fox and Shackman, 2019).

To address these questions, we combined fMRI with a novel threat-anticipation task in 99 adults. Advanced data acquisition and processing techniques enhanced resolution of subcortical regions. Building on earlier work (e.g. Pedersen et al., 2019), the Maryland Threat Countdown (MTC) paradigm is an fMRI-optimized variant of assays that have been validated in rodents and humans (Miles et al., 2011; Hefner et al., 2013). It takes the form of a 2 (*Valence:* Threat/Safety) × 2 (*Temporal Certainty:* Uncertain/Certain) event-related design (**Fig. 1**). On Certain Threat trials, subjects saw a descending stream of integers for 18.75 s, sufficiently long to enable the dissection of onset-evoked from sustained

hemodynamic responses. To ensure robust emotion, this anticipatory epoch ('countdown') always culminated with the delivery of a multi-modal reinforcer (aversive shock, photograph, and audio-clip). Uncertain Threat trials were similar, but the integer stream was randomized and presented for an uncertain and variable duration (*M*=18.75 s). Here, subjects knew the threat was coming, but they did not know *when* it would occur. Safety trials were similar, but terminated in benign reinforcers. Comparison of the well-matched anticipatory epochs enabled us to rigorously isolate circuits recruited during uncertain threat anticipation.

MATERIALS AND METHODS

Subjects

As part of an on-going prospective-longitudinal study focused on the emergence of anxiety disorders and depression, we used well-established measures of dispositional negativity (often termed neuroticism or negative emotionality; Shackman et al., 2018; Hur et al., 2019; Hur et al., *in press*) to screen 6,594 young adults (57.1% female; 59.0% White, 19.0% Asian, 9.9% African American, 6.3% Hispanic, 5.8% Multiracial/Other; *M*=19.2 years, *SD*=1.1 years). Screening data were stratified into quartiles (top quartile, middle quartiles, bottom quartile) separately for men and women. Individuals who met preliminary inclusion criteria were independently recruited from each of the resulting six strata. Given the focus of the larger study, approximately half the subjects were recruited from the top quartile, with the remainder split between the middle and bottom quartiles (i.e., 50% high, 25% medium, and 25% low), enabling us to sample a wide range of risk for the development of internalizing disorders. A total of 121 subjects were recruited. Of these, 2 withdrew during the imaging assessment due to excess distress. Of the 119 subjects who completed the imaging assessment, a total of 20 were excluded from analyses due to incidental

neurological findings (n=4), scanner problems (n=2), insufficient fMRI data (<2 usable scans), excessive global motion artifact (see below; n=3), or excessive task-correlated motion (see below, n=10). This yielded a final sample of 99 subjects (52 females; 65.7% White, 17.2% Asian, 8.1% African American, 3.0% Hispanic, 6.1% Multiracial/Other; M=18.8 years, SD=0.4 years), providing substantially greater power to detect medium-sized (0.5 < Cohen's d < 0.8) statistical effects (Geuter et al., 2018) compared to typical fMRI studies of uncertain threat anticipation (median N=29; range=15-108; Chavanne and Robinson, 2020). All subjects had normal or corrected-to-normal color vision; and reported the absence of lifetime neurological symptoms, pervasive developmental disorder, very premature birth, medical conditions that would contraindicate MRI, and prior experience with noxious electrical stimulation. All subjects were free from a lifetime history of psychotic and bipolar disorders; a current diagnosis of a mood, anxiety, or trauma disorder (past 2 months); severe substance abuse; active suicidality; and on-going psychiatric treatment as determined by an experienced masters-level diagnostistician using the Structured Clinical Interview for DSM-5 (First et al., 2015). Subjects provided informed written consent and all procedures were approved by the Institutional Review Board at the University of Maryland, College Park.

Maryland Threat Countdown (MTC) fMRI Paradigm

Paradigm Structure and Design Considerations. Building on earlier imaging work (Somerville et al., 2013; Grupe et al., 2016; Pedersen et al., 2019), the Maryland Threat Countdown (MTC) paradigm is an fMRI-optimized version of temporally uncertain-threat assays that have been validated using fear-potentiated startle and acute anxiolytic administration (e.g. benzodiazepine) in mice (Daldrup et al., 2015; Lange et al., 2017), rats (Miles et al., 2011), and humans (Hefner et al., 2013), enhancing its translational relevance. The MTC paradigm takes the form of a 2 (*Valence:* Threat/Safety) × 2 (*Temporal Certainty:* Uncertain/Certain) randomized event-related design (3 scans; 6 trials/condition/scan). Simulations were used to optimize the detection and deconvolution of task-related hemodynamic signals

(variance inflation factors <1.54). Stimulus presentation and ratings acquisition were controlled using Presentation software (version 19.0, Neurobehavioral Systems, Berkeley, CA).

On Certain Threat trials, subjects saw a descending stream of integers ('count-down;' e.g. 30, 29, 28...3, 2, 1) for 18.75 s. To ensure robust emotion, this anticipatory epoch always culminated with the delivery of a noxious electric shock, unpleasant photographic image (e.g. mutilated body), and thematically related audio clip (e.g. scream, gunshot). Uncertain Threat trials were similar, but the integer stream was randomized and presented for an uncertain and variable duration (8.75-32.5 s; *M*=18.75 s). Here, subjects knew that something aversive was going to occur, but they had no way of knowing precisely when it would occur. Consistent with recent recommendations (Shackman and Fox, 2016), the average duration of the anticipatory epoch was identical across conditions, ensuring an equal number of measurements (TRs/condition). Mean duration was chosen to enhance detection of task-related differences in the blood oxygen level-dependent (BOLD) signal (Henson, 2007), and to enable dissection of onset from genuinely sustained responses. Safety trials were similar, but terminated with the delivery of benign reinforcers (see below). Valence was continuously signaled during the anticipatory epoch by the background color of the display. Temporal certainty was signaled by the nature of the integer stream. Certain trials always began with the presentation of the number 30. As shown in **Fig. 1**, on uncertain trials integers were randomly drawn from a near-uniform distribution ranging from 1 to 45 to reinforce the impression that Uncertain trials could be much longer than Certain ones and to minimize incidental temporal learning ('time-keeping'). To mitigate potential confusion and eliminate mnemonic demands, a lower-case 'c' or 'u' was presented at the lower edge of the display throughout the anticipatory epoch. White-noise visual masks (3.2 s) were presented between trials to minimize persistence of the visual reinforcers in iconic memory. Subjects provided ratings of anticipatory fear/anxiety for each trial type during each scan using an MRI-compatible response pad (MRA, Washington, PA; **Fig. 1**). Subjects were

specifically instructed to rate the intensity of the fear/anxiety experienced during the prior anticipatory ('countdown') epoch using a 1 (*minimal*) to 4 (*maximal*) scale. A total of 6 additional echo-planar imaging (EPI) volumes were acquired at the beginning and end of each scan (see below).

Procedures. Prior to scanning, subjects practiced an abbreviated version of the paradigm—without electrical stimulation—until they indicated and staff confirmed that they understood the task. Benign and aversive electrical stimulation levels were individually titrated. *Benign Stimulation.* Subjects were asked whether they could "reliably detect" a 20 V stimulus and whether it was "at all unpleasant." If the subject could not detect the stimulus, the voltage was increased by 4 V and the process repeated. If the subject indicated that the stimulus was unpleasant, the voltage was reduced by 4V and the process repeated. The final level chosen served as the benign electrical stimulation during the imaging assessment (M=20.67, SD=6.23). *Aversive Stimulation.* Subjects received a 100 V stimulus and were asked whether it was "as unpleasant as you are willing to tolerate." If the subject indicated that they were willing to tolerate more intense stimulation, the voltage was increased by 10 V and the process repeated. If the subject indicated that the stimulus was too intense, the voltage was reduced by 5 V and the process repeated. The final level chosen served as the aversive electrical stimulation during the imaging assessment (M=115.21, SD=25.05). Following each scan of the MTC paradigm, we re-assessed whether stimulation was sufficiently intense and re-calibrated as necessary. In total, 32.3% of subjects adjusted the level of benign or aversive stimulation at least once during the imaging assessment.

Electrical Stimuli. Electrical stimuli (100 ms; 2 ms pulses every 10 ms) were generated using an MRI-compatible constant-voltage stimulator system (STMEPM-MRI; Biopac Systems, Inc., Goleta, CA). Stimuli were delivered using MRI-compatible, disposable carbon electrodes (Biopac) attached to the fourth and fifth phalanges of the non-dominant hand.

Visual Stimuli. Visual stimuli (1.8 s) were digitally back-projected (Powerlite Pro G5550, Epson America, Inc., Long Beach, CA) onto a semi-opaque screen mounted at the head-end of the scanner bore and viewed using a mirror mounted on the head-coil. A total of 72 photographs were selected from the International Affective Picture System (IAPS identification numbers)—*Benign:* 1670, 2026, 2038, 2102, 2190, 2381, 2393, 2397, 2411, 2850, 2870, 2890, 5390, 5471, 5510, 5740, 7000, 7003, 7004, 7014, 7020, 7026, 7032, 7035, 7050, 7059, 7080, 7090, 7100, 7140, 7187, 7217, 7233, 7235, 7300, 7950. *Aversive:* 1300, 3000, 3001, 3010, 3015, 3030, 3051, 3053, 3061, 3062, 3063, 3069, 3100, 3102, 3150, 3168, 3170, 3213, 3400, 3500, 6022, 6250, 6312, 6540, 8230, 9042, 9140, 9253, 9300, 9405, 9410, 9414, 9490, 9570, 9584, 9590. (Lang et al., 2008). Based on normative ratings, the aversive images were significantly more negative and arousing than the benign images, $t(70)>24.3$, $p<.001$. On a 1 (*negative/low-arousal*) to 9 (*positive/high-arousal*) scale, the mean valence and arousal scores were 2.2 (SD=0.6) and 6.3 (SD=0.6) for the aversive images, and 5.2 (SD=0.4) and 2.8 (SD= 0.3) for the benign images.

Auditory Stimuli. Auditory stimuli (0.80 s) were delivered using an amplifier (PA-1 Whirlwind) with in-line noise-reducing filters and ear buds (S14; Sensimetrics, Gloucester, MA) fitted with noise-reducing ear plugs (Hearing Components, Inc., St. Paul, MN). A total of 72 auditory stimuli (half aversive, half benign) were adapted from open-access online sources.

Peripheral Physiology Data Acquisition

Peripheral physiology was continuously acquired during each fMRI scan using a Biopac system (MP-150). Skin conductance (250 Hz; 0.05 Hz high-pass) was measured using MRI-compatible disposable electrodes (EL507) attached to the second and third phalanges of the non-dominant hand. For imaging analyses, measures of respiration and breathing were also acquired using a respiration belt and photo-plethysmograph (first phalange of the non-dominant hand).

MRI Data Acquisition

MRI data were acquired using a Siemens Magnetom TIM Trio 3 Tesla scanner (32-channel head-coil). Foam inserts were used to immobilize the participant's head within the head-coil and mitigate potential motion artifact. Subjects were continuously monitored from the control room using an MRI-compatible eye-tracker (Eyelink 1000; SR Research, Ottawa, Ontario, Canada). Head motion was monitored using the AFNI real-time plugin (Cox, 1996). Sagittal T1-weighted anatomical images were acquired using a magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence (TR=2,400 ms; TE=2.01 ms; inversion time=1060 ms; flip angle=8°; sagittal slice thickness=0.8 mm; in-plane=0.8 × 0.8 mm; matrix=300 × 320; field-of-view=240 × 256). A T2-weighted image was collected co-planar to the T1-weighted image (TR=3,200 ms; TE=564 ms; flip angle=120°). To enhance resolution, a multi-band sequence was used to collect oblique-axial echo planar imaging (EPI) volumes (multiband acceleration=6; TR=1,250 ms; TE=39.4 ms; flip angle=36.4°; slice thickness=2.2 mm, number of slices=60; in-plane resolution=2.1875 × 2.1875 mm; matrix=96 × 96). Images were collected in the oblique axial plane (approximately −20° relative to the AC-PC plane) to minimize potential susceptibility artifacts. Three 478-volume EPI scans were acquired. The scanner automatically discarded 7 volumes prior to the first recorded volume. To enable fieldmap correction, two oblique-axial spin echo (SE) images were collected in each of two opposing phase-encoding directions (rostral-to-caudal and caudal-to-rostral) at the same location and resolution as the functional volumes (i.e., co-planar; TR=7,220 ms; TE=73 ms). Following the last scan, subjects were removed from the scanner, debriefed, compensated, and discharged.

Skin Conductance Data Pipeline

Skin conductance data were processed using PsPM (version 4.0.2) and in-house Matlab code (Bach and Friston, 2013; Bach et al., 2018). Data from each scan were band-pass filtered (0.01-0.25 Hz), resampled

to match the TR used for fMRI data acquisition (1.25 s), and *z*-transformed. Using standard Matlab functions, SCR data were modeled in a manner that approximated that used for the fMRI data. A GLM was used to estimate skin conductance levels during the anticipatory epoch of each condition of the MTC paradigm (see above) for each subject (Bach et al., 2009; Bach et al., 2013; Bach, 2014). Predictors from the first-level fMRI model (see below) were convolved with a canonical skin conductance response function (Bach et al., 2010; Gerster et al., 2018), bandpass filtered to match the data, and *z*-transformed.

MRI Data Pipeline

Methods were optimized to minimize spatial normalization error and other potential sources of noise. Structural and functional MRI data were visually inspected before and after processing for quality assurance.

Anatomical Data Processing. Methods were similar to those described in other recent reports by our group (Hur et al., 2018; Smith et al., 2018; Tillman et al., 2018). T1-weighted images were inhomogeneity corrected using N4 (Tustison et al., 2010) and filtered using the denoise function in ANTS (Avants et al., 2011). The brain was then extracted using a variant of the BEaST algorithm (Eskildsen et al., 2012) with brain-extracted and normalized reference brains from the IXI database (https://brain-development.org/ixi-dataset). Brain-extracted T1 images were normalized to a version of the brain-extracted 1-mm T1-weighted MNI152 (version 6) template (Grabner et al., 2006) modified to remove extracerebral tissue. This was motivated by evidence that brain-extracted T1 images and a brain-extracted template enhance the quality of spatial normalization (Fein et al., 2006; Acosta-Cabronero et al., 2008; Fischmeister et al., 2013). Normalization was performed using the diffeomorphic approach implemented in SyN (version 1.9.x.2017-09.11; Klein et al., 2009; Avants et al., 2011). T2-weighted images were rigidly co-registered with the corresponding T1 prior to normalization and the brain

extraction mask from the T1 was applied. Tissue priors (Lorio et al., 2016) were unwarped to the native space of each T1 using the inverse of the diffeomorphic transformation. Brain-extracted T1 and T2 images were simultaneously segmented using native-space priors generated using FAST (FSL version 5.0.9) (Zhang et al., 2001) for use in T1-EPI co-registration (see below).

Fieldmap Data Processing. SE images were used to create a fieldmap in topup (Andersson et al., 2003; Smith et al., 2004; Graham et al., 2017). Fieldmaps were converted to radians, median filtered, and smoothed (2-mm). The average of the distortion-corrected SE images was inhomogeneity-corrected using N4, and brain-masked using 3dSkullStrip in AFNI (version 17.2.10; Cox, 1996). The resulting mask was minimally eroded to further exclude extracerebral voxels.

Functional Data Processing. EPI files were de-spiked using 3dDespike and slice-time corrected (to the center of the TR) using 3dTshift, inhomogeneity corrected using N4, and motion corrected to the first volume using a 12-parameter affine transformation implemented in ANTs. Recent work indicates that de-spiking is more effective than 'scrubbing' for attenuating motion-related artifacts (Jo et al., 2013; Siegel et al., 2014; Power et al., 2015). Transformations were saved in ITK-compatible format for subsequent use. The first volume was extracted for EPI-T1 co-registration. The reference EPI volume was simultaneously co-registered with the corresponding T1-weighted image in native space and corrected for geometric distortions using boundary-based registration (Greve and Fischl, 2009). This step incorporated the previously created fieldmap, undistorted SE, T1, white matter (WM) image, and masks. The spatial transformations necessary to transform each EPI volume from native space to the reference EPI, from the reference EPI to the T1, and from the T1 to the template were concatenated and applied to the processed (de-spiked and slice-time corrected) EPI data in a single step to minimize incidental spatial blurring. Normalized EPI data were resampled to 2-mm isotopic voxels using fifth-order b-splines and smoothed (6-mm FWHM) using 3DblurInMask.

Data Exclusions. To assess residual motion artifact, we computed the number of times the center of the brain (x=5, y=34, z=28) showed a volume-to-volume displacement >0.5 mm using the motion-corrected data. Scans with excess artifact (≥7.5%) were discarded. Three subjects with insufficient usable data (<2 scans) were excluded from analyses, while 6 subjects with 2 usable scans were retained. To assess task-correlated motion, we computed correlations between the design matrix and the motion estimates (see above). Scans showing extreme correlations (>2 *SD*) were discarded. On this basis, ten subjects with insufficient usable data (<2 scans) were excluded from analyses, while 19 subjects with 2 usable scans were retained.

Canonical First-Level fMRI Modeling. Modeling was performed using SPM12 (version 6678; https://www.fil.ion.ucl.ac.uk/spm). Band-pass was set to the hemodynamic response function (HRF) and 128 s for low and high pass, respectively. The MTC paradigm was modeled using variable-duration rectangular ('box-car') regressors time-locked to the anticipatory epochs of the Uncertain Threat, Certain Threat, and Uncertain Safety trials. Certain Safety trials were treated as an unmodeled ('implicit') high-level baseline. EPI volumes collected before the first trial, during intertrial intervals, and following the final trial were also unmodeled, and contributed to the baseline estimate. Regressors were convolved with a canonical HRF and its temporal derivative. The periods corresponding to the delivery of the four reinforcers and rating trials were modeled using a similar approach (**Fig. 1**). Volume-to-volume displacement and motion parameters (including 1- and 2-volume lagged versions) were also included, similar to other recent work (Reddan et al., 2018). To further attenuate potential noise, cerebrospinal fluid (CSF) time-series, instantaneous pulse and respiration rates, and their estimated effect on the BOLD time-series were also included as nuisance variates. ICA-AROMA (Pruim et al., 2015) was used to model several other potential sources of noise (brain-edge, CSF-edge, WM). These and the single ICA component showing the strongest correlation with motion estimates were included as additional nuisance variates.

EPI volumes with excessive volume-to-volume displacement (>0.25 mm), as well as those during and immediately following the delivery of aversive reinforcers, were censored.

Decomposing Canonical Effects Using Finite Impulse Response (FIR) Modeling. The canonical modeling approach estimates the amplitude of anticipatory activity under the assumption that it approximates a 'boxcar-like' square-wave function. This makes it tempting to conclude that regions showing significant activation represent sustained responses. Yet there is abundant evidence that a wide variety of other signals are plausible (e.g. Gonzalez-Castillo et al., 2015; Gungor and Paré, 2016; Sreenivasan and D'Esposito, 2019) and, importantly, can yield similarly strong statistical effects (**Fig. 2**). Addressing this ambiguity necessitates a finer decomposition of the signal underlying significant omnibus effects—a surprisingly rare approach in the neuroimaging literature. To do so, we identified the most extreme peak (e.g. BST) in each of the major regions identified in our canonical analyses. These peak locations were then interrogated using a finite impulse response (FIR) analysis, which provides estimates of the *shape* of anticipatory activity (Glover, 1999; Ollinger et al., 2001; for a similar approach by our group, see Guller et al., 2012). To perform the FIR modeling, variance related to reinforcer delivery, ratings, and the nuisance variables was removed from the preprocessed data using the canonical approach described above. Residualized data were bandpass filtered (.007813-0.2667 Hz) and normalized to the *SD* of the Certain Safety trials (i.e. the implicit baseline in the canonical HRF GLM). We then estimated the mean response at each TR of the anticipatory epoch for each condition of the MTC paradigm for each subject.

Experimental Design and Statistical Analyses

Overview. Study design is described in 'Maryland Threat Countdown (MTC) fMRI Paradigm.' The number of usable datasets, data exclusions, and power considerations are detailed in 'Subjects.'

In-Scanner Fear/Anxiety Ratings and Skin Conductance. Data were analyzed using standard repeated-measures GLM approaches with Huynh-Feldt correction for potential non-sphericity implemented in SPSS (version 24; IBM, Inc., Armonk, NY). Significant interactions were decomposed using simple effects. Figures were created using R Studio (http://www.rstudio.com) and yarrr (version 0.1.5) for R (version 3.6.1.; https://www.R-project.org).

Canonical Second-Level GLM. Standard whole-brain voxelwise GLMs (random effects) were used to compare anticipatory hemodynamic activity elicited by each threat-anticipation condition and its corresponding control condition (e.g. Uncertain Threat vs. Uncertain Safety). Significance was assessed using FDR $q<.05$, whole-brain corrected. As in prior work by our group (Shackman et al., 2013; Shackman et al., 2017), a minimum conjunction (logical 'AND') was used to identify voxels sensitive to both temporally certain *and* temporally uncertain threat anticipation (Nichols et al., 2005). We also directly examined potential differences in anticipatory activity between the two threat conditions (Certain Threat vs. Uncertain Threat). We did not examine hemodynamic responses to reinforcer delivery given the possibility of artifact. Some figures were created using MRIcron (http://people.cas.sc.edu/rorden/mricron). Clusters and local maxima were labeled using a combination of the Allen Institute, Harvard–Oxford, and Mai atlases (Frazier et al., 2005; Desikan et al., 2006b; Makris et al., 2006; Hawrylycz et al., 2012; Mai et al., 2015) and a recently established consensus nomenclature (ten Donkelaar et al., 2018).

Post Hoc FIR Modeling

We identified the most extreme peak in each of the major regions (e.g. MCC) identified in our canonical analyses (indicated by an asterisk in the accompanying figures). These peaks were then interrogated using FIR. As shown in **Fig. 1**, the duration of anticipatory epoch differed between certain (18.75 s) and uncertain trials (8.75-32.5 s; *M*=18.75 s), necessitating slightly different procedures for specific contrasts. For the comparison of Certain Threat to Certain Safety, responses were modeled for 15 TRs (1.25 s TR; total=18.125 s). Given the temporal resolution and autocorrelation of the BOLD signal, data were averaged for 3 windows (TR-1 to TR-5, TR-6 to TR-10, TR-11 to TR-15). For the comparison of Uncertain Threat to Uncertain Safety, responses were modeled for 24 TRs (total=30.00 s) and averaged for 4 windows, the first three corresponding to those used for certain trials and a fourth spanning TR-16 to TR-24. This choice was partially motivated by the modest number of trials with the longest anticipatory epoch (**Fig. 1**). For the comparison of the two threat conditions, responses were modeled for 15 TRs and averaged across 3 windows, as above. Data were analyzed using standard repeated-measures GLM approaches implemented in SPSS with Time and Condition as factors.

'Sustained' activity was defined as significantly greater mean activity during the 'middle' widows (Certain: TR-6 to TR-10; Uncertain: TR-6 to TR-10 and TR-11 to TR-15). This operational definition was motivated by several considerations. First, preliminary inspection of the FIR waveforms indicated that the onset of the anticipatory epoch evoked a substantial onset response in many regions. The magnitude of this initial response obscures early differences (0 to 6.25 s) between conditions, and collinearity precluded the inclusion of an onset predictor. Second, the Uncertain Threat condition only includes 3 windows (early,

middle, and late). Had we observed a significant difference between conditions that was limited to the late window, the interpretation would be indeterminate, as this could reflect a late-occurring sustained effect or a 'phasic' response evoked by the temporal imminence of reinforcer presentation. In light of these considerations, and in order to use a consistent definition across conditions, we operationally defined 'sustained' as a significant mean difference in the middle window(s).

This analytic approach effectively casts the whole-brain analyses as an exploratory (whole-brain) series of omnibus tests, with alpha inflation controlled using FDR $q<.05$, and the FIR analyses as a focused (one peak per region) series of post-hoc tests aimed at decomposing significant omnibus effects (i.e. identifying the windows of time within the anticipatory epoch that underlie significant omnibus effects). It merits comment that this approach necessarily yields optimistically biased effect-size estimates for the main effect of Condition and the Condition × Time interaction (Davenport and Nichols, 2020). As such, they should not be used to guide the design of future studies (e.g. prospective power analyses). Inferences necessarily apply only to the peak locations depicted in the accompanying figures (black-and-white asterisks) and not the entire parent region (e.g. MCC).

Comparison of BST and Amygdala Activity. To enable a fair comparison of hypothesized regional differences in threat sensitivity (see the Introduction), we used a combination of anatomical and functional criteria to independently identify BST and amygdala voxels that were most sensitive to each kind of threat. As shown in **Fig. 3**, each region was anatomically defined using an *a priori* probabilistic region of interest (ROIs) (Frazier et al., 2005; Desikan et al., 2006a; Theiss et al., 2017). Next, we extracted and averaged standardized regression coefficients for voxels showing significant (FDR $q<.05$,

whole-brain corrected) activation for each of the relevant contrasts, separately for each region: Uncertain Threat > Uncertain Safety, Certain Threat > Certain Safety, and Certain Threat > Uncertain Threat. Potential regional differences (i.e. Region × Condition interactions) were then assessed using standard repeated-measures GLM approaches implemented in SPSS. Nonparametric tests (Wilcoxon signed rank) yielded identical results (not reported).

Testing Whether the BST and Amygdala Show Equivalent Responses to Threat. Consistent with prior work by our group (McMenamin et al., 2009; McMenamin et al., 2010), we used the well-established two one-sided tests (TOST) procedure for formally testing whether the BST and amygdala show statistically equivalent activity during threat anticipation. While it is not possible to definitively show that the true difference in regional activity is zero, TOST provides a well-established and widely used framework for testing whether mean differences are small enough to be considered equivalent (Lakens, 2017; Lakens et al., 2018). Regression coefficients were extracted and averaged using the approach detailed in the prior section. For present purposes, we considered regional differences smaller than a 'medium' standardized effect for dependent means (Cohen's d_z=.35) to be equivalent (Lakens, 2017). TOST procedures were performed using the TOSTER package (version 0.3.4) for R.

RESULTS

Temporally Uncertain Threat anticipation elicits robust symptoms and signs of anxiety

As shown in **Fig. 1**, threat anticipation markedly increased subjective symptoms (in-scanner ratings) and objective signs (skin conductance) of anxiety, and this was particularly evident when the timing of

aversive stimulation was *un*certain. ***Anticipatory feelings.*** Subjects reported experiencing more intense fear/anxiety when anticipating aversive outcomes ($F(1,98)=543.27$, $p< .001$), and when anticipating outcomes with uncertain timing ($F(1,98)=85.46$, $p<.001$). The impact of threat on self-reported fear/anxiety was potentiated by temporal uncertainty (Valence × Uncertainty: $F(1,98)=13.08$, $p<.001$; Uncertain Threat > Certain Threat: $t(98)=7.58$, $p<.001$; Uncertain Safety > Certain Safety: $t(98)=4.90$, $p<.001$; Uncertain Threat > Uncertain Safety: $t(98)=21.98$, $p<.001$; Certain Threat > Certain Safety: $t(98)=20.36$, $p<.001$). ***Anticipatory arousal.*** Subjects showed elevated skin conductance levels when anticipating aversive outcomes ($F(1,98)=345.31$, $p<.001$), and when anticipating outcomes with uncertain timing ($F(1,98)=85.86$, $p<.001$). The impact of threat on skin conductance was potentiated by temporal uncertainty (Valence × Uncertainty: $F(1,98)=93.63$, $p<.001$; Uncertain Threat > Certain Threat: $t(98) = 11.53$, $p<.001$; Uncertain Safety > Certain Safety: $t(98) = -3.99$, $p< .001$; Uncertain Threat > Uncertain Safety: $t(98)=25.59$, $p<.001$; Certain Threat > Certain Safety: $t(98)=9.84$, $p<.001$). Taken together, these results confirm the validity of the MTC paradigm for understanding the neural circuits underpinning human anxiety.

Temporally Uncertain Threat anticipation recruits a distributed network of subcortical and cortical regions

Next, a voxelwise GLM was used to identify brain regions recruited during the anticipation of temporally Uncertain Threat (Uncertain Threat > Uncertain Safety; FDR $q<.05$, whole-brain corrected). As shown in **Fig. 4**, this highlighted a widely distributed network of regions previously implicated in the expression and regulation of human fear and anxiety (Fullana et al., 2016; Qi et al., 2018; Fox and Shackman, 2019; Chavanne and Robinson, 2020), including the MCC; AI extending into the frontal operculum (FrO); dlPFC extending to the frontal pole (FP); brainstem encompassing the periaqueductal grey (PAG); basal forebrain, in the region of the BST; and dorsal amygdala, in the region of the central and medial nuclei.

Heightened activity during the anticipation of Uncertain Threat was also evident in the orbitofrontal cortex, basal ganglia, hippocampus, and ventrolateral amygdala in the region of the lateral nucleus (**Extended Data Fig. 4-1**). Consistent with prior work (Choi et al., 2012; Grupe et al., 2016), Uncertain Threat anticipation was also associated with *reduced* activity in a set of midline regions that resembled the default mode network (e.g. anterior rostral sulcus, postcentral gyrus, and precuneus), as well as the posterior insula and parahippocampal gyrus (**Extended Data Fig. 4-2**). Reduced activity was also observed in the most rostral tip of the amygdala, underscoring the functional heterogeneity of this complex structure.

Temporally Uncertain Threat anticipation elicits sustained hemodynamic activity

Anxiety is widely conceptualized as a sustained state (Davis et al., 2010; Tye et al., 2011; LeDoux and Pine, 2016; Mobbs, 2018), and it is tempting to interpret clusters of enhanced activity (e.g. **Fig. 4**) through this lens. But do we actually see evidence of sustained responses during the anticipation of temporally Uncertain Threat? Although a wide variety of other signals are physiologically plausible (**Fig. 2**), the vast majority of fMRI studies never address this question; they instead assume the shape of the hemodynamic response and focus on estimates of response magnitude ('activation'). To address this ambiguity, we used a finite impulse response (FIR) approach to estimate responses elicited by the anticipation of Uncertain Threat and Uncertain Safety on a finer time-scale. Doing so revealed evidence of significantly sustained activity across key cortical (MCC, AI/FrO, dlPFC/FP) and subcortical (PAG, BST, dorsal amygdala) regions (Uncertain Threat > Uncertain Safety; 6.25-30 s; **Fig. 5** and **Extended Data Fig. 5-1**).

Temporally Certain Threat anticipation recruits an anatomically and functionally similar network

Having identified a distributed neural circuit sensitive to temporally Uncertain Threat, we used a parallel approach to identify regions recruited during the anticipation of *Certain* Threat (Certain Threat > Certain Safety; FDR q<.05, whole-brain corrected). As shown in **Fig. 4**, results were similar to those found for Uncertain Threat (**Extended Data Figs. 4-3** and **4-4**). In fact, a minimum conjunction analysis (Logical 'AND;' Nichols et al., 2005) revealed voxelwise co-localization in every key cortical and subcortical region, including the BST and dorsal amygdala (**Fig. 4** and **Extended Data Fig. 4-5**). FIR results provided additional evidence of functional convergence across conditions, with all but one of these key regions (PAG) showing sustained levels of heightened hemodynamic activity during the anticipation of Certain Threat (**Fig. 6** and **Extended Data Fig. 6-1**). Taken together, these results suggest that this network of subcortical and cortical regions is sensitive to multiple kinds of threat anticipation, both certain and uncertain.

The threat anticipation network can be fractionated into subdivisions

To determine whether regions recruited during threat anticipation are sensitive to temporal uncertainty, we directly compared the Uncertain and Certain Threat conditions (FDR q<.05, whole-brain corrected). This indicated that the threat anticipation network can be fractionated into subdivisions. As shown in **Fig. 7**, key cortical regions (MCC, AI/FrO, and dlPFC/FP) showed a further increase in activity during the anticipation of *Uncertain* Threat (**Extended Data Fig. 7-1**). In contrast, the BST and dorsal amygdala showed the reverse pattern, with relatively greater activity during the anticipation of *Certain* Threat (**Extended Data Fig. 7-2**). The PAG did not discriminate the two threat conditions. FIR analyses yielded similar conclusions (**Fig. 7** and **Extended Data Fig. 7-3**).

The anticipation of temporally Uncertain and Certain Threat elicits statistically indistinguishable responses in the extended amygdala

Our results indicate that the BST and dorsal amygdala—the two major subdivisions of the EA—respond similarly to threat anticipation. Both regions show significantly elevated activity during threat anticipation, and this is evident whether or not the timing of aversive stimulation is uncertain (**Fig. 4**). Furthermore, both regions showed parallel increases in activity during the anticipation of Certain Threat (**Figs. 6-7**). Yet it remains possible that the BST and the amygdala exhibit subtler differences in threat sensitivity. To rigorously test this, we directly compared regional responses for each of the threat contrasts (e.g. Uncertain Threat vs. Uncertain Safety), equivalent to testing the Region × Condition interactions. As shown in **Fig. 8**, mean differences were small to very-small and all non-significant (**Extended Data Fig. 8-1**). Likewise, the proportion of subjects showing numerically greater activity in either region never exceeded 55% (**Fig. 8**). Naturally, these results do not license claims of regional equivalence. While it is impossible to demonstrate that the true difference in regional activity is zero, the two one-sided tests (TOST) procedure provides a well-established and widely used statistical framework for testing whether mean differences—here, in regional activity—are small enough to be considered equivalent (Lakens, 2017; Lakens et al., 2018). For present purposes, we considered differences smaller than a 'medium' standardized effect (Cohen's d_z=.35) statistically equivalent. Results revealed significant equivalence for each of the threat contrasts (*p*s=.001-.03; **Fig. 8** and **Extended Data Fig. 8-1**). Although these statistical results clearly do not demonstrate that the amygdala and the BST are functionally interchangeable, they do enable us to decisively reject claims of strict functional segregation (i.e. that the BST is sensitive to uncertain danger, whereas the amygdala is not).

DISCUSSION

Uncertain threat anticipation is the prototypical trigger of anxiety (Grupe and Nitschke, 2013), a core theme that cuts across disorders, species, and assays, including novelty, darkness, and other so-called

'diffuse' threats. Despite the profound significance of anxiety for human health, the neural systems recruited by uncertain threat have remained incompletely understood. Leveraging a translationally relevant paradigm optimized for fMRI signal decomposition (**Fig. 1**), our results reveal that the anticipation of temporally uncertain aversive stimulation recruits a distributed network of fronto-cortical (MCC, AI/FrO, and dlPFC/FP) and subcortical (PAG, BST, and dorsal amygdala) regions (**Fig. 4**), mirroring robust changes in experience and psychophysiology (**Fig. 1**). Closer inspection of signal dynamics in these regions revealed evidence of sustained activity during the anticipation of Uncertain Threat (**Fig. 5**). Analyses focused on the anticipation of temporally Certain Threat revealed a remarkably similar pattern, with voxels sensitive to both kinds of threat evident in key cortical and subcortical regions (**Fig. 4**). Collectively, these observations suggest this network is sensitive to both certain and uncertain threat. Direct comparison of the threat conditions demonstrated that the threat anticipation network can be fractionated: cortical regions showed relatively greater activity during the anticipation of Uncertain Threat, whereas the extended amygdala showed relatively greater activity during the anticipation of Certain Threat (**Fig. 7**). While there is consensus that the BST and dorsal amygdala play a critical role in orchestrating adaptive responses to danger, their precise contributions to human anxiety have remained contentious (Klumpers et al., 2017; Luyck et al., 2019). Our results suggest that these regions respond similarly to different kinds of threat anticipation. Indeed, the present findings show that the BST and dorsal amygdala exhibit statistically indistinguishable hemodynamic responses to threat anticipation across a variety of 'head-to-head' comparisons (**Fig. 8**), reinforcing the possibility that they make similar contributions to human anxiety (Gungor and Paré, 2016; Shackman and Fox, 2016; Fox and Shackman, 2019).

Since the time of Freud (Freud, 1920), the distinction between certain ('*fear*') and uncertain ('*anxiety*') danger has been a key feature of prominent models of emotion and psychiatric disease (Kimmel, 1975;

Davis et al., 2010; Grupe and Nitschke, 2013; LeDoux and Pine, 2016; Mobbs, 2018; Fox and Shackman, 2019). Our findings show that the regions recruited during the anticipation of Certain and Uncertain Threat are co-localized at the voxelwise level in several key regions (**Fig. 4**). This common threat anticipation network encompasses subcortical regions—including the PAG, BST, and dorsal amygdala—that are critical for assembling appropriate defensive responses to uncertain threat in animals (Fadok et al., 2018; Fox and Shackman, 2019; Hur et al., 2019). But it also includes fronto-cortical regions—including the MCC, AI/FrO, and dlPFC/FP—that have received less empirical attention and are difficult or impossible to study in rodents (Vogt and Paxinos, 2014; Carlén, 2017; Roberts and Clarke, 2019; Roberts, 2020). These frontal regions have traditionally been associated with the controlled processing and regulation of emotion, cognition, and action (Shackman et al., 2011; Morawetz et al., 2017; Langner et al., 2018; Kroes et al., 2019) and more recently implicated in the conscious experience of emotion (Brown et al., 2019). Emerging evidence suggests that the MCC also contributes to the reactive avoidance of imminent threat (Qi et al., 2019). As shown in **Fig. 9**, the present results are well aligned with recent meta-analyses of neuroimaging studies of 'fear' (Fullana et al., 2016) and 'anxiety' (Chavanne and Robinson, 2020). Across studies encompassing hundreds of subjects, this work shows that the anticipation of *certain threat* (Pavlovian threat cues; the prototypical 'fear' stimulus in laboratory studies) and *uncertain threat* (instructed 'threat-of-shock') recruit an overlapping network of core regions, including the BST, consistent with our within-subjects results. Interestingly, the amygdala is not evident in either meta-analysis, contrary to mechanistic work in rodents, monkeys, and humans (Bechara et al., 1995; Antoniadis et al., 2007; Tovote et al., 2015). The cause of this discrepancy remains unclear (e.g. inadequate power, habituation), making it a key challenge for future research.

Our results provide insight into the functional architecture of the threat anticipation network, demonstrating that fronto-cortical regions prefer Uncertain over Certain Threat, whereas the BST and

dorsal amygdala show the reverse preference—*a difference in degree, not in kind*. In contrast to prior research, trivial differences cannot account for this nuance; the two threat conditions were pseudo-randomly intermixed and nearly identical in terms of their perceptual, nociceptive, motor, and statistical features (**Fig. 1**). What might explain the observed regional preferences? Aside from temporal certainty, the most conspicuous difference between the threat conditions is the degree of cognitive scaffolding. During Certain Threat trials, the descending stream of integers provides a precise and predictable index of momentary changes in threat imminence, encouraging a reactive, stimulus-bound cognitive mode. During Uncertain Threat trials this support is absent, necessitating a greater reliance on the kinds of sustained, endogenous representations that are the hallmark of fronto-cortical regions (Badre and Nee, 2018). A second notable difference between the two threat conditions is the intensity of anxiety. Consistent with prior work (Grillon et al., 2006; Nelson and Shankman, 2011; Somerville et al., 2013; Bennett et al., 2018), the anticipation of Uncertain Threat was associated with greater distress and arousal (**Fig. 1**). The observed increase in fronto-cortical activity could reflect either heightened anxiety or compensatory processes aimed at downregulating distress and arousal. Testing these non-exclusive hypotheses will require a multi-pronged approach that encompasses carefully optimized tasks and mechanistic interventions (e.g. transcranial magnetic stimulation, acute anxiolytic challenges, explicit/placebo regulation manipulations). Multivariate approaches are likely to be useful for linking specific facets of anxiety, including subjective feelings, to variation in the function of the threat anticipation network, and determining whether this reflects expressive or regulatory processes (Chang et al., 2015; Woo et al., 2017).

The present results add to a growing body of evidence indicating that the BST and dorsal amygdala, while certainly not interchangeable, are more alike than different (Shackman and Fox, 2016; Fox and Shackman, 2019). Anatomically, the BST and dorsal amygdala are characterized by similar patterns of connectivity,

cellular composition, neurochemistry, and gene expression (Fox et al., 2015a). Both regions are poised to trigger defensive responses to threat via dense projections to brainstem and subcortical effector regions (Fox et al., 2015a). Consistent with this perspective, neuroimaging studies in monkeys and humans have documented similar physiological responses in the two regions to a broad spectrum of anxiety-eliciting stimuli, including sustained exposure to novelty ('diffuse' threat; Fox et al., 2008) and intruder threat (Fox et al., 2015b); brief exposure (800 ms) to aversive images (Brinkmann et al., 2018); an unpredictably approaching tarantula (Mobbs et al., 2010); and 'jump-scares' in horror movies (https://identifiers.org/neurovault.collection:6237; Hudson et al., *in press*). Work in rodents reinforces the hypothesis that the BST and dorsal amygdala (Ce) are crucial substrates for human anxiety, showing that specific microcircuits within and between these two regions bi-directionally control defensive responses to a range of threatening cues and contexts (Fox and Shackman, 2019; Pomrenze et al., 2019; Griessner et al., *in press;* Pliota et al., *in press*). Notably, work using a variant of the MTC paradigm in mice demonstrates that cannabinoid projections from the Ce to the BST are necessary for mounting defensive responses during the anticipation of temporally uncertain shock (Lange et al., 2017), consistent with the present conclusions. While our understanding remains far from complete, this body of mechanistic and imaging observations underscore the need to revise models of anxiety—including the NIMH RDoC framework—that imply a strict segregation of certain and uncertain threat processing in the extended amygdala (LeDoux and Pine, 2016; National Institute of Mental Health, 2020b, a). The present results imply that the magnitude of regional differences in hemodynamic sensitivity to threat-uncertainty is modest ($<dz=.35$), conditional on known perceptual confounds or other moderators, or simply non-existent. An important challenge for the future will be to determine whether the *type* of threat uncertainty (e.g. temporal vs. likelihood vs. intensity) is a crucial determinant of regional differences in extended amygdala function (Williams et al., 2015; Clauss et al., 2019).

In conclusion, the neural networks recruited by temporally uncertain and certain threat are not categorically different, at least when viewed through the macroscopic lens of fMRI. We see evidence of anatomical co-localization—*not* segregation—in a number of key cortical and subcortical regions, in broad accord with animal models and recent imaging meta-analyses. This shared threat anticipation system can be functionally fractionated, with fronto-cortical regions showing relatively stronger engagement during the anticipation of temporally uncertain threat, and the BST and dorsal amygdala showing the reverse pattern. Across comparisons, the BST and dorsal amygdala evinced statistically indistinguishable responses during the anticipation of certain and uncertain threat, reinforcing the possibility that they make similar contributions to human anxiety. These observations provide a novel framework for conceptualizing fear and anxiety, and for guiding the development of mechanistic work aimed at developing more effective intervention strategies for extreme anxiety. A relatively large sample, well-controlled task, and advanced techniques for fMRI data acquisition and processing enhance confidence in the robustness and translational relevance of these results.

FIGURE LEGENDS

Figure 1. Maryland Threat Countdown (MTC) Paradigm. As shown schematically in panel ***a***, the MTC paradigm takes the form of a 2 (*Valence:* Threat/Safety) × 2 (*Temporal Certainty:* Uncertain/Certain) repeated-measures design. See the main text for a general description and Materials and Methods for details. Subjects provided ratings of anticipatory fear/anxiety for each trial type during each scan. Skin conductance was continuously acquired during scanning. Simulations were used to optimize the detection and deconvolution of task-related hemodynamic signals (variance inflation factors <1.54). Central panels depict the structure of each trial type. Trial valence was continuously signaled during the anticipatory epoch by the background color of the display. Safety trials were similar, but terminated with the delivery of benign stimuli (e.g. just-perceptible electrical stimulation). Trial certainty was signaled by the nature of the integer stream. Certain trials always began with the presentation of 30. On Uncertain trials, integers were randomly drawn from a uniform distribution ranging from 1 to 45 to reinforce the belief that uncertain trials could be much longer than certain ones. To mitigate potential confusion and eliminate mnemonic demands, a lower-case 'c' or 'u' was presented at the lower edge of the display throughout the anticipatory epoch (not depicted). As shown in panels ***b*** and ***c***, threat anticipation robustly increased subjective symptoms (in-scanner ratings) and objective signs (skin conductance) of anxiety, and this was particularly evident when the timing of aversive stimulation was uncertain (Valence × Certainty, *ps*<.001; Uncertain Threat > Certain Threat, *ps*<.001). Panels ***b*** and ***c*** depict the data (*black points; individual participants*), density distribution (*bean plots*), Bayesian 95% highest density interval (HDI; *colored bands*), and mean (*black bars*) for each condition. HDIs permit population-generalizable visual inferences about mean differences and were estimated using 1,000 samples from a posterior Gaussian distribution. Abbreviations—TR, repetition time (i.e. the time required to collect a single volume of fMRI data).

Fig. 2. Interpretive ambiguities of canonical HRF modeling. The canonical approach to fMRI analysis models the amplitude of anticipatory activity (*solid black line*) under the assumption that it approximates a 'boxcar-like' square-wave shape (*dotted line;* convolution of a canonical HRF with task duration). In some cases, such as the upper-left panel, the hemodynamic signal and the model will match. But in others, it will not. Importantly, a variety of physiologically plausible hemodynamic responses can produce similarly strong and statistically significant results (T = 52.556 in this example), highlighting the importance of modeling the BOLD signal on a finer temporal scale.

Fig. 3. Amygdala and BST ROIs. *BST.* The derivation of the probabilistic BST ROI (*green*) is detailed in (Theiss et al., 2017) and was thresholded at 0%. The seed mostly encompasses the supra-commissural BST, given the difficulty of reliably discriminating the borders of regions below the anterior commissure on the basis of T1-weighted images (Kruger et al., 2015). ***Amygdala.*** The derivation of the Harvard-Oxford probabilistic amygdala (*cyan*) is detailed in Refs. (Frazier et al., 2005; Desikan et al., 2006a) and was thresholded at 50%. Analyses employed ROIs decimated to the 2-mm resolution of the EPI data. For illustrative purposes, 1-mm ROIs are shown. Single-subject data were visually inspected to ensure that the ROIs were correctly aligned to the spatially normalized T1-weighted images. Abbreviation—BST, bed nucleus of the stria terminalis.

Fig. 4. The anticipation of temporally Uncertain and Certain Threat recruits broadly similar networks. Key regions (*cyan arrowheads*) showing significantly elevated activity during the anticipation of Uncertain Threat (*left column*) and Certain Threat (*center column*) compared to their respective control conditions. Voxels showing significantly increased activity in both contrasts are depicted in the *right column*. BST and dorsal amygdala images are masked to highlight significant voxels in extended amygdala (*green*). Coronal insets depict the thresholded statistical parametric maps without the additional mask. Taken together, these observations indicate that these regions are sensitive to both temporally certain and uncertain threat. For additional details, see **Extended Data Figs. 4-1** to **4-5**. Abbreviations—Ant., anterior; BST, bed nucleus of the stria terminalis; dlPFC, dorsolateral prefrontal cortex; FrO, frontal operculum; L, left; PAG, periaqueductal grey; WB, whole-brain corrected.

Fig. 5. Post hoc analyses confirm that regions sensitive to temporally Uncertain Threat show evidence of sustained hemodynamic activity. Mean responses to the anticipatory epoch were estimated on a TR-by-TR (1.25 s) basis for Uncertain Threat (*red*) and Uncertain Safety (*blue*) trials, using data from the local maxima of key clusters (*black-and-white asterisks in the left panels*) identified using a canonical analytic approach. Given the temporal resolution and autocorrelation of the hemodynamic signal, data were averaged for 4 windows (TR-1 to TR-5, TR-6 to TR-10, TR-11 to TR-15, and TR-16 to TR-24), spanning a total of 24 measurements (30 s). Windows are indicated by broken vertical lines. Shaded envelopes depict the standard error of the mean. Significant differences are indicated by the black asterisks in the right panels (*p*s<.05; **Extended Data Fig. 5-1**). Abbreviations—Ant., anterior; BST, bed nucleus of the stria terminalis; dlPFC, dorsolateral prefrontal cortex; FrO, frontal operculum; L, left; PAG, periaqueductal grey; TR, repetition time (the time needed to acquire a single volume of fMRI data).

Fig. 6. Post hoc analyses of regional responses to temporally Certain Threat and Certain Safety. Mean responses to the anticipatory epoch were estimated on a TR-by-TR (1.25 s) basis for Certain Threat (*red*) and Certain Safety (*blue*) trials, using data from the local maxima of key clusters (*black-and-white asterisks in the left panels*) identified using a canonical HRF GLM approach. Given the temporal resolution and autocorrelation of the hemodynamic signal, data were averaged for 3 windows (TR-1 to TR-5, TR-6 to TR-10, and TR-11 to TR-15), spanning a total of 15 measurements (18.75 s). Windows are indicated by broken vertical lines. Shaded envelopes depict the standard error of the mean. Significant differences are indicated by the black asterisks in the right panels (*ps*<.05; **Extended Data Fig. 6-1**). Abbreviations—Ant., anterior; BST, bed nucleus of the stria terminalis; dlPFC, dorsolateral prefrontal cortex; FrO, frontal operculum; L, left; PAG, periaqueductal grey.

Fig. 7. The threat anticipation network can be fractionated into subdivisions. The midcingulate cortex, anterior insula/frontal operculum, and dlPFC showed greater activity during the anticipation of Uncertain Threat (*left column*), whereas the BST and dorsal amygdala showed greater activity during the anticipation of Certain Threat (*center column*). Thresholds and other conventions are identical to **Fig. 4**. For additional details, see **Extended Data Figs. 7-1** and **7-2**. The r*ight column* depicts TR-by-TR (1.25 s) hemodynamic responses during the anticipation of Uncertain Threat (*solid red line*) and Certain Threat (*broken red line*). Data were extracted from the local maxima of key clusters (*black-and-white asterisks in the left and center columns*) identified using a canonical HRF GLM approach. Given the temporal resolution and autocorrelation of the hemodynamic signal, data were averaged for 3 windows (TR-1 to TR-5, TR-6 to TR-10, and TR-11 to TR-15), spanning a total of 15 measurements (18.75 s). Windows are indicated by broken vertical lines. Shaded envelopes depict the standard error of the mean. Significant differences are indicated by the black asterisks in the right panels (*p*s<.05; **Extended Data Fig. 7-3**). Abbreviations—Ant., anterior; BST, bed nucleus of the stria terminalis; dlPFC, dorsolateral prefrontal cortex; FrO, frontal operculum; L, left; PAG, periaqueductal grey.

Fig. 8. The BST and dorsal amygdala show statistically indistinguishable responses during threat anticipation. While it is impossible to demonstrate that the true difference in regional hemodynamic activity is zero, the two one-sided tests (TOST) procedure provides a well-established and widely used statistical framework for testing whether mean differences in regional activity are small enough to be considered equivalent (Lakens, 2017; Lakens et al., 2018). Results revealed significant equivalence for all contrasts (**Extended Data Fig. 8-1**). Figure depicts the data (*black points; individual participants*), density distribution (*bean plots*), Bayesian 95% highest density interval (HDI; *colored bands*), and mean (*black bars*) for each condition. HDIs permit population-generalizable visual inferences about mean differences and were estimated using 1,000 samples from a posterior Gaussian distribution. Inset ring plots indicate the percentage of subjects showing greater activity in the BST compared to the dorsal amygdala for each contrast.

Fig. 9. Certain and uncertain threat anticipation elicit broadly similar patterns of neural activity. Figure summarizes the results of two coordinate-based meta-analyses (CBMA) of functional neuroimaging studies. *Top-left* inset depicts the results for 27 'fear conditioning' studies (*N*=677), highlighting regions showing consistently greater activity during the anticipation of certain threat (CS+ > CS-; https://neurovault.org/collections/2472; Fullana et al., 2016). *Bottom-right* inset depicts the results for 18 'threat-of-shock' studies (*N*=693), highlighting regions showing consistently greater activity during the anticipation of uncertain threat (Threat > Safe; https://neurovault.org/collections/6012; Chavanne and Robinson, 2020). Visual inspection of the results (*red clusters*) suggests that the anticipation of certain and uncertain threat elicits qualitatively similar patterns, including heightened activity in the region of the BST. This impression is reinforced by the substantial correlation between the two whole-brain patterns, r = .69. Consistent amygdala activity was not detected in either meta-analysis. Note: The pattern correlation was estimated in Neurovault using a brain-masked, 4-mm transformation of the publicly available, vectorized meta-analytic maps (Gorgolewski et al., 2015). For illustrative purposes, every 10th voxel is depicted in the scatter plot**.** Abbreviations—BST, bed nucleus of the stria terminalis; CBMA, coordinate-based meta-analyses; L, left hemisphere; R, right hemisphere.

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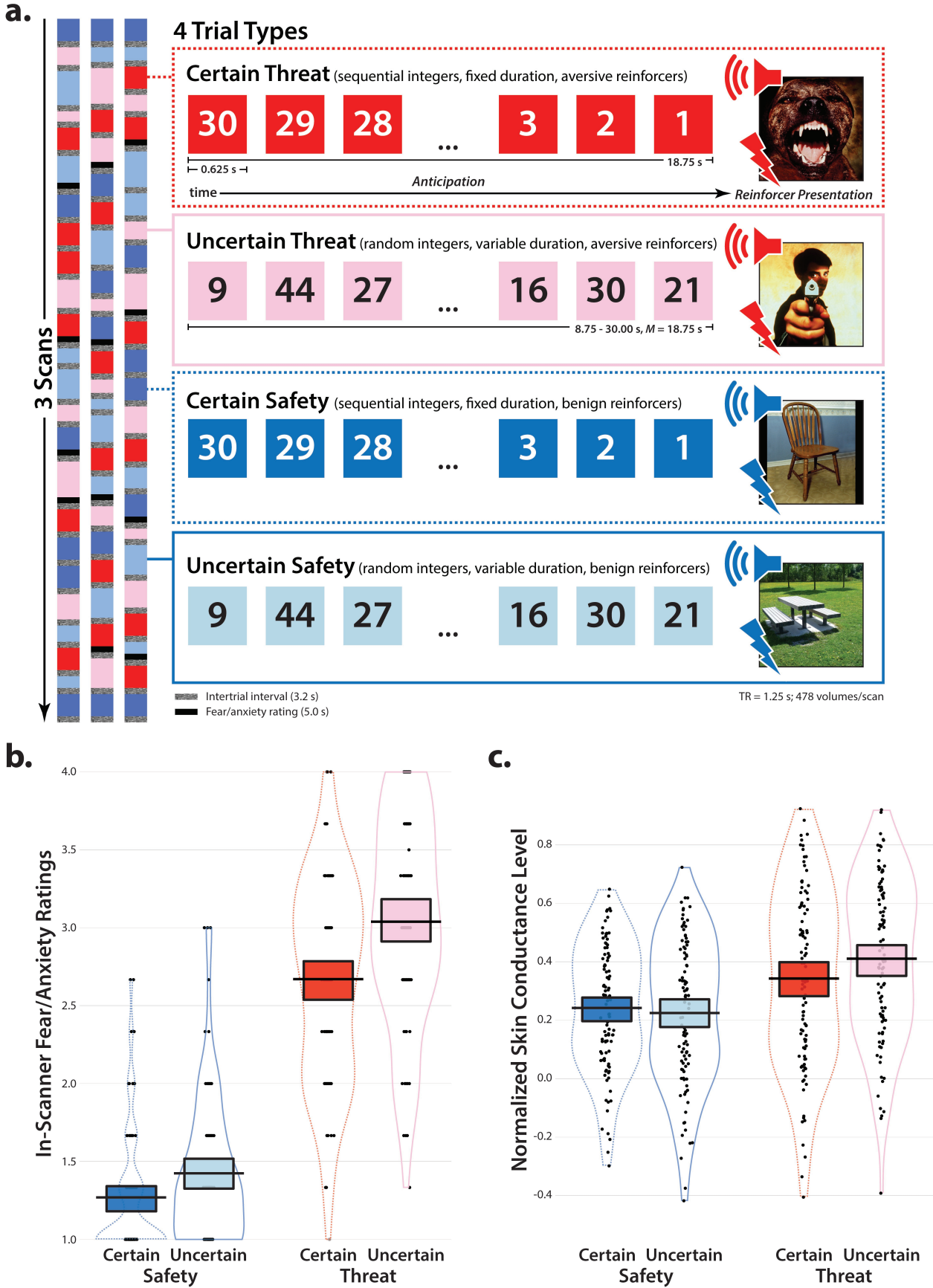
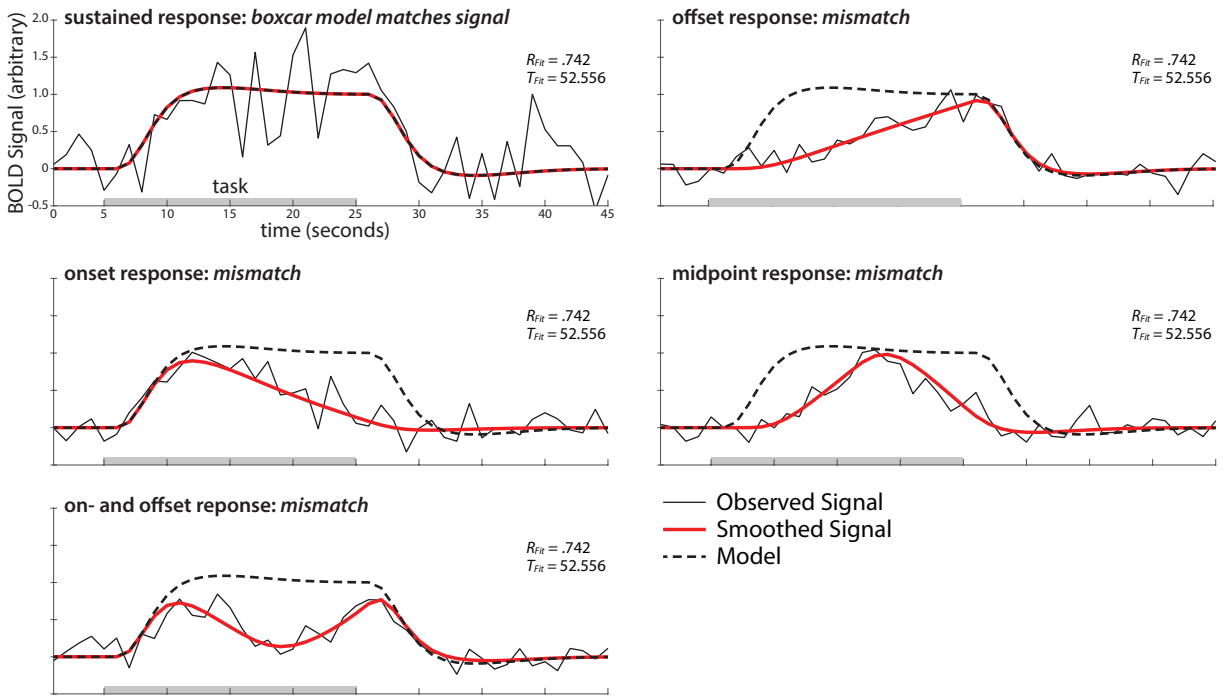
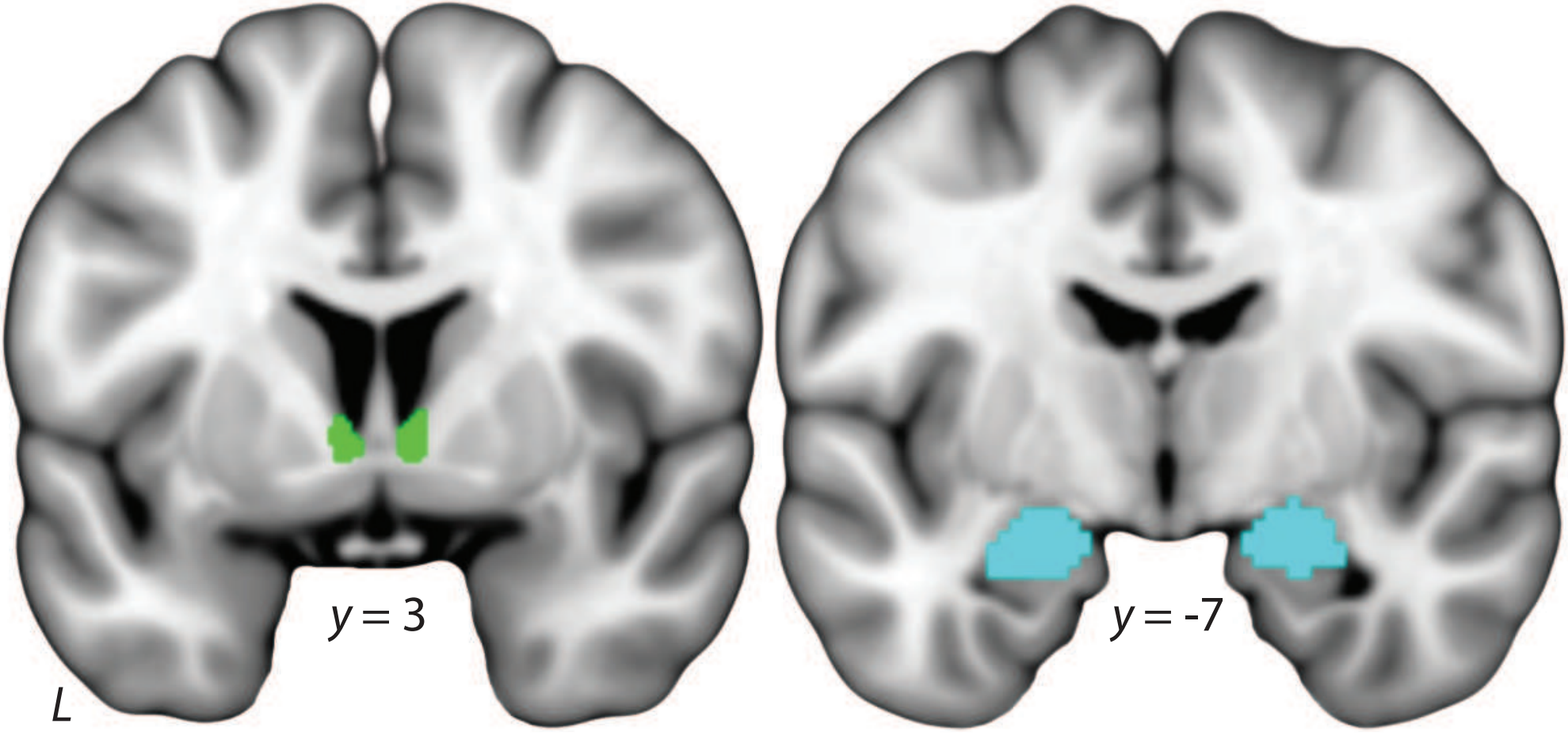
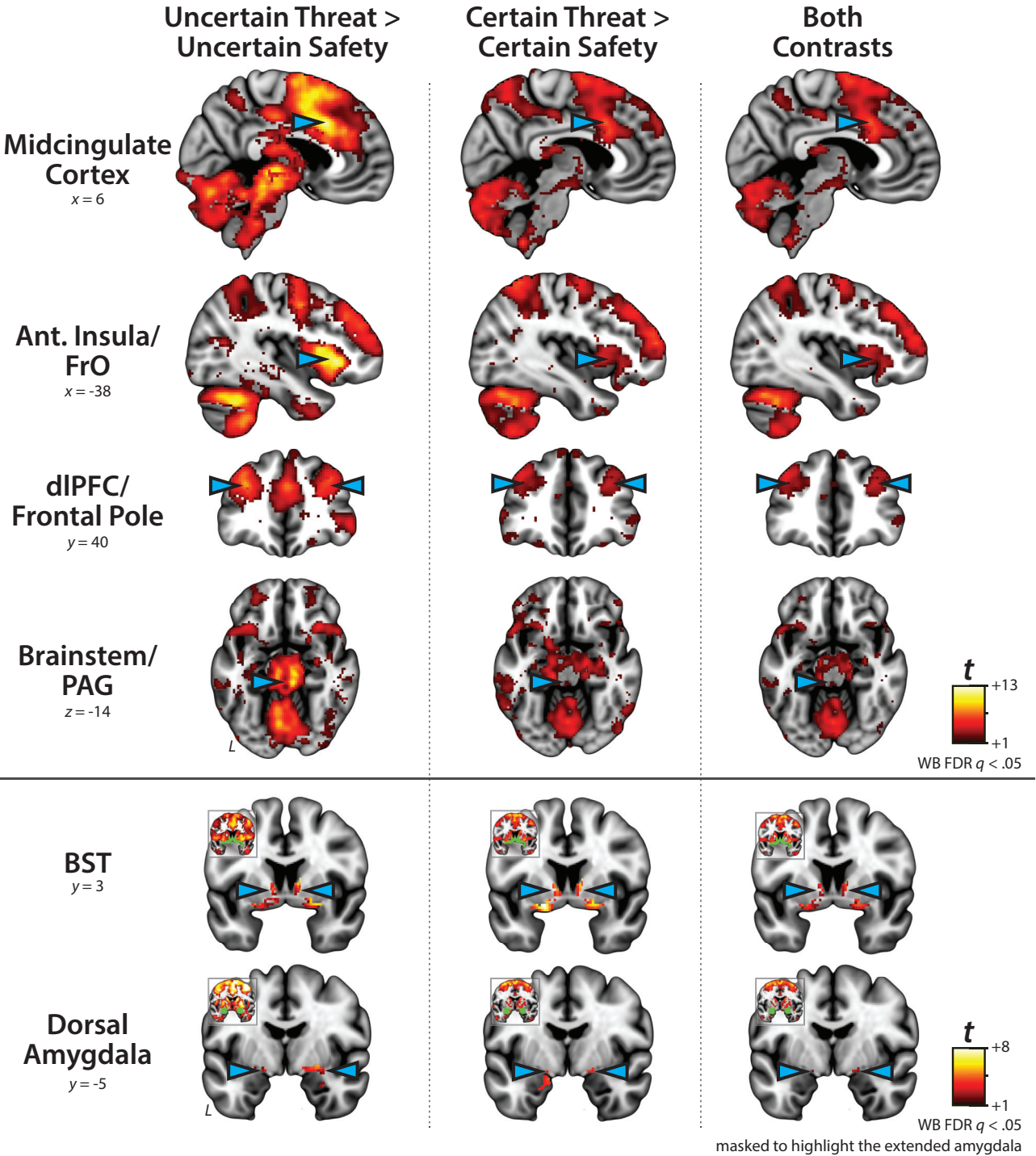
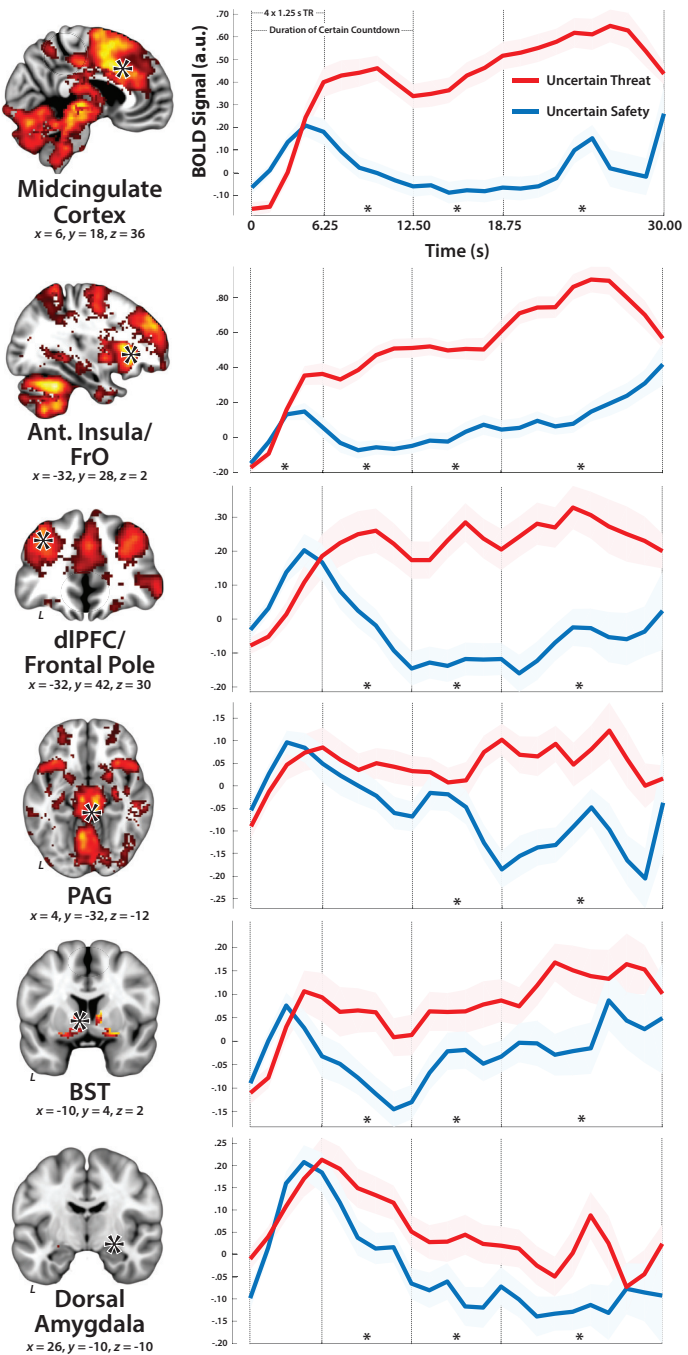

a.
4 Trial Types
3 Scans
Certain Threat (sequential integers, fixed duration, aversive reinforcers)
30 29 28 ... 3 2 1
0.625 s
18.75 s
time
Anticipation
Reinforcer Presentation
Uncertain Threat (random integers, variable duration, aversive reinforcers)
9 44 27 ... 16 30 21
8.75 - 30.00 s, M = 18.75 s
Certain Safety (sequential integers, fixed duration, benign reinforcers)
30 29 28 ... 3 2 1
Uncertain Safety (random integers, variable duration, benign reinforcers)
9 44 27 ... 16 30 21
Intertrial interval (3.2 s)
Fear/anxiety rating (5.0 s)
TR = 1.25 s; 478 volumes/scan
b.
In-Scanner Fear/Anxiety Ratings
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Certain Safety
Uncertain Safety
Certain Threat
Uncertain Threat
c.
Normalized Skin Conductance Level
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Certain Safety
Uncertain Safety
Certain Threat
Uncertain Threat

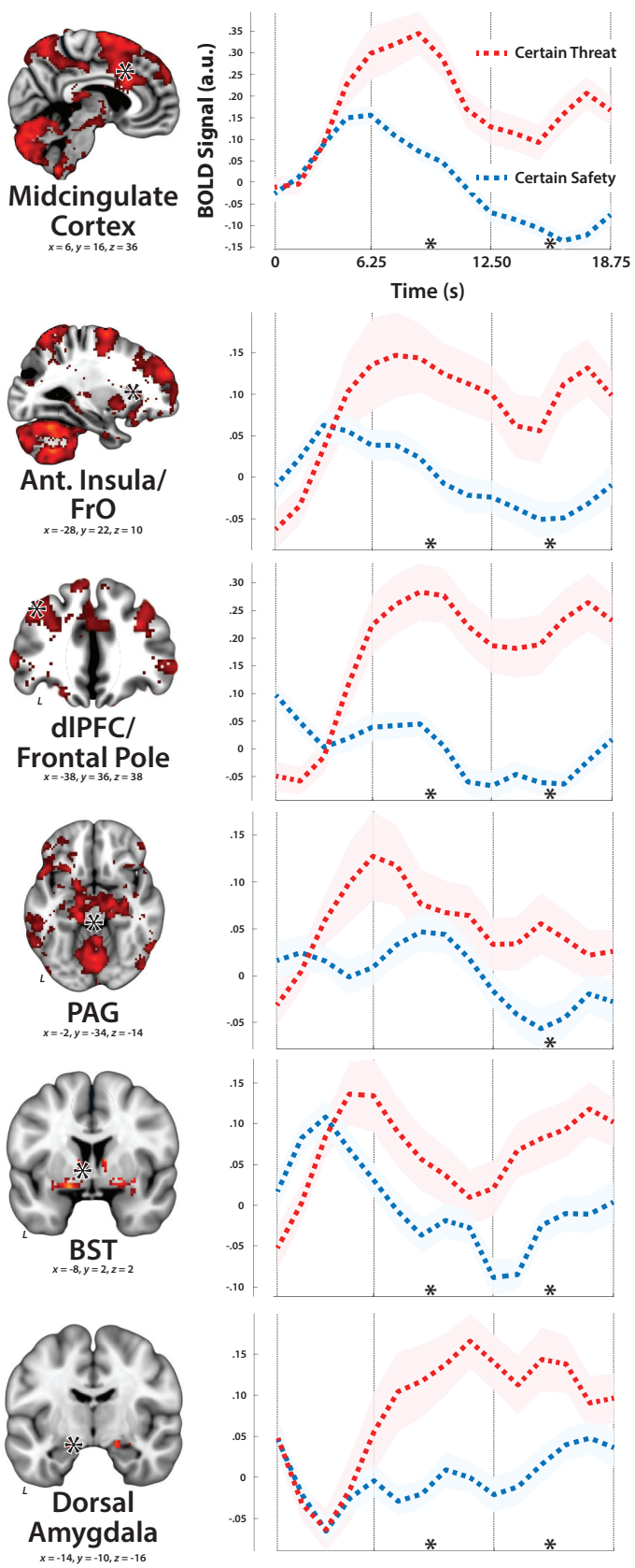

sustained response: *boxcar model matches signal*
BOLD Signal (arbitrary)
2.0
1.5
1.0
0.5
0
-0.5
task
0
5
10
15
20
25
30
35
40
45
time (seconds)
R_{Fit} = .742
T_{Fit} = 52.556
offset response: *mismatch*
R_{Fit} = .742
T_{Fit} = 52.556
onset response: *mismatch*
R_{Fit} = .742
T_{Fit} = 52.556
midpoint response: *mismatch*
R_{Fit} = .742
T_{Fit} = 52.556
on- and offset reponse: *mismatch*
R_{Fit} = .742
T_{Fit} = 52.556
Observed Signal
Smoothed Signal
Model

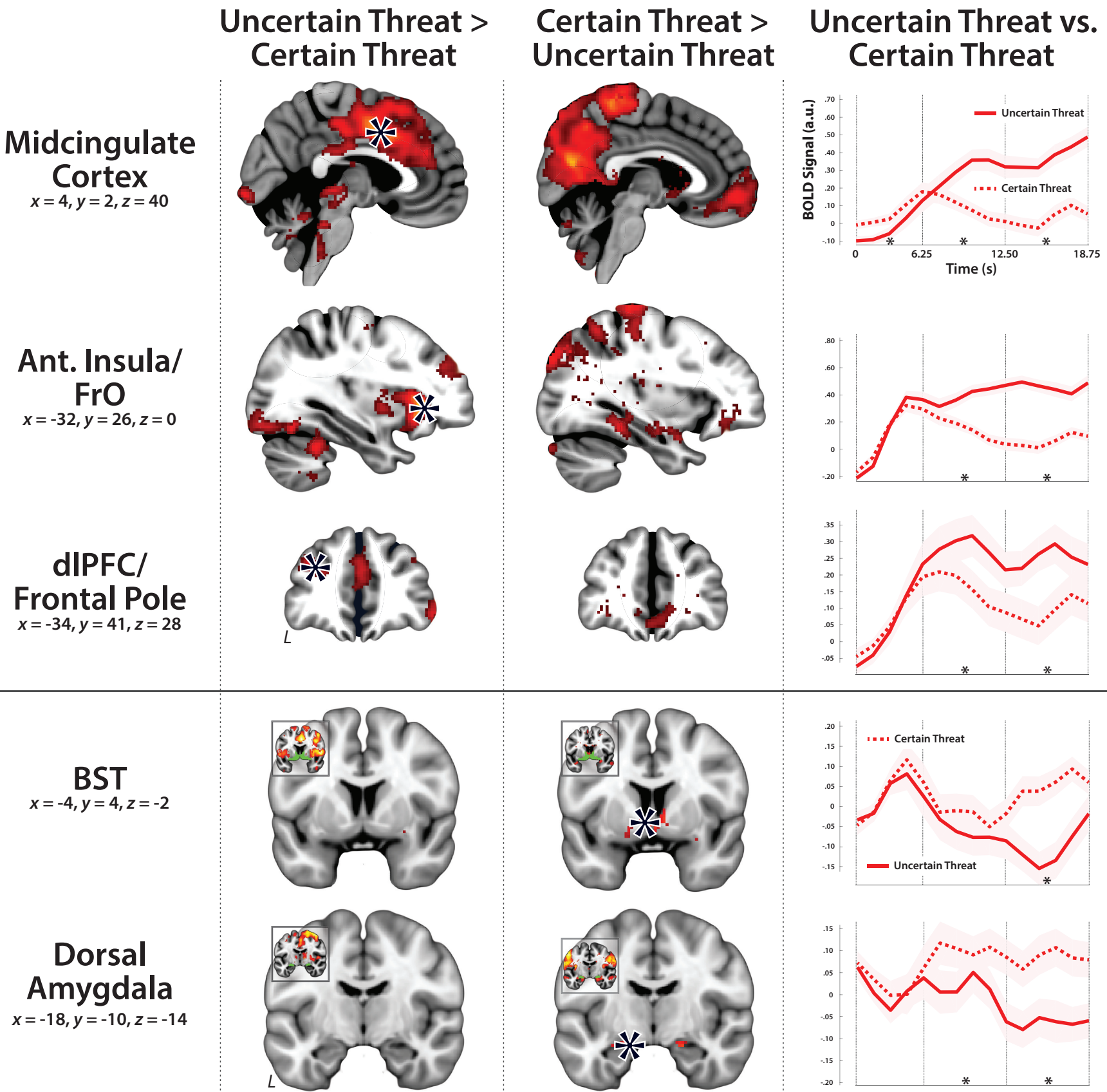


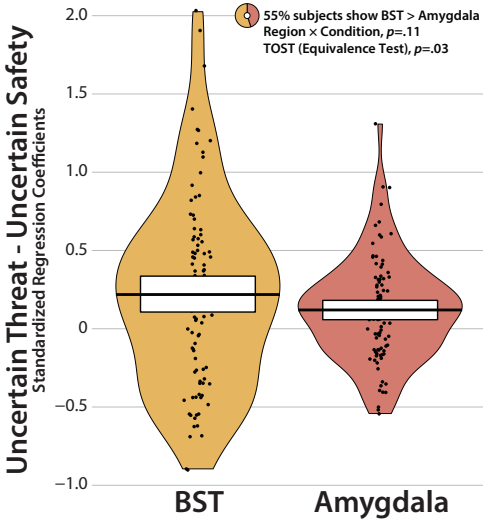
BST **Amygdala**

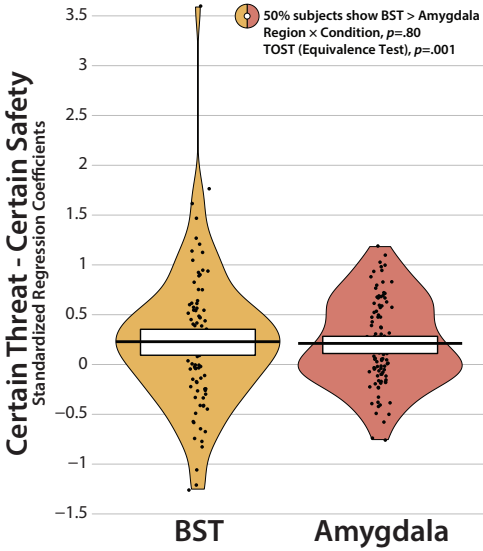

Uncertain Threat > Uncertain Safety
Certain Threat > Certain Safety
Both Contrasts
Midcingulate Cortex
x = 6
Ant. Insula/ FrO
x = -38
dlPFC/ Frontal Pole
y = 40
Brainstem/ PAG
z = -14
L
t
+13
+1
WB FDR q < .05
BST
y = 3
Dorsal Amygdala
y = -5
L
t
+8
+1
WB FDR q < .05
masked to highlight the extended amygdala

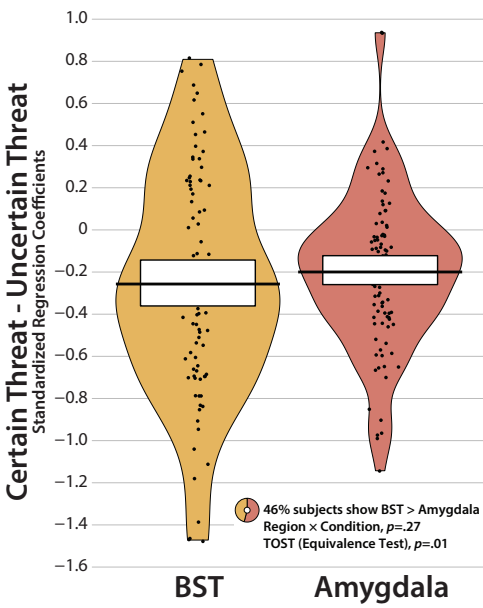

4 x 1.25 s TR
Duration of Certain Countdown
BOLD Signal (a.u.)
Uncertain Threat
Uncertain Safety
Time (s)
0
6.25
12.50
18.75
30.00
Midcingulate Cortex
x = 6, y = 18, z = 36
Ant. Insula/ FrO
x = -32, y = 28, z = 2
dlPFC/ Frontal Pole
x = -32, y = 42, z = 30
PAG
x = 4, y = -32, z = -12
BST
x = -10, y = 4, z = 2
Dorsal Amygdala
x = 26, y = -10, z = -10
L

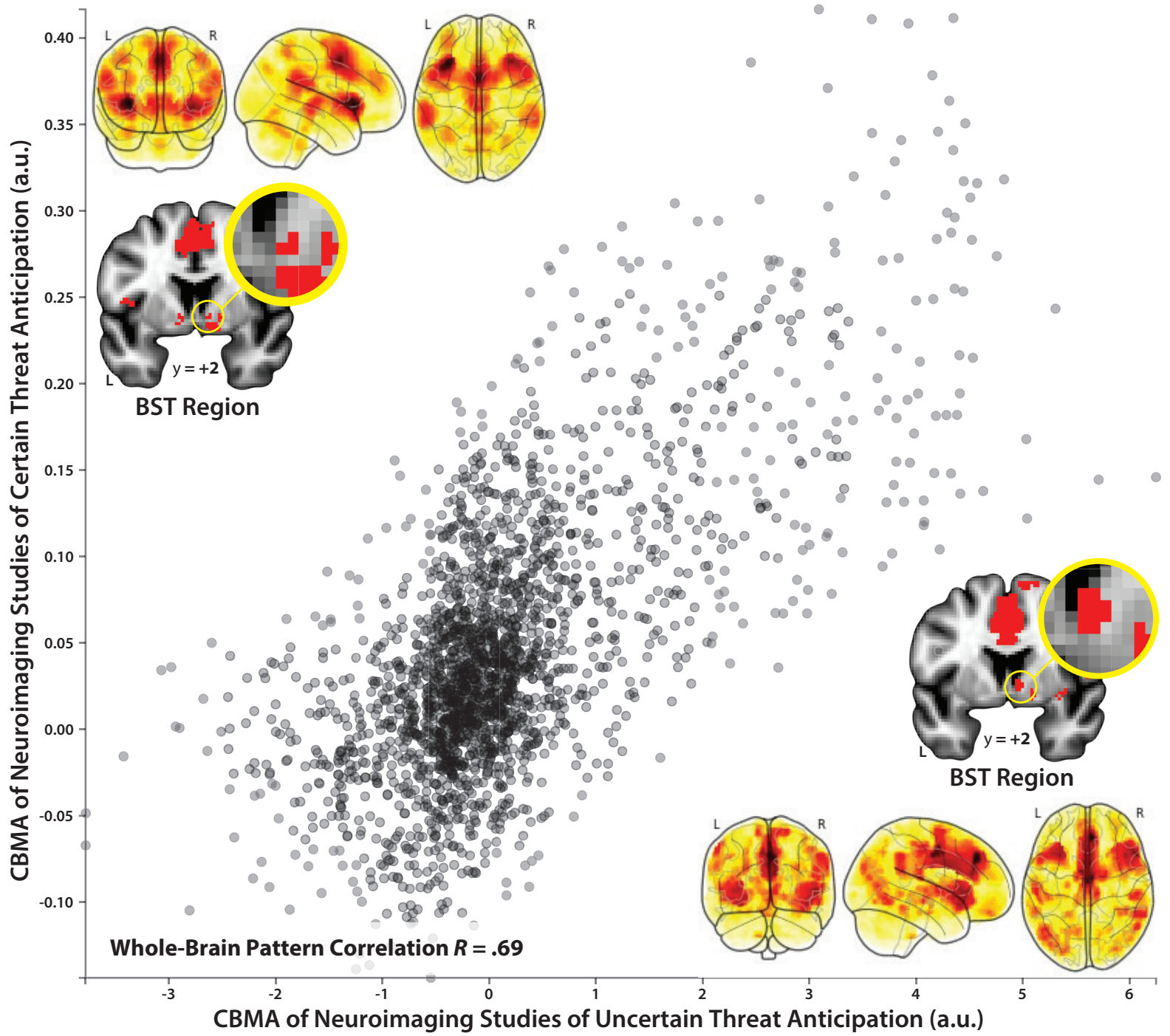

Midcingulate Cortex
x = 6, y = 16, z = 36
BOLD Signal (a.u.)
Certain Threat
Certain Safety
Time (s)
0
6.25
12.50
18.75
Ant. Insula/ FrO
x = -28, y = 22, z = 10
dlPFC/ Frontal Pole
x = -38, y = 36, z = 38
L
PAG
x = -2, y = -34, z = -14
BST
x = -8, y = 2, z = 2
Dorsal Amygdala
x = -14, y = -10, z = -16


Uncertain Threat > Certain Threat
Certain Threat > Uncertain Threat
Uncertain Threat vs. Certain Threat
Midcingulate Cortex
x = 4, y = 2, z = 40
Ant. Insula/ FrO
x = -32, y = 26, z = 0
dlPFC/ Frontal Pole
x = -34, y = 41, z = 28
BST
x = -4, y = 4, z = -2
Dorsal Amygdala
x = -18, y = -10, z = -14
L
BOLD Signal (a.u.)
Time (s)
0
6.25
12.50
18.75
Uncertain Threat
Certain Threat


55% subjects show BST > Amygdala
Region × Condition, p=.11
TOST (Equivalence Test), p=.03
Uncertain Threat - Uncertain Safety
Standardized Regression Coefficients
2.0
1.5
1.0
0.5
0
−0.5
−1.0
BST
Amygdala


50% subjects show BST > Amygdala
Region × Condition, p=.80
TOST (Equivalence Test), p=.001
Certain Threat - Certain Safety
Standardized Regression Coefficients
3.5
3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
BST
Amygdala


46% subjects show BST > Amygdala
Region × Condition, p=.27
TOST (Equivalence Test), p=.01
Certain Threat - Uncertain Threat
Standardized Regression Coefficients
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
BST
Amygdala


CBMA of Neuroimaging Studies of Certain Threat Anticipation (a.u.)
CBMA of Neuroimaging Studies of Uncertain Threat Anticipation (a.u.)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-3
-2
-1
0
1
2
3
4
5
6
L
R
y = +2
BST Region
Whole-Brain Pattern Correlation R = .69