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Dissociated neural substrates underlying impulsive choice and impulsive action

Qiang Wang [a,b], Chunhui Chen [a,b], Ying Cai [a,b], Siyao Li [a,b], Xiao Zhao [a,b], Li Zheng [a,b], Hanqi Zhang [a,b], Jing Liu [a,b], Chuansheng Chen [c], Gui Xue [a,b,*]

[a] State Key Laboratory of Cognitive Neuroscience and Learning & IDG/McGovern Institute of Brain Research, Beijing Normal University, Beijing 100875, PR China
[b] Center for Collaboration and Innovation in Brain and Learning Sciences, Beijing Normal University, Beijing 100875, PR China
[c] Department of Psychology and Social Behavior, University of California, Irvine 92697, United States

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ABSTRACT

There is a growing consensus that impulsivity is a multifaceted construct that comprises several components such as impulsive choice and impulsive action. Although impulsive choice and impulsive action have been shown to be the common characteristics of some impulsivity-related psychiatric disorders, surprisingly few studies have directly compared their neural correlates and addressed the question whether they involve common or distinct neural correlates. We addressed this important empirical gap using an individual differences approach that could characterize the functional relevance of neural networks in behaviors. A large sample (n = 227) of college students was tested with the delay discounting and stop-signal tasks, and their performances were correlated with the neuroanatomical (gray matter volume, GMV) and functional (resting-state functional connectivity, RSFC) measures, using multivariate pattern analysis (MVPA) and 10-fold cross-validation. Behavioral results showed no significant correlation between impulsive choice measured by discounting rate (k) and impulsive action measured by stop signal reaction time (SSRT). The GMVs in the right frontal pole (FP) and left middle frontal gyrus (MFG) were predictive of k, but not SSRT. In contrast, the GMVs in the right inferior frontal gyrus (IFG), supplementary motor area (SMA), and anterior cingulate cortex (ACC) could predict individuals' SSRT, but not k. RSFC analysis using the FP and right IFG as seed regions revealed two distinct networks that correspond well to the "waiting" and "stopping" systems, respectively. Furthermore, the RSFC between the FP and ventromedial prefrontal cortex (VMPFC) was predictive of k, whereas the RSFC between the IFG and pre-SMA was predictive of SSRT. These results demonstrate clearly neural dissociations between impulsive choice and impulsive action, provide new insights into the nature of impulsivity, and have implications for impulsivity-related disorders.

1. Introduction

The term impulsivity refers to "a tendency to engage in behavior that involves rashness, a lack of foresight or planning, or as a behavior that occurs without reflection or careful deliberation" (Dawe et al., 2004). There is a growing consensus that impulsivity is a multidimensional construct that comprises several components such as impulsive choice and impulsive action (Bari and Robbins, 2013; Dalley et al., 2011; Evenden, 1999). Specifically, impulsive choice is a tendency to prefer small immediate or likely rewards to large delayed or unlikely ones, often measured by the delay discounting task (Ainslie, 1975) as well as other tasks (e.g., Economides et al., 2015; Hare and Neumann, 2008; Robbins, 2002). In contrast, impulsive action reflects a failure of motor inhibition, often measured by the stop-signal task (Logan and Cowan, 1984) or the Go/NoGo task (Donders, 1969). An important question thus concerns whether impulsive choice and impulsive action involve common or distinct neural correlates.

Accumulating evidence has suggested that impulsive choice and impulsive action are the common characteristics of psychiatric disorders such as drug abuse (Bednarski et al., 2012; Fillmore and Rush, 2002; Hu et al., 2015; Kirby et al., 1999; Li et al., 2009; Li et al., 2010; Luo et al., 2013), pathological gambling (Alessi and Petry, 2003), tobacco addiction (Bickel et al., 1999; Billieux et al., 2010), and ADHD (Barkley, 1997; Paloyelis et al., 2010). For example, drug abusers not only prefer immediate but smaller rewards, but also have difficulties in inhibiting prepotent responses (Fillmore and Rush, 2002; Kirby et al., 1999) and show altered inhibitory control processes including response inhibition (Li et al., 2010), error processing (Luo et al., 2013), and conflict anticipation (Hu et al., 2015) during the stop signal task. However, due to the poor understanding of the etiology of these disorders, it is not clear whether these findings reflect a common mechanism of impulsive action and impulsive choice, or the comorbidity of these symptoms.

At the behavioral level, although studies using various questionnaires and scales suggested that the sub-dimensional scores of

* Corresponding author at: State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, PR China.
E-mail address: guixue@gmail.com (G. Xue).

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impulsive choice (e.g. non-planning impulsiveness and inattention scores) were correlated with impulsive action (e.g. errors of commission and omission) (Lansbergen et al., 2007; Shen et al., 2014; Wilbertz et al., 2014), behavioral tests of impulsive choice (with the delay discounting task) and impulsive action (with stop-signal task) found no strong correlation between them in either rats or humans (Broos et al., 2012; Solanto et al., 2001; van den Bos et al., 2014). In addition, whereas some studies indicated that individuals with higher trait impulsivity measured by Eysenck Personality Questionnaire (EPQ) showed prolonged SSRT (Logan et al., 1997), other studies reported that trait impulsivity measured by Barratt Impulsivity Scale (BIS) was not significantly correlated with SSRT (Farr et al., 2012).

At the neural level, imaging studies often emphasize distinctive frontal–basal ganglia networks for impulsive choice and impulsive action (Aron et al., 2004; Aron et al., 2014; Ghahremani et al., 2012; Peper et al., 2013; Peters and Büechel, 2011). For impulsive choice, it has been suggested that the anterior dorsomedial prefrontal cortex (i.e., frontal pole, FP) is involved in representing temporally more distant reward (Koritzky et al., 2013; Wang et al., 2014). In contrast, the decision value that guides decision is represented in the ventromedial prefrontal cortex and the ventral striatum (Hare et al., 2008; Kable and Glimcher, 2009; Lim et al., 2011), and is modulated by self-control mechanisms implemented in the lateral prefrontal cortex (Hare et al., 2009; Luo et al., 2009; Magen et al., 2014; McClure et al., 2004). In addition, a medial temporo-hippocampal network has also been implicated in perspective evaluation of future outcomes (Bari and Robbins, 2013; Peters and Büechel, 2011).

For impulsive action, existing studies have implicated distributed cortical and subcortical areas for response inhibition, including the right inferior frontal gyrus (IFG) and adjacent anterior insula (AI), anterior cingulate cortex (ACC), pre-SMA, and striatum (Aron et al., 2007b; Aron and Poldrack, 2005; Aron et al., 2004; Aron et al., 2014; Chambers et al., 2009; Chao et al., 2009; Duann et al., 2009; Hampshire and Sharp, 2015; Li et al., 2009; Li et al., 2006; Li et al., 2008; Sharp et al., 2010; Verbruggen and Logan, 2008; White et al., 2014; Zhang and Li, 2012). In particular, whereas the AI–ACC network is important for detecting behaviorally salient events, the right IFG and pre-SMA are important for implementing inhibition (Cai et al., 2014) through the frontostriatal connections (Alexander et al., 1986; Aron and Poldrack, 2006; Seger, 2008).

Using the individual difference approach, several previous studies have further explored the functional relevance of these networks in impulsive choice and impulsive action. For instance, impulsive choice has been linked to the activation level of the ventral striatum (VS) (Beck et al., 2009; Hariri et al., 2006), the GMV of the dorsolateral prefrontal cortex (Bjork et al., 2009), the white matter volume of right prefrontal subgyral region and hippocampus/parahippocampus (Yu, 2012), as well as the structural and functional connectivity between lateral prefrontal cortex and ventral striatum (Peper et al., 2013; van den Bos et al., 2014; van den Bos et al., 2015). In contrast, impulsive action has been linked to the GMVs (Tabibnia et al., 2011; van Gaal et al., 2011) and the fractional anisotropy (FA) of the pre-SMA and IFG (Madsen et al., 2010), the functional and structural connectivity between the IFG and pre-SMA (Aron et al., 2007a; Duann et al., 2009; Neubert et al., 2010), and the preSMA-subthalamic tract strength (Coxon et al., 2012; Forstmann et al., 2012).

To summarize, although many studies have examined the cognitive mechanisms of impulsive choice and impulsive action separately, few have directly compared them. The present study addressed this important empirical gap with an individual difference approach that can explore the functional relevance of different brain regions in impulsive behaviors. A relatively large sample of college students (n = 227) was tested using the delay discounting task and the stop-signal task, which, compared to self-reported assessments, showed improved stability, flexibility, and repeatability (Swann et al., 2002). Their behavioral performance was then correlated with GMV and resting-state functional connectivity (RSFC) data, using a multivariable support vector regression analysis with ten-fold cross-validation (He et al., 2013). Our large sample and the use of cross-validation helped to avoid the unrealistically large correlations obtained from a small sample size with simple correlational analysis (Vul et al., 2009). Based on existing results, we predicted that distinct frontal–subcortical systems would be associated with different aspects of individuals' impulsivity. In particular, the medial prefrontal cortex and ventral striatum would be associated with impulsive choice, whereas the lateral prefrontal cortex, pre-SMA, and dorsal striatum would be associated with impulsive action.

2. Materials and methods

2.1. Participants

Two-hundred and twenty-seven (84 males, 143 females) healthy Chinese college students (18–24 years old, mean age = 20.9 years, SD = 1.17) were recruited for this study. All of them had normal or corrected-to-normal vision and reported no history of psychiatric or neurological disease. Twenty-two additional participants were recruited but excluded from analysis because of short response time (<80 ms) on the stop-signal task (n = 7) or large head motion during fMRI scan (>2 mm) (n = 15). Written informed consent was obtained from each participant after a full explanation of the study purpose and procedure. This study was approved by the Institutional Review Boards of Beijing Normal University and Southwest University.

2.2. Behavioral tasks

The adaptive delay discounting task (van den Bos et al., 2014) and the stop-signal task (Xue et al., 2008) were used to measure individual differences in impulsive choice and impulsive action, respectively. In the adaptive delay discounting task, subjects were presented with a choice between a fixed immediate reward (SS) (RMB 60, approximately USD 10, paid today) and a varied delayed reward (LL) (RMB 78–108, approximately USD 13 to 18, to be paid in 15 to 45 days) (Fig. 1A). We assumed a hyperbolic function ($SV = A / (1 + k * D)$) for temporal discounting, where SV is the subjective value, A the reward magnitude, D the delay time, and k the delay discounting rate. The initial discounting rate was set to 0.02 and was increased when the participants chose the SS option, but decreased when they chose the LL option. For the first 20 trials (out of the total 60 trials), the step size for change of k was set to 0.01 and after that the step size decreased by 5% for each following step. Following previous studies (Johnson and Bickel, 2002; Lagorio and Madden, 2005), hypothetical money was used to serve as a valid proxy for real money.

The stop-signal paradigm consisted of a number of Go trials (75% trials) and Stop trials (25% trials). For each trial, an arrow pointing left or right was displayed on the computer screen. For the Go trials, participants were asked to respond as accurately and quickly as possible with a left or right key press (using the left or right index finger) in 1000 ms. For the Stop trials, a stop signal (red circle) appeared with a stop-signal delay (SSD) subsequent to the arrow stimulus, and participants were asked to withhold the response they already initiated (Fig. 1B). The SSD was determined by a tracking procedure to ensure approximately 50% inhibition rate. Specifically, the SSD would increase by 50 ms when the participants successfully inhibited their response and would decrease by 50 ms when they failed. To reduce participants' anticipation, four step-up and step-down algorithms (staircases) starting with SSD values of 140, 180, 220, and 260 ms were employed. These staircases were interleaved randomly and varied independently (Xue et al., 2008). Each participant finished 4 blocks of 64 trials, with each block lasting approximately 10 min. Subjects received feedback on the reaction time and stop rate after each block.