Addictive Behaviors 39 (2014) 1606–1621

Contents lists available at ScienceDirect

Addictive Behaviors

Differential associations between impulsivity and risk-taking and brain activations underlying working memory in adolescents

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HIGHLIGHTS

- Brain activation patterns differ during different stages of working memory (WM).
- Verbal and visuospatial WM tasks elicit shared and distinct brain activations.
- Risk-taking and impulsivity relate differently to WM brain activations in youth.
- Risk-taking correlated with subcortical brain activations in adolescents.
- Motor impulsivity correlated with cortical activations in adolescents.

ARTICLE INFO

Available online 18 December 2013

Keywords:
Adolescence
Impulsivity
Risk-taking
Working memory
Neuroimaging

ABSTRACT

Increased impulsivity and risk-taking are common during adolescence and relate importantly to addictive behaviors. However, the extent to which impulsivity and risk-taking relate to brain activations that mediate cognitive processing is not well understood. Here we examined the relationships between impulsivity and risk-taking and the neural correlates of working memory. Neural activity was measured in 18 adolescents (13–18 years) while they engaged in a working memory task that included verbal and visuospatial components that each involved encoding, rehearsal and recognition stages. Risk-taking and impulsivity were assessed using the Balloon Analogue Risk Task (BART) and the adolescent version of the Barratt Impulsiveness Scale—11 (BIS-11A), respectively. We found overlapping as well as distinct regions subserving the different stages of verbal and visuospatial working memory. In terms of risk-taking, we found a positive correlation between BART scores and activity in subcortical regions (e.g., thalamus, dorsal striatum) recruited during verbal rehearsal, and an inverse correlation between BART scores and cortical regions (e.g., parietal and temporal regions) recruited during visuospatial rehearsal. The BIS-11A evidenced that motor impulsivity was associated with activity in regions recruited during all stages of working memory, while attention and non-planning impulsivity was only associated with activity in regions recruited during recognition. In considering working memory, impulsivity and risk-taking together, both impulsivity and risk-taking were associated with activity in regions recruited during rehearsal; however, during verbal rehearsal, differential correlations were found. Specifically, positive correlations were found between: (1) risk-taking and activity in subcortical regions, including the thalamus and dorsal striatum; and, (2) motor impulsivity and activity in the left inferior frontal gyrus, insula, and dorsolateral prefrontal cortex. Therefore these findings suggest that while there may be some overlap in the neural correlates of working memory and their relationship to impulsivity and risk-taking, there are also important differences in these constructs and their relationship to the stages of working memory during adolescence.

Adolescence represents an important stage of development, underscored by distinct neurobiological and psychological changes in the adolescent brain and mind. Critically, it is a period that is associated with increased impulsivity and risk-taking behavior, characteristics that may prove detrimental in the emergence and maintenance of addictive behaviors. Consistent with this notion, in adolescents, higher levels of impulsivity are associated with increased substance use (Vitaro, Ferland, Jacques, & Ladouceur, 1998), problem-gambling behavior (Vitaro et al., 1998), Internet addiction (Cao, Su, Liu, & Gao, 2007) and earlier onset of alcohol-use disorders (Soloff, Price, Mason, Becker, & Meltzer, 2010). While much is known about the relationship between

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http://dx.doi.org/10.1016/j.addbeh.2013.12.007

impulsivity and risk-taking with respect to emotional and reward processing, little is known about whether these factors relate to components of cognitive functioning. This is especially important given that during adolescence, brain regions subserving many aspects of cognition are undergoing maturational change and may be uniquely associated with varying levels of individual differences in impulsivity and risk-taking—differences that may prove valuable in further understanding how these factors may relate to addiction. Therefore, the purpose of this study was to investigate the neural correlates of working memory and their relationship to impulsivity and risk-taking in an adolescent sample.

1. Adolescent risk-taking

Risk-taking has been defined as behavior that is "performed under uncertainty […], and without robust contingency planning and may frequently lead to negative consequences" (Balogh, Mayes, & Potenza, 2013, p. 2). Adolescence is characterized by increasing levels of risk-taking (Steinberg, 2008), and accordingly this has been associated with the greater reported rates of morbidity and mortality during this developmental period (Eaton et al., 2012). While evidence of risk-taking has been assessed using behavioral and self-report measures, our understanding of why increased risk-taking behavior is typically observed during adolescence has been greatly informed by neurobiological investigation. Specifically, a dual systems approach to adolescent risk-taking behavior proposes an important role for two neurobiological systems in the adolescent brain (Casey, Jones, & Hare, 2008; Steinberg, 2008). The first, the affective system is responsible for processing of reward and socioemotional information, and includes the amygdala, ventral striatum (VS), medial prefrontal cortex (mPFC), orbital frontal cortex (OFC) and insula. The second, the cognitive system, is responsible for executive functioning, and includes the prefrontal cortex (PFC) and parietal regions. Across the course of adolescence, both the affective and cognitive systems undergo significant change (Nelson, Leibenluft, McClure, & Pine, 2005), with the neural circuits underscoring affective systems maturing in advance of those underscoring cognitive systems (Casey et al., 2008; Steinberg, 2008). Thus, according to this model, increased rates of risk-taking behavior in adolescence reflect a relative imbalance between developing cognitive and affective neural systems.

Concurrently, it is also important to recognize that increases in adolescent risk-taking behavior have been associated with the development of neurocircuitry that underscores motivational drives and behaviors (Chambers, Taylor, & Potenza, 2003). Motivated behavior is thought to be a direct consequence of the primary motivational circuitry that comprises the PFC, striatum and thalamus. According to this model, increases in adolescent risk-taking behavior have been associated with the neurocircuitry that underscores either the promotion (e.g., the striatum) or the inhibition (e.g., PFC) of motivational drives and behaviors (Chambers et al., 2003). Resonating with a dual systems model, this motivational model posits that risk-taking behavior in adolescence reflects a delay in the maturation of the inhibitory systems relative to the promotional systems. Relatedly, a third account (Ernst & Fudge, 2009) has examined motivational drives and their relationship to risk-taking behavior, highlighting a role for an approach system (i.e., striatum), an avoidance system (i.e., amygdala) and a regulatory system (i.e., PFC). In this model, increased risk-taking reflects an imbalance between these three systems. Thus, the tendency for increased sensitivity to reward despite presence of potential harm during adolescence may be explained by a strong approach system, a weak avoidant system, and an inefficient regulatory system (Ernst, Pine, & Hardin, 2006).

2. Adolescent impulsivity

An important construct related to risk-taking behavior is impulsivity. Impulsivity is a multifaceted construct that can be defined as "a predisposition towards rapid, unplanned reactions to internal or external stimuli [with diminished] regard to the negative consequences of these reactions to the impulsive individuals or others" (Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001, p. 1784; Potenza, 2007). Accumulating evidence suggests a linear decrease in impulsivity from childhood into adulthood (Casey et al., 1997; Green, Fry, & Myerson, 1994; Steinberg et al., 2009), where adolescence represents a significant period in reductions of impulsivity (Fischer, Biscaldi, & Gezeck, 1997; Smith, Xiao, & Bechara, 2012). Moreover, neuroimaging data suggest that decreases in impulsivity during adolescence may be associated with maturation of brain regions underscoring cognitive control (Eppinger, Nystrom, & Cohen, 2012; Hooper, Luciana, Conklin, & Yarger, 2004).

Impulsivity can be assessed by self-report and behavioral measures that yield specific dimensions of impulsivity that relate to three general areas: decision-making, attention, and motor responding (de Wit, 2009; Patton, Stanford, & Barratt, 1995; Stanford et al., 2009). These dimensions are informative in fractionating impulsivity, and appear important clinically with each impulsive dimension being differentially related to psychiatric illnesses (Swann, Anderson, Dougherty, & Moeller, 2001). Behavioral tasks have been designed to capture these elements of impulsivity, largely consisting of decision-making and response inhibition tasks, where impairments in multiple domains may be indicative of higher levels of impulsivity. These behavioral paradigms have been incorporated with functional neuroimaging approaches in an attempt to understand the potential neural correlates of impulsivity (Fineberg et al., 2009).

3. Working memory

Central to the current study is the exploration of whether risk-taking and impulsivity are associated with the neural correlates of cognitive functioning, specifically working memory. Working memory refers to the provisional storage and manipulation of information essential for task performance or goal directed behavior (D'Esposito, 2007; D'Esposito, Detre, Alsop, & Shin, 1995). Information held in working memory is only temporary and remains for a short duration of time. However, active maintenance and rehearsal strategies can facilitate storage of this information over longer periods (D'Esposito, 2007). Notably, working memory is not considered a unitary system, but may consist of a number of subsystems to facilitate information processing (Baddeley & Hitch, 1974). Concurrently, investigations have begun to separate out the different processing stages of working memory to facilitate investigation into the neural correlates of this critical executive function. Specifically, research has focused on the notion that working memory consists of three distinct stages: encoding, rehearsal, and recognition (Bedwell et al., 2005; Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002).

Common and unique brain regions have been identified with the different stages of working memory. During encoding, regions including dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), frontal gyrus and striatum are recruited (Narayanan et al., 2005; Nyberg et al., 1996). Rehearsal and active maintenance are associated with activity in the frontal gyrus, ventrolateral prefrontal cortex (VLPFC), DLPFC, ACC, premotor cortex, thalamus, parietal cortex and caudate (Jonides et al., 1998; Narayanan et al., 2005; Olesen, Macoveanu, Tegner, & Klingberg, 2007). Finally, storage and retrieval of information (i.e., recognition) has been associated with the parietal cortex (Jonides et al., 1998; Smith & Jonides, 1997, but see also Fiez et al., 1996; Grasby et al., 1993), with other areas also associated with retrieval being frontal regions, ACC, left parietal cortex, thalamus and insula (Narayanan et al., 2005; Nyberg et al., 1996).

Although several studies have begun to explore the neural correlates of working memory (Cohen et al., 1997; D'Esposito et al., 1995), few studies have directly compared the neural correlates of encoding, rehearsal and recognition of verbal and non-verbal stimuli. Studies have suggested that verbal and non-verbal stimuli are organized by hemispheric asymmetry, with verbal content associated with increased activity in the left hemisphere and spatial content associated with