Developmental Cognitive Neuroscience 34 (2018) 101–113

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn

Individual differences in functional brain connectivity predict temporal discounting preference in the transition to adolescence

Jeya Anandakumar[a,1], Kathryn L. Mills[b,*,1], Eric A. Earl[a], Lourdes Irwin[a], Oscar Miranda-Dominguez[a], Damion V. Demeter[e], Alexandra Walton-Weston[a], Sarah Karalunas[c], Joel Nigg[c], Damien A. Fair[a,c,d]

[a] *Department of Behavioral Neuroscience, Oregon Health & Science University, Portland, OR, United States*
[b] *Department of Psychology, University of Oregon, Eugene, OR 97403, United States*
[c] *Department of Psychiatry, Oregon Health & Science University, Portland, OR, United States*
[d] *Advanced Imaging Research Center, Oregon Health & Science University, Portland, OR, United States*
[e] *Department of Psychology, University of Texas at Austin, Austin, TX, United States*

ARTICLE INFO

Keywords:
Delay discounting
fMRI
Intrinsic connectivity
Longitudinal
Resting state

ABSTRACT

The transition from childhood to adolescence is marked by distinct changes in behavior, including how one values waiting for a large reward compared to receiving an immediate, yet smaller, reward. While previous research has emphasized the relationship between this preference and age, it is also proposed that this behavior is related to circuitry between valuation and cognitive control systems. In this study, we examined how age and intrinsic functional connectivity strength within and between these neural systems relate to changes in discounting behavior across the transition into adolescence. We used mixed-effects modeling and linear regression to assess the contributions of age and connectivity strength in predicting discounting behavior. First, we identified relevant connections in a longitudinal sample of 64 individuals who completed MRI scans and behavioral assessments 2–3 times across ages 7–15 years (137 scans). We then repeated the analysis in a separate, cross-sectional, sample of 84 individuals (7–13 years). Both samples showed an age-related increase in preference for waiting for larger rewards. Connectivity strength within and between valuation and cognitive control systems accounted for further variance not explained by age. These results suggest that individual differences in functionalbrain organization can account for behavioral changes typically associated with age.

1. Introduction

Temporal discounting (also known as inter-temporal choice or delay discounting) is the process of assessing the value of waiting for a future reward depending on the magnitude of the reward and the delayed time. Individuals vary in their temporal discounting behavior, with some having a stronger preference for taking a smaller immediate reward versus waiting for a larger reward, and vice versa (Sadaghiani and Kleinschmidt, 2013). Previous experimental studies suggest a positive relationship between chronological maturation (age) and the tendency to prefer waiting for the larger reward (de Water et al., 2014; Steinberg et al., 2009), although some studies have found evidence for a non-linear relationship in the transition into adolescence (Scheres et al., 2014). Interestingly, the development of temporal discounting with age may be a stable marker of liability for disinhibitory psychopathologies such as ADHD even when psychopathological symptoms change with age (Karalunas et al., 2017). It has been proposed that brain function and organization can explain individual differences in temporal discounting behavior (Christakou et al., 2011; Hare et al., 2014; Li et al., 2013; Scheres et al., 2013; van den Bos et al., 2014). Therefore, in this study, we analyzed how chronological maturation interacts with functional brain organization to predict temporal discounting.

1.1. Temporal discounting as a measure of decision-making preference

Tasks assessing temporal discounting behavior can be used to measure an individual's preference for a smaller-sooner reward (SSR) in comparison to a larger-later reward (LLR) (Green et al., 1997). These tasks typically ask individuals to choose between two rewards that vary in both the reward size and the required delay time until the amount is

* Corresponding author.
E-mail address: klmills@uoregon.edu (K.L. Mills).
[1] Contributed equally to this work.

https://doi.org/10.1016/j.dcn.2018.07.003
Received 29 January 2018; Received in revised form 1 July 2018; Accepted 16 July 2018
Available online 30 July 2018

acquired (Myerson and Green, 1995). For example, participants typically respond to several questions in the following format: "At the moment, what would you prefer?" Below the question two options are presented (e.g. "$7.00 now", "$10 in 30 days"). The SSR and LLR vary in both delay interval and reward size over successive trials; this way, the subjective value of temporal reward can be measured. Individuals preferring the SSR are characterized to have greater temporal discounting; conversely, individuals preferring the LLR are characterized to have less temporal discounting. One way to measure this subjective value of temporal reward is through the use of indifference points (the delay duration at which the magnitude of SSR equals the magnitude of LLR) (Richards et al., 1999). The indifference points are useful in calculating a single index of discounting rate, and in determining the value of the delayed reward (Yi et al., 2010). Specifically, plotting the indifference points in a series yields a discount curve, which describes the rate at which the value of reward decreases over time.

1.2. Brain networks involved in temporal discounting

Cortico-striatal circuitry is involved in decision-making processes (Haber and Knutson, 2009), including temporal discounting (Peters and Büchel, 2011). In the present study, we focus on two cortico-striatal systems (defined *a priori*) that have been consistently correlated with different outcomes of an individual's preference and value (Peters and Büchel, 2011; van den Bos et al., 2014): a valuation system (amygdala, medial orbitofrontal cortex, posterior cingulate cortex, ventromedial prefrontal cortex, and ventral striatum) and a cognitive control system (ventral lateral prefrontal cortex, dorsal anterior cingulate cortex, dorsolateral prefrontal cortex, dorsal striatum, and inferior frontal cortex) (See Fig. 1a). Specifically, increased structural connectivity between the striatum and cortical control regions have been found to be related to decreased temporal discounting, whereas increased structural connectivity between the striatum and subcortical valuation regions were related to increased temporal discounting in adults (van den Bos et al., 2014). We also assessed connectivity between these networks and the supplementary motor area and hippocampus, given their involvement in intertemporal choice behavior (Peters and Büchel, 2010; Scheres et al., 2013; van den Bos et al., 2014).

Brain networks involved in temporal discounting can be interrogated with MRI in multiple ways, including task-based fMRI studies in which participants are asked to make temporal discounting decisions. Overall, it has been theorized that adults with high temporal discounting preference are more likely to show greater recruitment of the control network and less recruitment of the valuation network when choosing a LLR over a SSR (van den Bos and McClure, 2013; Volkow and Baler, 2015). While task-evoked brain activity can inform us on the functionality of cortical networks during specific contexts, intrinsic brain activity at rest can be used to measure an individual's functional brain organization. The intrinsic activity of the brain reflects, in part, past activities, and these fluctuations impact future behavior (Sadaghiani and Kleinschmidt, 2013). Brain functionality and fluctuations are believed to determine and shape connectivity patterns. Here, we study the brain's intrinsic connectivity using resting-state functional connectivity MRI (rs-fcMRI) (Power et al., 2014b), which characterizes the functional relationship between brain regions while a participant is not performing a specific task by correlating slow spontaneous fluctuation of the blood oxygen level dependent (BOLD) signal. These intrinsic activity correlations can reveal the cohesive connections and interactions present in neuronal networks (Boly et al., 2008). Previous studies in adults have found that intrinsic brain connectivity within cortico-striatal networks were related to an individual's temporal discounting preference (Calluso et al., 2015; Li et al., 2013).

1.3. Development of brain networks underlying temporal discounting

It is hypothesized that differential rates of maturation across cortico-striatal systems, and the protracted development of the interconnections between them, are related to changes in behavior across development (Casey, 2015; Costa Dias et al., 2012, 2015; van den Bos et al., 2015). In adults, it has been theorized that greater recruitment of control networks (and less recruitment of the valuation networks) are indicative of choosing the LLR, however, it is currently unclear if this brain-behavior relationship is present throughout development. One of the first task-based fMRI studies of temporal discounting examined the impact of age-related (ages 12–32 years; males) changes in brain activation when deciding between a SSR and a LLR (Christakou et al., 2011). This study demonstrated that when choosing an immediate reward, *increased* recruitment of the vmPFC and *decreased* recruitment of the ventral striatum, insula, anterior cingulate, occipital, and parietal cortices was related to increasing age and preference for LLR. Further, greater coupling between the ventral striatum and vmPFC was also related to increasing age and preference for LLR, suggesting that increased functional connectivity between the vmPFC and ventral striatum (regions of the valuation network) might be one neural mechanism underlying developmental changes in the preference for delayed rewards.

Another theory is that neural systems involved in three cognitive processes: valuation (i.e., the value placed on a certain stimuli or outcome), cognitive control (i.e., engaging in goal-directed cognitive processes), and prospection (i.e., thinking about the future), are involved in the process of temporal discounting (Peters and Büchel, 2011). Using this framework, Banich et al. (2013) compared the behavioral and neural correlates of temporal discounting in younger (14–15 years) and older (17–19 years) adolescents, and how these measures related to an individual's self-reported tendency to think beyond the present. Behaviorally, older adolescents were more likely to choose a delayed reward over an immediate reward, and were slower than younger adolescents to choose the immediate reward (Banich et al., 2013). The pattern of brain activity related to intertemporal decision making was more distinct when choosing between immediate versus delayed rewards in the older adolescents compared to the younger adolescents (Banich et al., 2013). Across groups, individuals who reported a greater tendency to think beyond the present showed decreased recruitment of cognitive control regions during the temporal discounting task. These results suggest that both age and individual differences are related to the neural processing of temporal discounting.

Another study found that greater white matter integrity in pathways connecting the frontal and temporal cortices with other areas of the brain were positively correlated with the preference for delayed rewards across ages 9–23 years (Olson et al., 2009). Some of these correlations were developmentally related, whereas some of the effects appeared to be age-independent. For example, the relationship between greater white matter integrity in right frontal and left temporal regions and increased preference for delayed reward was not attributable to age. However, the relationship between integrity of white matter in left frontal, right temporal, right parietal (as well as some subcortical-cortical circuits) and the preference for delayed reward was age-related, as these white matter tracts also increased in integrity across the age range studied. These results show that both age and individual differences in neural circuitry are related to an individual's preference for immediate versus delayed rewards. A recent longitudinal study examined the relationship between temporal discounting and fronto-striatal circuitry in individuals between the ages of 8–26 (Achterberg et al., 2016). This study found that preference for LLR increased non-linearly between childhood and early adulthood, and that greater fronto-striatal white matter integrity was related to the preference for LLR (Achterberg et al., 2016).

Taken together, these studies demonstrate that people, on average, show increasing preference to wait for larger rewards rather than take immediate (smaller) rewards as they get older, but the increase may be nonlinear. Individual differences across development in temporal discounting preference are related to differences in functional brain