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Functional magnetic resonance imaging of temporally distinct responses to emotional facial expressions

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Abstract

Understanding the temporal dynamics of brain function contributes to models of learning and memory as well as the processing of emotions and habituation. In this article, we present a novel analysis technique to investigate spatiotemporal patterns of activation in response to blocked presentations of emotional stimuli. We modeled three temporal response functions (TRFs), which were maximally sensitive to the onset, early or sustained temporal component of a given block type. This analysis technique was applied to a data set of 29 subjects who underwent functional magnetic resonance imaging while responding to fearful, happy, and sad facial expressions. We identified brain regions that uniquely fit each of the three TRFs for each emotional condition and compared the results to the standard approach, which was based on the canonical hemodynamic response function. We found that voxels within the precuneus fit the onset TRF but did not fit the early or the sustained TRF in all the emotional conditions. On the other hand, voxels within the amygdala fit the sustained TRF, but not the onset or early TRF, during presentation of fearful stimuli, suggesting a spatiotemporal dissociation between these structures. This technique provides researchers with an additional tool in order to investigate the temporal dynamics of neural circuits.

INTRODUCTION

Functional magnetic resonance imaging (fMRI) allows for the characterization of changes in brain function over space and time (Menon & Kim, 1999). Novel methods directed at investigating changes in the temporal dynamics of brain activation are valuable to researchers interested in models of brain function such as adaptation (Krekelberg, Boynton, & van Wezel, 2006), repetition suppression (Grill-Spector, Henson, & Martin, 2006) and sensitization

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(Strauss et al., 2005). The differential time-course of brain activation is also of particular interest to those investigating models of emotion-related brain function (Garrett & Maddock, 2001, 2006; Ishai, Pessoa, Bickle, & Ungerleider, 2004; Phillips et al., 2001; Winston, Henson, Fine-Goulden, & Dolan, 2004).

Previous studies investigating the temporal dynamics of brain activation during emotional tasks have mainly used two approaches. One approach has been applied to event-related designs, and compares the signal obtained during presentations of individual trials (Ishai et al., 2004; Winston et al., 2004). However, most studies to date continue to use blocked designs, which are statistically more powerful (Bandettini & Cox, 2000; Miezin, Maccotta, Ollinger, Petersen, & Buckner, 2000), and which are particularly well suited for emotion studies that seek to generate sustained emotional feeling states. Thus, approaches that analyze temporal dynamics of brain response to blocked stimulus presentations continue to be useful and important.

A second approach has been applied to blocked fMRI designs, and compares early versus late blocks of stimuli (Breiter et al., 1996; Feinstein, Goldin, Stein, Brown, & Paulus, 2002; Phan, Liberzon, Welsh, Britton, & Taylor, 2003; Protopopescu et al., 2005; Strauss et al., 2005; Wright et al., 2001). This approach is well suited to identify brain regions that are activated in the early or late stages of the experiment, but does not reveal any information about short-term temporal dynamics within blocks. Our approach is designed to accomplish this latter goal. Specifically, our approach is designed to identify brain regions that respond to either the onset (and only the onset) of a given block (“onset”), or to only the early (but not late) component of the block (“early”), or that show a sustained pattern of activation throughout the duration of the block (“sustained”).

We applied this approach to an fMRI data set collected during the performance of a gender discrimination task of emotional facial expressions (fearful, happy, sad, and neutral). We then compared these results to those obtained with the canonical hemodynamic response function (HRF; contrasting emotional and neutral blocks). *A priori* regions of interest included those previously reported in emotional face studies (Breiter et al., 1996; Critchley et al., 2000; Lange et al., 2003; Morris et al., 1998; Phillips et al., 2004; Whalen et al., 2001; Winston et al., 2004), including the amygdala (Morris et al., 1998) and fusiform gyrus (Dolan et al., 1996; Pessoa, McKenna, Gutierrez, & Ungerleider, 2002).

Furthermore, we predicted specific temporal response patterns to emotional stimuli in different brain regions, based on studies that identified differential time-courses of signal in visual areas using electrophysiological measures (Braeutigam, Bailey, & Swithenby, 2001; McCarthy, Puce, Belger, & Allison, 1999; Noguchi, Inui, & Kakigi, 2004; Puce, Allison, & McCarthy, 1999) and limbic areas using fMRI (Breiter et al., 1996; Feinstein et al., 2002; Phan et al., 2003; Protopopescu et al., 2005; Strauss et al., 2005; Wright et al., 2001). In particular, we predicted that visual areas such as the occipital and posterior parietal/temporal cortices would exhibit transient temporal patterns of activation, while limbic areas would exhibit more sustained temporal patterns of activation primarily during the negative emotional (fear and sad) facial expression conditions.

METHODS

Modeling and comparison of temporal response functions

Considerable research has characterized the amplitude, latency and width of the blood-oxygen-level dependent (BOLD) response to stimulus presentations. This canonical pattern of signal change has been termed the hemodynamic response function (HRF) (Bellgowan, Saad, & Bandettini, 2003). The HRF is used to predict BOLD signal change in response to stimuli presented in both event-related (Buckner, 2003) and blocked designs (Menon & Kim, 1999)

and has been used to dissociate activation based on temporal characteristics (Henson, Price, Rugg, Turner, & Friston, 2002a; Visscher et al., 2003). Based on this previous research, the temporal response functions utilized in the current analysis technique were characteristic of the properties of the canonical (standard) HRF.

Figure 1 displays the three temporal response functions (TRFs), which were generated by convolving the canonical HRF with three different functions to reflect BOLD signal maximally sensitive to the onset, early or sustained temporal components within a given block of 18 seconds (s) (six stimulus presentations). The onset TRF (oTRF) was modeled to be predictive of signal primarily driven by the presentation of the first trial (one presentation, 3 s) within a given block. In particular, the peak of the oTRF was modeled to occur roughly 6 s following onset of the initial stimulus within a block. This time-course of signal is consistent with event-related research demonstrating that the peak of the HRF occurs roughly 4–8 s following the presentation of a single stimulus (Buckner, 2003; Buckner et al., 1996). The early TRF (eTRF) was modeled to be reflective of signal primarily driven by the early (first half: three presentations, 9 s) component within a given block. The peak of the eTRF was modeled to occur roughly 10 s following the initial stimulus within a block. This was based on previous research identifying peak BOLD signal to occur 8–14 s following the initial presentation of a stimulus presented for a comparable duration (Boynton, Engel, Glover, & Heeger, 1996). The sustained TRF (sTRF) was modeled to be reflective of signal that was consistently active throughout the entire block (six presentations, 18 s). The latency and shape of the sTRF were based on research identifying BOLD signal response to stimuli presented for a similar duration (Boynton et al., 1996).

In order to identify regions that displayed signal change reflective of the temporal components of the functions described above within a given block type, the parameters for each function (oTRF, eTRF and sTRF) were entered separately for each stimulus condition (averaged across block type: fear, happy and sad) within a single model using SPM software (Wellcome Department of Cognitive Neurology, London, UK). Condition-specific signal for each block type was defined as change of BOLD response during a particular emotional condition (fear, happy or sad), relative to a neutral baseline condition (neutral faces). The neutral baseline was held constant (sustained). This analysis therefore identifies voxels that fit a defined temporal function specific to a particular emotional condition (relative to neutral) and not simply to task blocks in general.

Our analysis was aimed at localizing regions whose signal fit a specific TRF to a greater extent relative to the other two TRFs within a given emotional condition block type. Given that each TRF has some level of overlap with each of the other two TRFs (Figure 1) and they are therefore correlated with one another, we used a masking approach in order to isolate which TRF most appropriately fit the time course of activity in a given voxel. Specifically, for any given TRF and contrast condition, we masked all voxels that were significantly activated with either of the other two TRFs. Thus, voxels were only considered to fit a given TRF in each condition if that voxel did not significantly fit any other TRF within that condition.

Subjects

Twenty-nine healthy right-handed subjects (14 females) were recruited. The subjects' mean age was 22.4 years ($SD=2.8$; range: 18–29). The subjects had no history of brain injury, reported no substance abuse within the past 6 months, were not on any mood-altering medication, and had no physical limitations that prohibited them from participating in an fMRI experiment. This study was approved by the Stony Brook University and Yale University Institutional Review Boards.

Experimental design

Subjects were placed into the scanner, while they made gender discriminations of emotional facial expressions. Face stimuli were presented in blocks of fearful, sad, happy and neutral emotional facial expressions. The duration of each trial was 3 s, consisting of a 1-s fixation cross followed by 2 s of stimulus presentation. Trials for each condition were presented in four blocks of 6 trials each (18 s duration) (one run total). The order of block presentation was pseudo-randomized such that within a group of four blocks, each condition was selected once at random and within the entire experiment no condition was repeated. This design should therefore reduce carryover effects by randomizing the probability of a particular condition preceding another condition. Throughout the entire experiment, no trials were repeated (all were novel). Each run began and ended with a 30-s fixation period.

Image acquisition

Whole-brain imaging data were acquired on a 3 T Siemens Trio Scanner. For structural whole-brain images, a three-dimensional high-resolution spoiled gradient scan (SPGR) and a T1 scan (24 slices, 5 mm thickness; oriented parallel to the line between the anterior and posterior commissure) were conducted. Functional images were acquired using a gradient echo T2*-weighted echoplanar imaging (EPI) scan, conducted with a flip angle of 80°, repetition time (TR)=1.5 s, echo time (TE)=30 ms, and a field of view (FOV)=220×220 mm matrix.

Image analysis

Functional data were preprocessed and statistically analyzed using SPM2 (Wellcome Department of Imaging Neuroscience, London, UK). The images were temporally realigned to the middle slice, spatially realigned to the first in the time series, and coregistered to the T1 volume image, which was segmented and normalized to the gray matter template. Spatial transformations derived from normalizing to the segmented gray matter were then applied to all functional volumes, which were spatially smoothed with an 8 mm full width–half maximum isotropic Gaussian filter.

Fixed-effects models were used at the individual subject level of analysis and random effects models were used for group-level analyses (Friston, Jezzard, & Turner, 1994). At the individual level, models were created (general linear model) in order to represent all conditions and TRFs and all data were then high-pass filtered. On an individual level, contrasts were created comparing each TRF for each emotional condition to the neutral face condition, resulting in a total of nine comparisons for each subject (3 emotional conditions×3 TRFs). For comparisons between the onset TRFs and the neutral condition, movement parameters for each direction (x, y and z) were entered in order to control for the head motion that may have occurred during the onset of each block. The TRFs within each emotional condition were then utilized in order to localize regions that uniquely fit these functions. Voxels were considered to uniquely fit a specific TRF for a given emotional condition if they were significant at the $p<.01$ (uncorrected) 20 voxel extent threshold but were not significant (at the same threshold) for any of the other two TRFs within the same emotional condition (whole brain). We used a slightly reduced statistical threshold ($p<.05$ uncorrected; 10 voxel extent) within *a priori* regions of interest (amygdala and fusiform gyrus).

The results obtained via the above outlined procedure were compared to results obtained via the standard approach of fMRI blocked design analysis. Specifically, *t*-contrasts between each emotional condition (fear, happy, sad) and the neutral condition were created on an individual level and random effects models were used for group-level analyses. We used a statistical threshold of $p<.05$ (uncorrected) 20 voxel extent for this analysis.

RESULTS

Spatiotemporal activation in response to fearful facial expressions

Table 1 lists and Figure 2 displays activity that uniquely fit each temporal response function during the processing of fearful relative to neutral facial expressions. A comparison of regions of activation between the temporal response functions reveals that several brain regions implicated in affective attention and facial processing display signal change fitting certain temporal response functions but not others during the fearful facial expression condition. In particular, voxels within the left and right precuneus were found to fit the onset TRF (Montreal Neurological Institute (MNI): -22, -74, 24; 3226 voxels; $t=4.24$, $p<.001$) but not the early or the sustained TRF. Voxels within the left angular gyrus were also found to fit the onset TRF (MNI: -40, -78, 32; 83 voxels; $p<.001$) but not the early or the sustained TRF. Voxels within the right rostral anterior cingulate were found to fit the early TRF (MNI: 10, 24, -8; 225 voxels; $t=3.87$, $p<.001$) but not the onset or the sustained TRF. Voxels within the right amygdala were found to fit the sustained TRF (MNI: 28, -6, -14; 12 voxels; $t=2.36$, $p=.013$) but not the onset or the early TRF. Figure 3 plots data from two loci identified in this analysis: right precuneus and right fusiform gyrus. As can be seen, the signal in the right precuneus exhibits a pattern of activity reflective of the oTRF and the signal in the right fusiform gyrus exhibits a pattern of activity reflective of the sTRF.

Spatiotemporal activation in response to happy facial expressions

Table 2 lists and Figure 4 displays activity that uniquely fit each temporal response function during the processing of happy relative to neutral facial expressions. Several brain regions implicated in affective attention and facial processing contained voxels that fit certain temporal response functions but not others during the happy facial expression condition. In particular, voxels within the right precuneus were found to fit the onset TRF (MNI: 22, -76, 24; 387 voxels; $t=4.12$, $p<.001$) but not the early or the sustained TRF. Voxels within the left insula were also found to fit the onset TRF (MNI: -42, -22, -4; 72 voxels, $t=3.60$, $p<.001$) but not the early or the sustained TRF. Voxels within the right medial frontal gyrus were found to fit the early TRF (MNI: 10, 18, 54; 703 voxels; $t=5.70$, $p<.001$) but not the onset or the sustained TRF. Voxels within the left and right inferior parietal lobule were found to fit the sustained TRF (left: MNI: -40, -28, 36; 53 voxels; $t=3.25$, $p=.002$; right: MNI: 52, -40, 36; 81 voxels; $t=3.01$, $p=.003$) but not the onset or the early TRF. Voxels within the left fusiform were also found to fit the sustained TRF (MNI: -24, -44 -14; 22 voxels; $t=2.48$, $p=.010$) but not the onset or the early TRF.

Spatiotemporal activation in response to sad facial expressions

Table 3 lists and Figure 5 displays activity that uniquely fit each temporal response function during the processing of sad relative to neutral facial expressions. Again, several brain regions implicated in affective attention and facial processing contained voxels that fit certain temporal response functions but not others during the sad facial expression condition. In particular, voxels within the right precuneus were found to fit the onset TRF (MNI: 6, -46, 48; 7168 voxels; $t=7.03$, $p<.001$) but not the early or the sustained TRF. Voxels within the right rostral anterior cingulate were also found to fit the onset TRF (MNI: 10, 40, -6; 91 voxels; $t=6.65$, $p=.001$) but not the early or the sustained TRF. Voxels within the left and right fusiform gyrus were found to fit the early TRF (left, MNI: -22, -44, -12; 61 voxels; $t=2.98$, $p=.003$; right, MNI: 30, -42, -10; 27 voxels; $t=2.57$, $p=.008$) but not the onset or the sustained TRF. Voxels within the right inferior frontal gyrus were found to fit the sustained TRF (MNI: 54, 32, 0; 40 voxels; $t=3.22$, $p=.002$) but not the onset or the early TRF.

Activation revealed by the standard approach of blocked design analysis

Table 4 lists activation revealed with the standard HRF. This method revealed several clusters previously identified to display increased signal change during emotional (fear, happy and sad), relative to neutral, facial expressions. In particular, voxels within the right amygdala were identified to display greater activation during the fearful, relative to the neutral, facial expression condition (MNI: 28, -12, -16; 83 voxels; $t=3.32$; $p=.001$). Voxels within the left fusiform gyrus were identified to display greater activation during the fearful (MNI: -40, -54, -24; 374 voxels; $t=3.36$; $p=.001$) and the sad (MNI: -44, -48, -12; 31 voxels; $t=3.13$; $p=.002$), relative to the neutral facial expression condition. This approach also identified that voxels within the right middle temporal gyrus displayed greater activation during each of the emotional (fear, happy and sad), relative to the neutral, facial expression conditions (fear, MNI: 42, -46, -14; 2453 voxels; $t=5.10$; $p<.001$; happy, MNI: 50, -36, 10; 108 voxels; $t=2.56$; $p=.008$; sad, MNI: 54, -42, 4; 839 voxels; $t=3.77$; $p<.001$).

DISCUSSION

In this article, we have introduced a technique that spatially dissociates brain regions based on differential temporal responses to blocks of emotional stimuli. By applying this method to an fMRI data set of blocked presentations, we have identified unique sets of brain structures that are primarily responsive to the onset, early or sustained temporal components of blocks of fearful, happy and sad facial expressions. The use of this technique may be of particular interest to researchers investigating brain function in relation to models of sensitization or habituation/adaptation.

A comparison of the results obtained utilizing the temporal response functions to those obtained with the standard HRF here, or by others (Breiter et al., 1996; Critchley et al., 2000; Killgore & Yurgelun-Todd, 2004; Lange et al., 2003; Morris et al., 1998; Phillips et al., 2004; Whalen et al., 2001), demonstrates that this technique may provide additional temporal resolution of fMRI data sets. For example, recent meta-analyses have reported variability between studies of emotional processing (Costafreda, Brammer, David, & Fu, in press; Phan, Wager, Taylor, & Liberzon, 2004). Our data suggest that these inconsistent findings may be in part due to the fact that these studies have utilized experimental designs with different block lengths. The results provided here demonstrate that separate neural networks are engaged depending on the temporal specificity in which emotional stimuli are presented. The function of these networks may correspond to psychological mechanisms such as encoding and the maintenance of this information on line.

Other studies have investigated changes in relatively short time-courses of activation in response to a wide variety of tasks using different methods (Chen & Desmond, 2005; Henson, Price et al., 2002; Henson, Shallice, Gorno-Tempini, & Dolan, 2002b; Ishai et al., 2004; Seifritz et al., 2002). For example, Seifritz et al. (2002) used an elegant blind data-driven independent component analysis (ICA) in order to characterize the temporal response of the auditory cortex to sounds, and Henson et al. (2002a) developed a novel whole brain analysis technique for event-related studies that identifies voxels that display latency differences relative to the canonical HRF. Future work could directly compare divergent and convergent results obtained from these techniques to yield a more complete picture of brain temporal dynamics.

We found that the pattern of precuneus activity fit the onset temporal response function during all the emotional conditions but not the early or sustained functions. The precuneus has been implicated in memory processes (Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Lundstrom, Ingvar, & Petersson, 2005) and visuo-spatial imagery (Cavanna & Trimble, 2006). The fact that we observed precuneus activity to be greatest during the beginning of each block may suggest that this structure is engaged in attributing greater salience to these initial visually

presented stimuli compared to those stimuli presented later. Behaviorally, this may correspond to greater retention of the “onset” presented stimuli (primacy effect) relative to those presented later (Hay, Smyth, Hitch, & Horton, 2007).

The fusiform gyrus exhibited activity that fit all of the TRFs during the fearful condition, only the early TRF during the sad condition and only the sustained TRF during the happy condition. The fact that we observed fusiform activation regardless of emotional valence is consistent with prior work (Dolan et al., 1996; Pessoa, McKenna, Gutierrez, & Ungerleider, 2002). However, we now show that in the *temporal domain*, the fusiform gyrus *does* discriminate between facial expressions of differing valence. This is a clear illustration that obtaining information about temporal characteristics of brain regions can reveal processes that were previously unknown. The challenge for future work is to develop models that take this temporal information into account to predict brain dynamics or explain existing patterns of brain dynamics.

The signal obtained from the right amygdala fit the sustained TRF during the fearful condition but not any of the other TRFs, nor did the signal significantly fit any of the other TRFs during any of the other emotional conditions. On the one hand, this finding is consistent with the view that the amygdala is particularly engaged in response to fear-inducing conditions in the environment (Whalen, 1998) and is consistently activated by exposure to fearful facial expressions (Johnstone et al., 2005). On the other hand, our observation of sustained amygdala activation contradicts other accounts that reported rapid habituation of the amygdala, such as those that compared amygdala activation to fearful stimuli during early versus late blocks (Breiter et al., 1996; Wright et al., 2001). These inconsistencies likely reflect methodological differences in the temporal and stimulus parameters. With respect to temporal parameters, both other studies used much longer time blocks and longer experimental runs than we did. For example, blocks in the study by Breiter et al (1996) lasted 36 s and were interspersed with 4-min rest periods. Block duration in the study by Wright et al. (2001) was 80 s. To determine whether a similar comparison of early-versus-late blocks would replicate their results, we conducted such an analysis but failed to see any evidence for amygdala habituation. It is therefore possible that the amygdala does not exhibit habituation when shorter (18-s) blocks and experimental runs are used. A second possibility as to why we did not replicate the observations by Breiter et al. (1996) and Wright et al. (2001) may be the choice of stimulus parameters. Both other studies used repeated presentations of face stimuli, which may have exacerbated the likelihood of amygdala habituation. In contrast, our study did not repeat face presentations, which may have minimized the likelihood of amygdala habituation. The parameters that enhance or reduce amygdala habituation remain to be fully elucidated.

Differences in the temporal dynamics of BOLD response may be a neural marker of habituation (adaptation) (Grill-Spector, Henson, & Martin, 2006; Winston et al., 2004). For example, the structures that fit the onset TRF and not the early or the sustained TRF may be habituating more quickly relative to structures found to fit the sustained TRF. Differences in habituation are thought to moderate several psychological processes such as rumination (Siegle, Steinhauer, Thase, Stenger, & Carter, 2002) and novelty seeking (Martindale, Anderson, Moore, & West, 1996). One prediction derived from the evidence presented here is that those who have a high affinity towards novel experiences may exhibit greater onset activation compared to those who have a lower affinity towards novelty. Clearly, studying the temporal dynamics of brain function during emotional processing may provide insights to how people differ in social and affective tendencies.

The technique presented here is limited to several constraints defined by the experimental design as well as the analysis procedure itself. The fMRI data set used in the current analysis consisted of blocks of only one particular length (six presentations; 18 s). It would be of

particular interest to utilize this analysis technique on a data set with longer block durations and of varying length. This type of analysis may clarify some of the time-course characteristics of amygdala and fusiform function previously discussed. We also did not directly statistically compare TRFs to one another within the same emotional condition. This approach was not utilized due to the relatively high correlation between each of the TRFs. We instead used a masking and threshold approach where activations were only considered significant if they were responsive to one TRF but not to either of the other two. In addition, our analysis technique was constrained to only three different temporal response functions (onset, early and sustained), which were assumed to be linearly related to one another. Studies have shown that the HRF to single events may peak from 2 to 8 s and is variable across people (Aguirre, Zarahn, & D'Esposito, 1998). Certain theoretical models of brain function may predict that activation occurs later versus earlier in a block of stimuli and would therefore use TRFs modeled to be particularly reflective of sensitivity to late versus early trials within a block.

In conclusion, we have presented a technique for blocked-design fMRI studies that localizes brain regions by their temporal activation characteristics. We applied this technique to an existing data set collected during the processing of emotional facial expressions and demonstrated that regions previously implicated in affective attention and facial processing displayed unique and dissociable time-courses of activation during blocks of emotional stimuli, as in the case of the precuneus and the amygdala. We also showed that temporal information can yield novel insights into brain processes of emotion. Most notably, we replicated earlier reports that the fusiform gyrus activates to various emotional facial expressions, as measured with the canonical HRF. However, we then showed that the fusiform gyrus does discriminate emotional facial expressions when temporal dynamics of its activation are taken into account. Current models of brain emotional processing need to be updated to incorporate this kind of temporal information. The technique we introduced here will be useful in generating new data for temporal models of brain affective processing and hopefully in testing future predictions generated by these models.

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Figure 1.

Temporal response functions (TRFs) fitted to represent sensitivity to the onset, early or sustained temporal components within a block of stimuli. The oTRF was modeled to reflect activation driven by the first presentation within a block. The eTRF was modeled to reflect activation driven by the first half of presentations within a block. The sTRF was modeled in order to reflect activation driven by all of the presentations throughout a block.

Figure 2.

Spatiotemporal activation in response to fearful facial expressions. Voxels significantly fitting each TRF are overlaid on axial slices of a template brain taken every eight slices from $z=-8$ to 56. Voxels that significantly fit the oTRF, eTRF, and sTRF are displayed in red, yellow, and green, respectively.

Figure 3.

Extracted averaged time-course from two regions of interest, the right precuneus (A) and the right fusiform gyrus (B), during the fearful face condition. (A) Signal obtained from the right precuneus (MNI: 10, -22, 46) identified to fit the oTRF during the fearful face condition. Data are plotted with the *x*-axis representing scan number (throughout averaged blocks) and *y*-axis representing percentage signal change relative to neutral. (B) Signal obtained from the right fusiform gyrus (MNI: 42, -48, -20) identified to fit the sTRF during the fearful face condition. Data are plotted with the *x*-axis representing scan number (throughout averaged blocks) and *y*-axis representing percentage signal change relative to neutral. Error bars represent standard error from the mean.

Figure 4.

Spatiotemporal activation in response to happy facial expressions. Voxels significantly fitting each TRF are overlaid on axial slices of a template brain taken every 8 mm from $z=-8$ to 56. Voxels that significantly fit the oTRF, eTRF, and sTRF are displayed in red, yellow, and green, respectively.

Figure 5.

Spatiotemporal activation in response to sad facial expressions. Voxels significantly fitting each TRF are overlaid on axial slices of a template brain taken every 8 mm from $z=-8$ to 56. Voxels that significantly fit the oTRF, eTRF, and sTRF are displayed in red, yellow, and green, respectively.

TABLE 1

Spatiotemporal activation in response to fearful facial expressions

Condition and loci	Cluster sizeT score	MNI coordinates			
		p value	x	y	z
Fear: oTRF (Red)					
L/R. Medial frontal and precuneus	34425.12	<.001	10	-22	46
L/R. Precuneus and cuneus	32264.24	<.001	-22	-74	24
R. Superior temporal gyrus	11234.82	<.001	38	-34	16
L. Angular gyrus	834.57	<.001	-40	-78	32
L. Superior temporal gyrus	7354.38	<.001	-42	-28	4
R. Insula	2154.13	<.001	48	-8	-20
L. Inferior parietal lobule	434	<.001	-64	-30	36
R. Precentral gyrus	1253.93	<.001	58	-2	10
R. Thalamus	1443.85	<.001	18	-24	6
L. Thalamus	473.61	.001	-16	-32	8
R. Middle temporal gyrus	623.55	.001	46	-70	28
L. Inferior frontal gyrus	283.4	.001	-38	30	8
L. Middle temporal gyrus	303.1	.002	-36	-62	18
L. Fusiform	903.25	.001	-30	-46	-12
R. Fusiform	452.29	.015	20	-36	-16
Fear: eTRF (yellow)					
R. Posterior cingulated	6574.73	<.001	12	-56	26
R. Insula	1863.92	<.001	38	-14	2 R.
Rostral anterior cingulated	2253.87	<.001	10	24	-8
L. Middle occipital gyrus	1113.8	<.001	-16	-92	14
R. Lingual gyrus	383.5	.001	10	-76	-2
R. Cuneus	1033.45	.001	18	-80	22
R. Precentral gyrus	673.38	.001	20	-28	72
R. Precentral gyrus	1393.34	.001	54	-8	6
L. Lingual gyrus	483.17	.002	-12	-78	-4
R. Insula	273.05	.002	42	-6	-10
L. Superior occipital gyrus	492.99	.003	-36	-82	28
L. Fusiform	162.42	.011	-30	-54	-4
Fear: sTRF (green)					
R. Middle occipital gyrus	1914.43	<.001	26	-96	4
R. Fusiform	603.74	<.001	42	-48	-20
R. Middle temporal gyrus	803.56	<.001	52	-10	-14
L. Middle occipital gyrus	493.44	.001	-28	-90	2
R. Inferior frontal gyrus	383.17	.002	52	34	4
R. Superior temporal gyrus	703	.003	50	-42	10
R. Amygdala	122.36	.013	28	-6	-14
R. Fusiform	462.52	.001	38	-34	-20

Note: L, left; R, right; x, y, and z coordinates, T score, and p value apply to the most significant voxel within each cluster.

TABLE 2

Spatiotemporal activation in response to happy facial expressions

Condition and loci	Cluster sizeT score	p value	MNI coordinates		
			x	y	z
Happy: oTRF (red)					
R. Precentral gyrus	2604.34	<.001	20	-30	72
R. Precuneus	3874.12	<.001	22	-76	24
R. Superior temporal gyrus	1333.98	<.001	60	-24	-2
L. Insula	723.6	.001	-42	-22	-4
L. Cuneus	1563.53	.001	-10	-76	30
R. Superior temporal gyrus	373.46	.001	52	-10	10
R. Middle cingulate gyrus	943.39	.001	4	-26	48
R. Precuneus	253.19	.002	10	-62	68
Happy: eTRF (yellow)					
R. Medial frontal gyrus	7035.7	<.001	10	-18	54
L. Cuneus	9434.88	<.001	-18	-86	28
L. Lingual gyrus	2424.8	<.001	-14	-74	-4
R. Cuneus	6984.46	<.001	10	-78	30
R. Rostral anterior cingulate	2984.29	<.001	14	22	-8
R. Cuneus	1583.35	.001	10	-74	6
L. Superior temporal gyrus	333.31	.001	-52	-12	-4
R. Precentral gyrus	1853.28	.001	54	-10	14
L. Superior temporal gyrus	243.22	.002	-46	-16	-2
L. Parahippocampal gyrus	303.15	.002	-26	-46	-6
R. Precentral gyrus	333.11	.002	40	-16	40
Happy: sTRF (green)					
L. Inferior parietal lobule	533.25	.002	-40	-28	36
R. Inferior parietal lobule	813.01	.003	52	-40	36
L. Fusiform	222.48	.01	-24	-44	-14

Note: L, left; R, right; x, y, and z coordinates, T score, and p value apply to the most significant voxel within each cluster.

TABLE 3

Spatiotemporal activation in response to sad facial expressions

Condition and locus	Cluster size	T score	p value	MINI coordinates		
				x	y	z
<i>Sad: oTRF (red)</i>						
R/L. Precuneus	7168	7.03	<.001	6	-46	48
L. Lingual gyrus	540	5.22	<.001	-10	-74	-4
R. Superior frontal gyrus	80	4.51	<.001	22	58	6
L. Middle cingulate gyrus	22	3.83	<.001	-10	-14	36
R. Rostral anterior cingulate	91	3.65	.001	10	40	-6
L. Inferior parietal lobule	58	3.47	.001	-34	-32	34
R. Inferior parietal lobule	66	3.39	.001	44	-40	28
L. Postcentral gyrus	48	3.37	.001	-24	-32	64
R. Insula	33	3.21	.002	40	-18	-8
L. Insula	23	2.84	.004	-38	-18	-2
<i>Sad: eTRF (yellow)</i>						
R. Superior temporal gyrus	323	5.13	<.001	34	-36	12
R. Cuneus	92	4.06	<.001	20	-76	32
L. Angular gyrus	111	3.69	<.001	-38	-80	32
L. Parahippocampal gyrus	29	3.22	.002	-22	-44	-10
L. Fusiform	61	2.98	.003	-22	-44	-12
R. Fusiform	27	2.57	.008	30	-42	-10
<i>Sad: sTRF (green)</i>						
R. Middle temporal gyrus	855	4.02	<.001	48	-12	-14
R. Inferior frontal gyrus	40	3.22	.002	54	32	0

Note: L, left; R, right; x, y, and z coordinates, T score, and p value apply to the most significant voxel within each cluster.

TABLE 4

Activation in response to emotional facial expressions (standard approach)

Condition and locus	Cluster sizeT score	p value	MNI Coordinates		
			x	y	z
<i>Fear-Neu</i>					
R. Middle temporal gyrus, extend into R. Fusiform	24535.1	<.001	42	-46	-14
L. Middle occipital gyrus	4024.55	<.001	-28	-90	2
L. Fusiform	3743.36	.001	-40	-54	-24
R. Hippocampus, extend into R. Amygdala	833.32	.001	28	-12	-16
R. Inferior frontal gyrus	1622.94	.003	50	30	8
<i>Happy-Neu</i>					
L. Postcentral, extend into L. Inferior parietal lobule	5203.33	.001	-36	-26	42
R. Superior temporal gyrus	1283.32	.001	36	-34	10
R. Middle frontal gyrus	233.08	.002	40	42	28
R. Middle cingulate cortex	1512.94	.003	8	-24	42
R. Inferior frontal cortex	1152.86	.004	54	26	-2
R. Anterior cingulate	1822.63	.007	12	10	34
L. Hippocampus	702.6	.007	-24	-26	-6
R. Middle temporal gyrus	1082.56	.008	50	-36	10
R. Precuneus	2982.53	.009	12	-72	42
L. Inferior frontal gyrus	1012.43	.011	-48	20	-4
R/L. Medial frontal gyrus	3682.41	.011	0	-4	58
R. Middle frontal gyrus	262.31	.014	40	26	44
L. Lingual gyrus	472.31	.014	-8	-70	-4
L. Middle occipital gyrus	212.2	.018	-28	-92	0
R. Middle frontal gyrus	232.01	.027	40	-2	54
<i>Sad-Neu</i>					
R. Middle temporal gyrus	8393.77	<.001	54	-42	4
R. Middle frontal gyrus	653.65	.001	38	24	48
R. Cuneus	3503.55	.001	6	-70	26
L. Inferior parietal extend into L. Postcentral gyrus	23183.2	.002	-34	-4	48
R. Inferior frontal gyrus	1083.15	.002	56	22	28
L. Fusiform	313.13	.002	-44	-48	-12
R. Supplementary motor area	1233.11	.002	8	-20	54
L. Lingual gyrus	483.04	.003	-10	-68	-4
R. Superior temporal gyrus	762.5	.009	36	-34	12
L. Precentral gyrus	1012.5	.009	-36	-2	26
R. Superior parietal lobule	1372.48	.01	32	-64	44
L. Cuneus	1602.46	.01	-22	-82	42
L. Middle temporal gyrus	322.41	.011	-50	-52	6
R. Middle frontal gyrus	972.38	.012	40	0	54
R. Postcentral gyrus	462.17	.019	26	-40	62
L. Precuneus	211.98	.028	-6	-76	40
L. Medial frontal gyrus	301.94	.031	-4	-4	54

Note: L, left; R, right; x, y, and z coordinates, T score, and p value apply to the most significant voxel within each cluster.