Decision ambiguity is mediated by a late positive potential originating from cingulate cortex

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ABSTRACT

People often make decisions in the face of ambiguous information, but it remains unclear how ambiguity is represented in the brain. We used three types of ambiguous stimuli and combined EEG and fMRI to examine the neural representation of perceptual decisions under ambiguity. We identified a late positive potential, the LPP, which differentiated levels of ambiguity, and which was specifically associated with behavioral judgments about choices that were ambiguous, rather than passive perception of ambiguous stimuli. Mediation analyses together with two further control experiments confirmed that the LPP was generated only when decisions are made (not during mere perception of ambiguous stimuli), and only when those decisions involved choices on a dimension that is ambiguous. A further control experiment showed that a stronger LPP arose in the presence of ambiguous stimuli compared to when only unambiguous stimuli were present. Source modeling suggested that the LPP originated from multiple loci in cingulate cortex, a finding we further confirmed using fMRI and fMRI-guided ERP source prediction. Taken together, our findings argue for a role of an LPP originating from cingulate cortex in encoding decisions based on task-relevant perceptual ambiguity, a process that may in turn influence confidence judgment, response conflict, and error correction.

Introduction

We are frequently bombarded by sensory information whose relevance to a behavioral choice is ambiguous, and we often have to make decisions when choice options have uncertain outcomes. A distributed network of brain areas is implicated in decision making under ambiguity and risk (Krain et al., 2006). In particular, the prefrontal cortex, striatum, anterior insula, and amygdala have been implicated in ambiguous monetary gambles (Hsu et al., 2005; Huettel et al., 2006; Levy et al., 2010) and the inferior frontal gyrus (IFG) and posterior parietal cortex are associated with ambiguous outcome anticipation (Bach et al., 2009). In goal-directed navigation and reinforcement learning, medial prefrontal cortex and basal ganglia are involved in resolving ambiguity (Yoshida and Ishii, 2006), whereas

lesions of the orbitofrontal cortex impair decisions under ambiguity and risk (Hsu et al., 2005). While many of these studies have focused on value-based decisions, and have separately studied risk and ambiguity, we here investigated perceptual decisions when the mapping of stimulus category to choice was ambiguous.

In the perceptual domain, unpredictability of stimuli, even without any motivational information, activates the amygdala in both mice and humans (Herry et al., 2007). One highly salient stimulus category encountered in everyday life that features pronounced ambiguity are facial expressions of emotions, which are frequently confused with one another (Young et al., 1997). A recent study has shown that single neurons in the human amygdala signal levels of emotion ambiguity (Wang et al., 2017). However, these prior studies leave unclear exactly what is represented in the brain, and at what point in processing

ambiguity arises. A larger literature has focused on a scalp-evoked late positive potential (LPP, beginning about 400 ms after stimulus onset) that is sensitive to ambiguous facial expressions (Calvo et al., 2013) as well as to racially ambiguous faces (Willadsen-Jensen and Ito, 2006). The LPP is also involved in evaluating socially relevant concepts (Cunningham et al., 2005), processing affective pictures (Cuthbert et al., 2000; Schupp et al., 2000; Leite et al., 2012), and coding stimulus uncertainty (Sutton et al., 1965a). Given the LPP's role in coding faces, emotion, uncertainty, and combinations of these attributes, we here directly tested how the LPP responds to ambiguous emotional faces, and importantly, which specific attribute the LPP encodes. Furthermore, the LPP is not only associated with accumulating sensory information but also determining choices (O'Connell et al., 2012; Kelly and O'Connell, 2013; Murphy et al., 2015), two aspects that we aimed to further tease apart in the present study with a series of control experiments. Finally, we also investigated how the LPP emerges and unfolds in time, providing mechanistic insight of how the LPP encodes perceptual ambiguity.

Source estimation in prior studies has suggested that the LPP arises from a distributed brain network, including the anterior cingulate cortex (ACC), posterior cingulate cortex (PCC), and insula (Liu et al., 2012; Peng et al., 2012; Yoder and Decety, 2014). On the one hand, the dorsal ACC (dACC) is thought to play a role in cognitive control, including the detection of performance errors and the monitoring of conflict (Cole et al., 2009; Alexander and Brown, 2010; Shackman et al., 2011; Sheth et al., 2012; Shenhav et al., 2013), reward-based decision making and learning more generally (Kennerley et al., 2006), and representation of both social and physical pain (Lieberman and Eisenberger, 2005). On the other hand, the ventral ACC (vACC) is involved in fear extinction (Etkin et al., 2011) and emotion regulation (Etkin et al., 2015). Across many decision-making paradigms and stimulus modalities, greater vACC activation is associated with the choice with greater positive value (Rushworth and Behrens, 2008; Bartra et al., 2013). In particular, vACC activation reflects both value comparison and confidence in the value comparison process (De Martino et al., 2013), even if no explicit confidence judgment is required of the participants (Lebreton et al., 2015). While there are functional segregations within the ACC (see (Shackman et al., 2011; Etkin et al., 2015) for details) and a single unifying principle that might encompass the function of the entire ACC remains elusive, most of the above functions involve the processing of ambiguity in some form. Ambiguity inherently involves conflict in how sensory information maps onto categories or choices, requires continuous monitoring of ongoing actions, triggers dynamic adjustments in cognitive control, and inversely correlates with confidence in judgment. Prior research has shown that ambiguous decision making is associated with activity in both dACC and vACC (Krain et al., 2006). Ambiguous emotional faces relative to unambiguous emotional faces activate the dACC, whereas ambiguous affective decisions relative to ambiguous gender decisions activate the vACC (Simmons et al., 2006). We therefore hypothesized that the ACC is involved in processing faces with ambiguous emotions, and we here used a combination of source localization together with fMRI in order to help further constrain the putative generators of the LPP within the ACC.

In this study, we found that the LPP encodes levels of perceptual ambiguity. In order to characterize the nature of the LPP and elaborate its role in coding ambiguity, we used a combination of EEG and fMRI, and found that the LPP was strongly associated with choices made about ambiguous stimuli, but not mere perception of ambiguous stimuli. This relationship was formally captured by a statistical mediation model, and two additional experiments directly manipulating whether decisions were made, and whether decisions were about ambiguity, confirmed the specificity of the LPP in coding ambiguity. We also found that a stronger LPP emerged in the context of ambiguous stimuli, but diminished in the context of unambiguous stimuli. The LPP was localized to the vACC, PCC, and insula, and fMRI

and fMRI-guided ERP source prediction confirmed these regions. Together, our results reveal a neural signature from a specific network of brain regions that encodes the ambiguity with which stimuli can be classified into categorical decisions.

Materials and methods

Subjects

In the main task (face judgment task with fear-happy morphed emotions), 23 subjects (17 female, mean age and SD, 22.4 ± 2.17 years) participated in the electroencephalogram (EEG) experiment, 19 subjects (15 female, 20.9 ± 2.02 years) participated in the functional magnetic resonance imaging (fMRI) experiment, and 24 subjects (16 female, 22.3 ± 3.39 years) participated in the behavioral experiment with confidence ratings. Furthermore, 18 subjects (13 female, 19.8 ± 1.20 years) participated in the EEG control experiment with speeded response, 15 subjects (9 female, 20.7 ± 1.61 years) participated in the EEG control experiment of behavioral response, and 32 subjects (15 female, 20.6 ± 1.79 years) participated in the EEG control experiment of ambiguity context. All subjects were unique and involved in only one separated experiment. All subjects provided written informed consent according to protocols approved by the institutional review board of the South China Normal University.

Stimuli and task

In the face judgment task with fear-happy morphed emotions, stimuli were morphed expression continua between exemplars of fearful and happy expressions. Four individuals (two female) were chosen from the STOIC database (Roy et al., 2007), a database of face images expressing highly recognizable emotions. For each individual we selected unambiguous exemplars of fearful and happy expressions as evaluated with normative rating data provided by the database creators. To generate the morphed expression continua for this experiment, we interpolated pixel value and location between fearful exemplar faces and happy exemplar faces using a piece-wise cubic-spline transformation over a Delaunay tessellation of manually selected control points. We created 5 levels of fear-happy morphs, ranging from 30% fear/70% happy to 70% fear/30% happy in steps of 10% (Fig. 1B). Low-level image properties were equalized by the SHINE toolbox (Willenbockel et al., 2010) (The toolbox features functions for specifying the (rotational average of the) Fourier amplitude spectra, for normalizing and scaling mean luminance and contrast, and for exact histogram specification optimized for perceptual visual quality).

In each trial, a face was presented for 1 s followed by a question prompt asking subjects to make the best guess of the facial emotion. Subjects reported faces as fearful or happy by pressing a button on the keyboard (behavioral and EEG subjects) or response box (fMRI subjects) with either their left or right index fingers. After stimulus offset, subjects had 2 s to respond, otherwise the trial was aborted and discarded. Subjects were instructed to respond as quickly as possible, but only after stimulus offset. No feedback message was displayed and the order of faces was completely randomized for each subject. An inter-trial-interval (ITI) was jittered randomly with a uniform distribution between 1 and 2 s for behavioral and EEG subjects and 2–8 s for fMRI subjects. Behavioral subjects performed 252 trials in 3 blocks, EEG subjects performed 252 trials in 2 blocks, and fMRI subjects performed 168 trials in 2 blocks. All trials were pooled for analysis. In each block, there were equal numbers of trials for each morph level and each identity.

Behavioral subjects also performed a confidence rating. After emotion judgment and a 500 ms blank screen, subjects were asked to indicate their confidence of judgment, by pushing the button '1' for 'very sure', '2' for 'sure' or '3' for 'unsure'. As with the emotion judgment, subjects had 2 s to respond before the trial was aborted,