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Modulation of reward-related neural activation on sensation seeking across development

Samuel W. Hawes[a,*], Rajpreet Chahal[b], Michael N. Hallquist[c], David J. Paulsen[d], Charles F. Geier[c], Beatriz Luna[d,e]

[a] Florida International University, Center for Children and Families, Department of Psychology, 11200 SW 8th Street, Miami, FL 33199, United States
[b] University of California, Davis, Department of Psychology, 135 Young Hall, One Shields Avenue, Davis, CA 95616, United States
[c] Pennsylvania State University, Department of Psychology, 140 Moore Building, University Park, PA 16801, United States
[d] University of Pittsburgh, Department of Psychology, 121 Meyran Avenue, Pittsburgh, PA 15213, United States
[e] University of Pittsburgh, Department of Psychiatry, 121 Meyran Avenue, Pittsburgh, PA 15213, United States

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ABSTRACT

Sensation seeking is a personality construct associated with an increased propensity for engaging in risk-taking. Associations with deleterious outcomes ranging from mental health impairments to increased mortality rates highlight important public health concerns related to this construct. Although some have suggested that increased neural responsivity to reward within the ventral striatum (e.g., nucleus accumbens) may drive sensation seeking behaviors, few studies have examined the neural mechanisms associated with stable individual differences in sensation seeking across development. To address this issue, the current study used functional magnetic resonance imaging to examine the association between neural responding to reward and stable patterns of sensation seeking across a three-year follow-up period among healthy adolescents and young adults ($N = 139$). Results indicated that during early adolescence (~ages 10–12), increased reactivity to reward within the nucleus accumbens (NAcc) was associated with lower levels of sensation seeking across a three-year follow-up. In middle adolescence (~ages 12–16), there was no evidence of a relationship between NAcc reactivity and sensation seeking. However, during the transition from late adolescence into adulthood (~ages 17–25), heightened reward-related reactivity in the NAcc was linked to increased sensation seeking. Findings suggest that the neural mechanisms underlying individual differences in trait-like levels of sensation seeking change from early to late adolescence.

1. Introduction

Sensation seeking is a personality trait associated with a propensity to seek out novel, highly stimulating experiences, and the willingness to take risks in pursuit of these experiences (Zuckerman and Kuhlman, 2000). Compared to low sensation seekers, individuals high in sensation seeking ascribe fewer consequences and less danger to their involvement in risky activities (Horvath and Zuckerman, 1993; Zuckerman and Kuhlman, 2000). In some instances, such as engagement in some acts of courage and bravery, evidence suggests that sensation-seeking may play an important role in promoting these functional behaviors (Neria et al., 2000). However, an extensive body of research has also documented links between sensation seeking and an array of deleterious outcomes such as severe substance use impairments (Ball et al., 1994), comorbid psychopathology (Slutske et al., 2002), poorer treatment outcomes (Staiger et al., 2007), and increased rates of physical injury and mortality (Cservenka et al., 2013). The high societal costs attributed to this facet of personality have led to its recognition as an important public health concern (Steinberg, 2008), and further underscores the need to improve our understanding of its development.

Sensation seeking has a genetic basis (Joseph et al., 2009; Terracciano et al., 2011), with heritability estimates generally ranging from 40% to 60% (Stoel et al., 2006). In addition, shared genetic factors underlie sensation seeking and externalizing psychopathology such as substance dependence and conduct disorder (Harden and Mann, 2015; Mann et al., 2016). Changes in the incentive processing system, particularly increased responsivity to reward, likely plays a key role in explaining individual differences in sensation seeking (Dalley et al., 2007; Harden and Mann, 2015; Zuckerman, 1984). Research investigating neural sensitivity to rewards as a marker of sensation seeking has largely focused on key regions in the mesolimbic dopamine (DA)

* Correspondence to: Florida International University, AHC, Rm #434, 11200 SW 8th Street, Miami, FL 33199, United States.
E-mail address: Samuel.hawes@fiu.edu (S.W. Hawes).

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system, particularly the nucleus accumbens (NAcc) (Bornovalova et al., 2009; Ikemoto and Panksepp, 1999). Findings across basic and clinical science indicate that the DA system undergoes dramatic alterations beginning around the onset of puberty (Galvan, 2010; Wahlstrom et al., 2010). For example, animal research has shown that DA levels in the striatum increase during adolescence (Andersen et al., 1997) and that the firing rate of DA neurons increase at the beginning in adolescence, peak during late adolescence, and decline into adulthood (McCutcheon and Marinelli, 2009). Similarly, research in humans suggests that compared to other age groups, adolescents appear to experience particularly exaggerated reactivity to rewards in the NAcc (Galvan, 2010; Geier et al., 2010; Luciana et al., 2012; Luna et al., 2013; Padmanabhan et al., 2011; Paulsen et al., 2015), a region that is a principal target of DA neurons (Haber and Knutson, 2010; Ikemoto and Panksepp, 1999).

Accumulating evidence suggests NAcc response to reward may be related to increased sensation seeking during late adolescence and adulthood. There is a particular interest in delineating this association in adolescence given that sensation seeking is often found to peak at this time (Steinberg, 2008). Initial studies report somewhat discordant findings. Using a monetary incentive delay task (MID) among a sample of 26 adolescents (ages 12–16), Bjork et al., (2008), found a positive relationship between NAcc activation to anticipated rewards and sensation seeking ($p < .05$). Similarly, using a rewarded delayed response task with children (ages 7–11) and adolescents (ages 13–17), Galvan et al., (2007) found an association between NAcc response and risk perception in adolescents but not in children. Finally, Cservenka et al. (2013) using a modified version of the Wheel of Fortune task found no differences in NAcc activity to reward feedback between High ($n = 27$) and Low ($n = 27$) sensation seeking adolescents (mean age = 13.94, *SD* = 1.05). In sum, although a direct relationship between NAcc reward response and sensation seeking has yet to be clearly established; if such a relationship does exist, it appears this association may vary by both task and age.

Emerging literature indicates that the role of the mesolimbic system may change through development as several lines of evidence suggest that there may be a peak in dopamine availability (Padmanabhan and Luna, 2014; Wahlstrom et al., 2010). fMRI studies have reported that activity in NAcc may be different in children than at older ages. Using a rewarded cognitive control task, Paulsen et al. (2015) found increased NAcc activation in children even in the absence of rewards was associated with better cognitive control, while greater reliance on NAcc later in development was associated with decreased control. Continued predominant reliance on NAcc at later ages may reflect persistent immaturities in transitioning to reliance on cognitive control regions. However, probing the predictive significance of neuroimaging data on later outcomes has been difficult.

Typically neuroimaging analyses consider brain activation as the outcome of interest (i.e., dependent variable). Recently, more studies have begun to implement a *brain-as-predictor* approach, wherein brain activation is modeled as an independent variable that can be used to predict longitudinal outcomes. In this approach, regions of interest are defined a priori based on strong empirical and theoretical evidence. Next, neural activation in the a priori specified region or regions is measured, followed by the collection of longitudinal data on the outcome of interest (see Berkman and Falk, 2013 for a more detailed review). In this manner, an analytic model can be specified to probe the predictive validity of the hypothesized brain region to predict the longitudinal outcome data. This methodology provides a more direct manner for testing theoretical models, that can inform ecologically validity and long-term outcomes (Berkman and Falk, 2013; Gonzalez and Berman, 2010).

1.1. Current study

The current study investigated activation in NAcc, given its well established role in reward processing, as a biomarker of sensation seeking across development. Reward sensitivity was assessed in 139 participants ranging in age from 10- to 25-years-old using an incentivized antisaccade task. Sensation seeking was assessed at the time of the scan and then at two follow-ups conducted one-and-a-half years apart. Reward sensitivity was specified as a predictor of trait sensation seeking using a latent variable modeling framework. Developmental effects were investigated by examining the moderating influence of participant's age on the association between reward related brain activity and sensation seeking. Given previous evidence suggesting that the association between NAcc activation and markers of risk taking may differ with development (Galvan et al., 2007; Paulsen et al., 2015), we hypothesized that reward activation in the NAcc would similarly show a different association with sensation seeking across age.

2. Materials and methods

2.1. Participants

Data was collected as part of an ongoing neuroimaging study focused on characterizing the neural basis of cognitive control across development. Participants included a community based sample of healthy volunteers from Pittsburgh and surrounding areas who underwent behavioral and neuroimaging testing. Volunteers were native English speakers screened by phone to ensure no neurological, psychiatric, or eye movement problems, a negative history of medications known to affect brain function or eye movements, and no first degree relatives with schizophrenia or bipolar disorder. In addition, all participants had far visual acuity of at least 20/40 (corrected or uncorrected) and were screened for non-removable metal on the body, claustrophobia, and weight under 300 pounds to ensure scanner eligibility.

This study initially included 171 participants, with the sample being further refined by only including cases which met the following inclusionary criteria: runs with fewer than 15% volumes having greater than .3 mm head motion between volumes; visits sharing 90% of whole-brain coverage with all other subjects; subject visits with greater than 50% accuracy in antisaccade performance per condition; visits with 20 or more correct antisaccade trials per condition; and subjects having available data on the sensation seeking measure. This resulted in a final sample of size of 139 participants (76 females) ranging in age from 10- to 25-years-old (M=16.43, SD=3.77). Participants were assessed for IQ using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), and demonstrated scores in the normal range (M=110.99, SD=11.64). There were no associations found between any study control variables (i.e., gender, IQ, ethnicity), however, participant's gender was related to the study outcome ($B = -.21$, $p < .05$) and therefore controlled for in all study analyses. No differences were found between participants included in this study's final sample when compared to those meeting exclusionary criteria in terms of IQ ($t(169) = -1.13$, $p > .05$), gender ($\chi^2(1) = .973$, $p > .05$), ethnicity ($\chi^2 = 1.67(1)$, $p > .05$), or scores on the sensation seeking measure ($t(169) = -.244$, $p > .05$). However, on average, excluded participants (M = 14.73, SD = 3.39) were younger than those included in the final study sample (M = 16.44, SD = 3.75; $t = -2.60(169)$, $p < .05$). All experimental procedures in this study were approved by the Institutional Review Board at the University of Pittsburgh. Participants were paid US $75 for their participation in the study in addition to any performance-related earnings.

2.2. Procedures

Immediately prior to scanning, participants were asked to choose a reward to work towards based on their performance, which included a series of gift cards to retail locations or $25 cash. Participants were then instructed to rate how ‘valuable’ (7-point Likert scale) they