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Mechanisms of impulsive choice: III. The role of reward processes

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ABSTRACT

Two experiments examined the relationship between reward processing and impulsive choice. In Experiment 1, rats chose between a smaller-sooner (SS) reward (1 pellet, 10 s) and a larger-later (LL) reward (1, 2, and 4 pellets, 30 s). The rats then experienced concurrent variable-interval 30-s schedules with variations in reward magnitude to evaluate reward magnitude discrimination. LL choice behavior positively correlated with reward magnitude discrimination. In Experiment 2, rats chose between an SS reward (1 pellet, 10 s) and an LL reward (2 and 4 pellets, 30 s). The rats then received either a reward intervention which consisted of concurrent fixed-ratio schedules associated with different magnitudes to improve their reward magnitude discrimination, or a control task. All rats then experienced a post-intervention impulsive choice task followed by a reward magnitude discrimination task to assess intervention efficacy. The rats that received the intervention exhibited increases in post-intervention LL choice behavior, and made more responses for larger-reward magnitudes in the reward magnitude discrimination task, suggesting that the intervention heightened sensitivities to reward magnitude. The results suggest that reward magnitude discrimination plays a key role in individual differences in impulsive choice, and could be a potential target for further intervention developments.

1. Introduction

Impulsive choice has been traditionally evaluated by presenting choices between smaller-sooner (SS) and larger-later (LL) rewards (e.g., $10 in 1 month vs. $100 in 10 months). When the LL reward is optimal in terms of reward rate, individuals who prefer the SS outcome are regarded as impulsive, while those who prefer the LL outcome are regarded as self-controlled (e.g., Galtress et al., 2012a). This distinction is critical, as individual differences in childhood impulsivity have been shown to predict societal status and financial success in adulthood (Mischel et al., 1989) and such individual differences among substance abusers have been shown to predict treatment success from rehabilitation programs (MacKillop and Kahler, 2009; Stanger et al., 2012; Washio et al., 2011). Moreover, impulsivity-based behavioral deficits have been found among substance abusers (e.g., Bickel and Marsch, 2001), pathological gamblers (e.g., Dixon et al., 2003), and obese individuals (e.g., Bruce et al., 2011; Weller et al., 2008), as well as clinical populations with disorders such as attention deficit hyperactivity disorder (ADHD; e.g., Barkley et al., 2001) schizophrenia (Heerey et al., 2007), bipolar disorder (Ahn et al., 2011), depression (Imhoff et al., 2013), borderline personality disorder (Lawrence et al., 2010), and Parkinson's disease with a comorbidity of impulsive-compulsive behavior (Housden et al., 2010). Moreover, individual differences in impulsive choice behavior are stable in both human (Baker et al., 2003; Jimura et al., 2011; Johnson et al., 2007; Kirby, 2009; Matusiewicz et al., 2013; Ohmura et al., 2006; Peters and Büchel, 2009) and non-human animals (Marshall et al., 2014; Peterson et al., 2015), suggesting that impulsivity reflects a trait variable. Accordingly, there has been heightened interest in understanding the underlying mechanisms that govern individual differences in impulsive choice (e.g., Galtress et al., 2012a; Marshall et al., 2014; Peters and Büchel, 2011).

Impulsive choice procedures are designed to pit reward magnitude against reward delay. Accordingly, two primary mechanisms driving individual differences in impulsive choice include sensitivity to changes in both reward magnitude and the passage of time (see Galtress et al., 2012a). Indeed, computations of subjective value integrate the delay and magnitude of the SS and LL rewards during value-based decision making (e.g., Peters and Büchel, 2011). Several previous studies have confirmed the relationship between temporal processing and impulsive choice behavior (for reviews, see Kirkpatrick et al., 2015; Wittmann and Paulus, 2008). For example, the tendency to make impulsive choices has been shown to be positively correlated with poor temporal discrimination ability in rats

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(Marshall et al., 2014; McClure et al., 2014), and impulsive humans tend to exhibit deficits in timing tasks (Baumann and Odum, 2012; Darcheville et al., 1992; van den Broek et al., 1992). In addition, methamphetamine increased impulsive choice and those increases have been linked to a decreased sensitivity to delay (Pitts and Febbo, 2004). Indeed, Kim and Zauberman (2009) suggested that previous factors that have been associated with impulsive choice, such as age (e.g., Green et al., 1994), income (e.g., Green et al., 1996), intelligence (e.g., Shamosh and Gray, 2008), and drug abuse (e.g., Bickel and Marsch, 2001), may be comprehensively accounted for by subjective differences in temporal processing. Thus, in both human and non-human animals, temporal processing appears to be a critical underlying mechanism of impulsive choice behavior (Kirkpatrick et al., 2015; Marshall et al., 2014; Smith et al., 2015).

In terms of the relationship between reward processing and impulsive choice, Ballard and Knutson (2009) showed that individuals' activations in brain regions associated with reward processing were a negative function of the tendency to make more impulsive choices (also see Benningfield et al., 2014), while Eppinger et al. (2012) reported that impulsive choice behavior was positively correlated with activity in the brain's reward system in response to immediate reward (also see Hariri et al., 2006; McClure et al., 2007; Wilbertz et al., 2012). Additionally, lesions of the nucleus accumbens, a node within the brain's core valuation circuit (see Galtress et al., 2012b; Peters and Büchel, 2010), increased impulsive choice (e.g., Cardinal et al., 2001; Galtress and Kirkpatrick, 2010), although other reports have shown that partial inactivation of the nucleus accumbens decreased impulsive choice (Moschak and Mitchell, 2014). Overall, reward processing appears to be fundamentally associated with impulsive choice, but these connections are not as well documented in the behavioral domain (particularly in rodent models) as the temporal processing deficits.

In conjunction with the neurobiological evidence connecting impulsive choice with reward processing, Locey and Dallery (2009) suggested that the traditional hyperbolic discounting equation [i.e., $A/(1+kD)$] should include a free parameter (S) accounting for individual differences in sensitivity to reward magnitude [i.e., $A^S/(1+kD)$]. This suggests that we should expect to find a significant correlation between impulsive choice and sensitivity to reward magnitude. However, recent research in our laboratory failed to find a significant relationship between the rats' LL choice behavior and their reward magnitude discrimination in a discrete-trial multiple variable-interval schedules of reinforcement task (Marshall et al., 2014). This failure to observe the predicted relationship may have been due to task demands and task structure. The task that was used to assess reward discrimination involved presenting rats with specific magnitudes and measuring their responses to those magnitudes. Specifically, rats received pseudo-alternating variable interval schedules on the left and right levers that were associated with 1 pellet on each side. Then, the reward magnitude was increased for one of the levers and response rates were measured. In this case, the effect of magnitude on behavior was measured purely through response rates rather than through choice behavior. The effects of reward magnitude on behavior have been suggested to be augmented when individuals' behaviors rather than experimental manipulations determine the reward experienced (see Bonem and Crossman, 1988). In other words, the behavioral effects of manipulations of reward magnitude may have been stronger if the rats were able to choose one reward magnitude over another (e.g., impulsive choice task) rather than when the rats were forced to experience one reward magnitude over another (e.g., multiple variable-interval schedules). Therefore, given the input of reward magnitude into computations of subjective value, it is critical to determine the relationship between reward processing and impulsive choice using alternative measures of reward magnitude discrimination that may better capture this relationship. This was the primary goal of Experiment 1 in the present report.

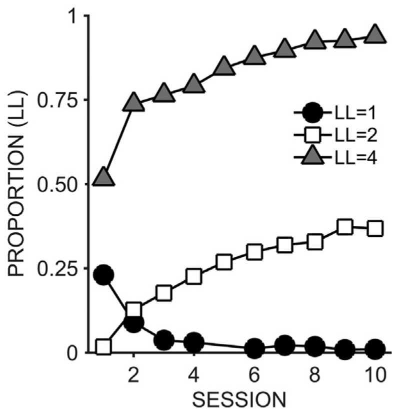

Fig. 1. Mean proportion of choices for the larger-later (LL) outcome as a function of session and LL reward magnitude (1, 2, or 4 pellets). The first session of the LL = 1 phase corresponds to the first session of the overall choice task, while the first sessions of the LL = 2 and LL = 4 phases correspond to the sessions immediately following the tenth sessions of the LL = 1 and LL = 2 phases, respectively.

A second goal was to determine whether we could change impulsive choice behavior by giving targeted training to increase reward magnitude discrimination, providing complimentary evidence for a direct link between reward discrimination and impulsive choice. There have not been any previous studies that have directly examined this issue, particularly in rats. One possible intervention targeting reward processing mechanisms was conducted by Stein et al. (2013), who implemented a reward bundling procedure between two phases of impulsive choice tasks. In this reward bundling procedure (see Ainslie and Monterosso, 2003), SS and LL rewards were delivered throughout a trial. For example, if the size of the bundle was three, then an SS choice resulted in three SS rewards (e.g., 1 pellet × 3 deliveries), while an LL choice resulted in three LL rewards (e.g., 3 pellets × 3 deliveries); in the bundle conditions, each of the SS and LL rewards were separated by the length of the LL delay. Accordingly, the greater the bundle, the more that the rats would be exposed to LL delays and differential reward magnitudes. Stein et al. (2013) showed that the greater the reward bundling, the more often rats chose LL rewards in the post-test impulsive-choice phase. Interestingly, these results were explained not in terms of exposure to differential reward bundling, but in terms of the greater exposure to LL delays throughout the reward bundling procedure for the rats that received greater bundles of reward (Stein et al., 2013). This explanation corroborates the impact of a *time*-based intervention on impulsive choice (e.g., Smith et al., 2015), in that greater exposure to reward delays promoted more self-controlled choice. However, an alternative explanation for the effects of reward bundling may relate to exposure to differential reward magnitudes (see Białaszek and Ostaszewski, 2012). In sum, an analysis of whether a *reward*-based intervention would reduce impulsive choice via improvements in reward processing has yet to be conducted. Experiment 2 of the present report sought to address this issue by determining the effects of a novel reward-based intervention task on impulsive choice.

2. Experiment 1

2.1. Methods

2.1.1. Animals

Twenty-four experimentally-naïve male Sprague-Dawley rats (Charles River) were used in the experiment. They arrived to the facility (Kansas State University, Manhattan, KS) at approximately