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THE ACTIVITY IN THE ANTERIOR INSULAE IS MODULATED BY PERCEPTUAL DECISION-MAKING DIFFICULTY

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Abstract—Previous neuroimaging studies provide evidence for the involvement of the anterior insulae (INSs) in perceptual decision-making processes. However, how the insular cortex is involved in integration of degraded sensory information to create a conscious percept of environment and to drive our behaviors still remains a mystery. In this study, using functional magnetic resonance imaging (fMRI) and four different perceptual categorization tasks in visual and audio-visual domains, we measured blood oxygen level dependent (BOLD) signals and examined the roles of INSs in easy and difficult perceptual decision-making. We created a varying degree of degraded stimuli by manipulating the task-specific stimuli in these four experiments to examine the effects of task difficulty on insular cortex response. We hypothesized that significantly higher BOLD response would be associated with the ambiguity of the sensory information and decision-making difficulty. In all of our experimental tasks, we found the INS activity consistently increased with task difficulty and participants' behavioral performance changed with the ambiguity of the presented sensory information. These findings support the hypothesis that the anterior insulae are involved in sensory-guided, goal-directed behaviors and their activities can predict perceptual load and task difficulty.

Key words: functional magnetic resonance imaging, task difficulty, response time, salience network.

INTRODUCTION

The anterior insulae (INSs) have widespread efferent and afferent projections and functional connection with a large-scale network of sensorimotor, affective, and cognitive regions (Mesulam and Mufson, 1982a,b; Deen et al., 2011; Cauda et al., 2012; Touroutoglou et al., 2012; Chang et al., 2013; Uddin et al., 2014). The INSs, along with other brain areas, have been shown to be involved in various cognitive processes (Heekeren et al., 2004; Rushworth et al., 2004; Ho et al., 2009; Venkatraman et al., 2009; Menon and Uddin, 2010; Wiech et al., 2010; Woolgar et al., 2011; Krebs et al., 2012; Srinivasan et al., 2013), yet, their role in perceptual decision-making (PDM) still remains to be understood. Insular cortex has been traditionally considered as a limbic structure (Mesulam and Mufson, 1982b; Augustine, 1996) and was found active across a wide variety of paradigms involving the subjective awareness of feelings, including studies of anger, disgust, judgments of trustworthiness, sexual arousal, subjective feelings of empathy (Craig, 2003, 2009). However, this area may not be restricted to these roles. In our current work, we challenge this notion by examining the role of INSs in PDM using an experimental paradigm that uses decision-making on two facial expressions with clear and noisy images. We hypothesize that if the insular activation is the function of perceived emotional expression, clear picture types should activate it more as the affective salience is clearly visible in clear pictures compared to noisy pictures.

Furthermore, INS activities were reported while facing uncertainty and risk in various perceptual and reward based experimental tasks (Ernst and Paulus, 2005; Preuschoff et al., 2008; Singer et al., 2009; Gu et al., 2010; Lamm and Singer, 2010). Insular cortices have been suggested to participate in attentional control in such tasks because more activation was observed on cognitively demanding tasks compared to easy tasks (Philiastides and Sajda, 2007; Heekeren et al., 2008; Tosoni et al., 2008) as harder task required more attentional resources. However, the other studies suggested that higher insular activity during ambiguous sensory information (i.e. harder task) might be due to the uncertainty in perceptual decision which might reflect the uncertainty in choosing an appropriate action (Ho et al., 2009; Woolgar et al., 2011; Shenhav et al., 2013).

The effort in a cognitive process of integrating sensory information should be reflected in the brain activity underlying a difficult task compared to the one with an easier task, which would further support its integrative

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Abbreviations: BOLD, blood oxygen level dependent; C, color coherence; dACC, dorsal anterior cingulate cortex; fMRI, functional magnetic resonance imaging; GLM, general linear model; IC, color incoherence; INSs, anterior insulae; MNI, Montreal Neurological Institute; PDM, perceptual decision-making; RDM, random dots motion; RT, response time; TR, repetition time.

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role in PDM (Kurth et al., 2010; Sterzer and Kleinschmidt, 2010; Chang et al., 2013; Langner and Eickhoff, 2013). In recent years, there has been increasing evidence from functional neuroimaging studies that the insular cortex is involved in a more diverse set of perceptual paradigm; for example, visual (Rebola et al., 2012), auditory discrimination (Binder et al., 2004), audiovisual asynchrony–synchrony discrimination (Lamichhane and Dhamala, 2015b), language and music perception (Platel et al., 1997; Mutschler et al., 2007; Ackermann and Riecker, 2010). Similar to the previous studies with PDM paradigm (Thielscher and Pessoa, 2007; Venkatraman et al., 2009; Gu et al., 2010; Deen et al., 2011; Chang et al., 2013; Shenhav et al., 2013; Lamichhane and Dhamala, 2015b), we aimed to expand our understanding of insular function by running the same perceptual-tasks used in the previous studies over the past decade.

We measured the BOLD activity in four PDM experiments: (1) face-house discrimination task, (2) happy-angry face discrimination task, (3) audio-visual asynchrony and synchrony perception task, and (4) random dots motion direction discrimination (RDM) task. These tasks were different from each other in terms of stimulus modality [single or multiple sensory modality (task 3), between-category discrimination (task 1) or within-category discrimination (task 2), static-moving stimuli (task 4), but all were perceptual in nature. The experiments 1 and 4 were the most popular tasks to investigate PDM in the visual domain (for details, see Experimental procedures section). Similarly, experiment 3 provided us the opportunity for such study with multiple sensory approaches. Here, we looked at the INS activities associated with PDM, with a prediction of higher insular activation for the increased in the ambiguity in the sensory information. We examined how they were correlated with behaviors. We investigated whether the insular cortex activity was associated with perceptual decision-making and, if so, how the availability of sensory information and difficulty of decision-making modulate the activity. In all experimental tasks, we first established that the ambiguity of the presented sensory information changed the participants' behavioral performance and affected the decision response times. Finally, looking at the brain response of tasks on insular cortex, we investigated whether INSs serve as centers for integration of sensory information, which would be necessary for a perceptual decision leading to a behavioral action including a motor response.

EXPERIMENTAL PROCEDURES

Participants

This study included four experiments with these tasks: (1) face-house categorization, (2) happy-angry face categorization, (3) audio-visual asynchrony and synchrony perception, and (4) random dots motion direction discrimination. These tasks, perceptual in nature, allow us the opportunity to examine and explore the PDM in multi (bi-) sensory domain (in task 3) and in visual domain (remaining other three tasks). In experiments 1 and 3, there were thirty-three human participants (17 females, 16 males; mean age ± standard deviation = 27.5 ± 4.7 years) whereas in experiments 2 and 4, there were thirty-two participants (16 males, 16 females; mean age ± standard deviation = 27.6 ± 4.7 years). Thirty two participants were common and completed all four tasks. They completed tasks in two visits, two tasks in each visit; experiments 1 and 3 in the first visit (3 functional scanning sessions of experiment 1 in sequence first and then a functional scanning session of experiment 3), and remaining experiments 2 and 4 in the second visit (4 functional scanning sessions. Behavioral experiments were performed outside the scanner and then the corresponding functional scanning sessions were carried out inside the scanner. They all had normal or corrected to normal vision and reported normal neurological history. Out of 33 participants, 4 reported that they were left handed, 2 reported that they used both hands equally but preferred left hand for writing, and remaining 27 reported that they were right handed. They provided written signed informed consent forms and were compensated for their participation in the experiments. Institutional Review Board for Joint Georgia State University and Georgia Institute of Technology Center for Advanced Brain Imaging, Atlanta, Georgia, USA approved this study.

Stimuli and experimental task paradigms

The stimulus software presentation (http://www.neurobs.com) was used to display stimuli (detail is given below, and shown in Fig. 1) and to randomize task trial sequences (Fig. 1) in all tasks. Each experimental task was divided into two separate sessions: the first session involved acquiring behavioral data outside the MRI scanner and the second session was inside the scanner where we acquired both fMRI and behavioral data. Outside the MRI scanner, participants were asked to indicate their decisions as quickly and as accurately as possible by the left and right mouse clicks for the given two stimuli. They were instructed to press the space bar in the computer keyboard to proceed to the next trial. Inside the MRI scanner, participants were instructed to focus on the central crossbar on the screen during experimental run. They were asked to perceive the presented stimuli, to wait for the display of a question mark on the screen and then to indicate their choice by pressing a response key on a button-box by using either right index or the middle finger. In both sessions, the stimulus types with their times of presentation and the response times to that stimuli were recorded. Prior to the experimental tasks, they were briefly explained about the study and the tasks. In addition, they took part in a practice session, which helped them to be familiar with the sample stimuli and the experimental tasks.

Experiment 1: face-house categorization task. We used a total of 14 images of faces and 14 images of houses as stimuli. All pictures were downloaded from F.A.C.E. Training – an interactive training by Paul