Published in final edited form as:

Addict Behav. 2014 November ; 39(11): 1606–1621. doi:10.1016/j.addbeh.2013.12.007.

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

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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

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Disclosures

The authors report no conflicts of interest. Dr. Potenza has consulted for Lundbeck and Ironwood pharmaceuticals; has had financial interests in Somaxon pharmaceuticals; received research support from Mohegan Sun Casino, Psyadon pharmaceuticals, the National Center for Responsible Gambling, the National Institutes of Health (NIH), Veterans Administration; has participated in surveys, mailings, or telephone consultations related to drug addiction, impulse-control disorders, or other health topics; has consulted for gambling, legal and governmental entities on issues related to addictions or impulse-control disorders; has provided clinical care in the Connecticut Department of Mental Health and Addiction Services Problem Gambling Services Program; has performed grant reviews for the NIH and other agencies; has guest edited journal sections; has given academic lectures in grand rounds, Continuing Medical Education events, and other clinical or scientific venues; and has generated books or book chapters for publishers of mental health texts.

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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, dorsolateral and ventrolateral 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 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.

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 characterised by increasing levels of risk-taking (Steinberg, 2008a), 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, 2008a). The first, the affective system is responsible for processing of reward and socioemotional information, and includes the amygdala, ventral striatum (VS), medial prefrontal (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, 2008a). 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 et al., 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).

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 these 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., 2010).

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 increased activity in the right hemisphere (Rothmayr et al., 2007, Smith & Jonides, 1997). Furthermore, within non-verbal tasks, some studies have implicated dorsal areas in object location and ventral areas in object characteristics (Owen, Doyon, Petrides, & Evans, 1996). This dorsal-ventral dissociation has also been explained across a second dimension that suggests the involvement of ventral areas in maintenance and the involvement of the dorsal areas of prefrontal cortex in manipulation and monitoring of the stored information (D'Esposito, Postle, Ballard, & Lease, 1999). Taken together, there is accumulating support for distinct as well as overlapping neural correlates of working

memory, and that the stimulus material employed in working memory tasks may be differentially processed as a function of their content (verbal, non-verbal).

Working Memory, Impulsivity, and Risk-Taking

Our goal in the present study was to examine the neural correlates of working memory for both verbal and visuospatial information and their relationship to impulsivity and risk-taking. To date, most research has focused on the relationship between impulsivity and working memory, with the notion being that two processes may be functionally related (Mika et al., 2012). This may be in part owing to the potential for common processes underscoring these two constructs. For instance, attention is required for encoding and maintaining information in working memory, and decreases in attention are associated with higher levels of impulsivity (Awh, Vogel, & Oh, 2006; Patton et al., 1995). Indeed, evidence suggests that there may be a relationship between inattention and impulsivity in some clinical samples (Winstanley, Eagle, & Robbins, 2006), with particular focus on frontal and parietal regions, areas that may be important to sustained attention (Posner & Petersen, 1990). At the same time, in exploring this potential relationship between working memory and impulsivity, some studies have reported that low working memory capacity is associated with increased vulnerability to heightened impulsive behavior (Finn, Justus, Mazas, & Steinmetz, 1999; Hinson, Jameson, & Whitney, 2003). Furthermore, increasing working memory load seems to impair decision-making (Hinson et al., 2003). Building on this work, emerging data also supports the notion that working memory training may reduce levels of impulsivity in adults (Bickel et al., 2011; Beck, Hanson, Puffenberger, Benninger, & Benninger, 2010; Klingberg, Forssberg, & Westerberg, 2002).

At a neurobiological level, studies have sought to identify common brain regions underlying both impulsivity and working memory. Patients with lesions in DLPFC and posterior VMPFC show poor performance on both working memory and impulsivity tasks (Bechara, Damasio, Tranel, & Anderson, 1998; Manes et al., 2002). In studies combining demands on working memory and impulsivity (indexed by inhibition), common activity was observed in the medial frontal gyrus, DLPFC, bilateral inferior parietal lobule, putamen and insula (Hester, Murphy, & Garavan, 2004; Kelly, Hester, Foxe, Shpaner, & Garavan, 2006). Building on this work, McNab and colleagues (2008) performed a conjunction analysis to determine the overlapping brain regions of working memory (verbal and spatial) and inhibition (Go/no-go, Stop signal task and Flanker task). Common brain activations were found in the right IFG, right middle frontal and right parietal regions across both working memory and inhibitory tasks. Other regions showing overlap included the left IFG, insula, parietal and precentral regions.

Notably, more recent research has investigated the role of impulsivity as a mediating variable when examining the relationship between working memory and risk-taking behavior in adolescents. Two recent studies have reported that impulsivity mediates the relationship between performance on working memory tasks and real-world risk-taking behavior, namely early initiation of sexual behavior (Khurana et al., 2012a) and early alcohol use (Khurana et al., 2012b). However, there is some evidence to suggest that the type of impulsivity may be important in understanding this relationship (Romer et al., 2009).

Consequently, employing methods that utilize dimensions of impulsivity are necessary for studies in this area. Taken together, emerging behavioral evidence suggests relationships between working memory and risk-taking and impulsivity, although the neural correlates of these relationships, and how these pertain to each processing stage within working memory, is not known.

Current Study

The purpose of this adolescent study was three-fold. First, we examined the neural correlates of working memory during encoding, rehearsal, and recognition (immediate, delayed) in a verbal and visuospatial working memory task. Second, we investigated the relationship between the neural correlates of working memory to impulsivity by employing the adolescent version of the Barratt Impulsiveness Scale 11 (BIS-11A; Fossati, Barratt, Acquarini, & Ceglie, 2002). This measure divides impulsivity into dimensions of inattention, motor and non-planning impulsivity (Patton, Stanford, & Barratt, 1995). Third, we investigated the relationship between the neural correlates of working memory and risk-taking behavior as measured by the Balloon Analogue Risk Task (BART; Lejuez et al., 2002).

We hypothesized that we would replicate past research examining the neural correlates of working memory in our adolescent sample; specifically, we predicted that the DLPFC and ACC would be recruited during encoding; the VLPFC, parietal cortex, premotor cortices and ACC would be recruited during rehearsal; and the DLPFC, ACC and insula would be activated during recognition and delayed recognition. We also hypothesized that impulsivity would be correlated with the neural substrates of working memory. Specifically we predicted that: (1) given past research on response inhibition (Aron, Robbins, & Poldrack, 2004; Chambers et al., 2006; Menon, Adelman, White, Glover, & Reiss, 2001; Swick, Ashley, & Turken, 2008), motor impulsivity would be associated with activity in IFG/VLPFC and cortical motor regions comprising premotor and supplementary motor areas; (2) attention impulsivity would be associated with areas implicated in sustained attention, namely right frontal and parietal regions (Posner & Petersen, 1990); and (3) non-planning impulsivity would be associated with activity in the DLPFC and VMPFC. Finally, consistent with the dual systems model (Casey, Jones, & Hare, 2008; Steinberg, 2008a), we hypothesized that risk-taking behavior would be inversely correlated with activity in frontal and parietal regions (regions implicated in cognitive control) and positively correlated with activity in subcortical areas comprising the striatum and insula (regions implicated in affective processing).

Methods

Participants

21 healthy adolescents (12 males, 9 females; aged 13–18 years; Mean (SD) IQ=89.92 (8.40)) were recruited from an existing longitudinal study (Mayes et al., 2005). Exclusion criteria included any major axis-I psychiatric disorder, any evident language delays, and regular (daily or weekly) use of substances. Individuals with any active medical or neurological disease, pregnancy and claustrophobia were excluded. Of these 21 participants,

3 were subsequently excluded from analysis due to excessive head motion. Therefore, the final sample consisted of data from 18 participants. All participants were given a financial incentive for participating in the study. The Human Investigation Committee of Yale University, School of Medicine, approved this study and written informed consent of parents and child assent was obtained prior to participation.

Measures

Barratt Impulsiveness Scale for Adolescence (BIS-11A; Fossati et al., 2002)—

The BIS-11A is a 30-item self-report questionnaire adapted from the Barratt Impulsiveness Scale (BIS-11) to measure trait impulsivity in adolescents. This scale comprises of 6 primary factors clustered into 3 secondary factors; specifically, (1) Attention Impulsiveness (i.e., attention impulsivity, cognitive instability); (2) Motor Impulsiveness (i.e., motor impulsivity, self-control); and (3) Non-Planning Impulsiveness (i.e., perseverance, cognitive complexity). Responses are scored based on a 4-point Likert-scale (Rarely/Never; Occasionally; Often; Almost always/Always). The total score ranges from 30 to 120, with higher scores signifying increased impulsivity. The BIS-11A has moderate internal consistency (Cronbach's $\alpha = 0.78$; Fossati et al, 2002) and has been effectively used to measure impulsivity in healthy adolescent populations such that it can differentiate smokers from non-smokers (Melanko, Leraas, Collins, Fields, & Reynolds, 2009; Reynolds & Fields, 2012) and is related to onset and frequency of alcohol use and smoking (Fossati et al, 2002). Furthermore, construct validity is evident from the relationship between BIS-11 and measures assessing impulse-related behavioral disorders (e.g., attention-deficit hyperactivity disorder (ADHD), aggression; Fossati et al, 2002). It is a short and easy measure requiring a third- to fourth-grade reading level (Zaparniuk & Taylor, 1997). BIS-11A data were collected approximately a year prior to imaging.

Balloon Analogue Risk Task (BART; Lejuez et al., 2002)—The BART is a computer-based measure assessing risk-taking propensity. The task consists of 30 trials. During each trial, participants pump (inflate) a simulated balloon. Each balloon has its own explosion threshold, varying between 1–128 pumps, with the average break/explosion point being 64 pumps. Participants receive 2 cents for each pump they make, but if the balloon explodes, the money earned for that trial (balloon) is lost. Participants can stop pumping at any point and collect their winnings from that trial. Risk-taking is measured by the average number of pumps for successful trials; i.e., trials where the balloons did not explode (Lejuez et al, 2002). Higher scores indicate greater propensity of risk-taking.

The BART is a reliable and valid measure widely used across adult and adolescent populations (Lejuez, Aklin, Bornoalova, & Moolchan, 2005). Studies have shown the BART is associated with a range of real-world risk-taking behaviors, including addictive behaviors (e.g., alcohol, smoking and drug use) (Aklin et al., 2005, Lejuez et al., 2003a), health and safety behaviors (e.g., helmet use, seatbelt use, unsafe sex) (Lejuez et al., 2002, 2003a), and “trait” measures (e.g., of sensation seeking, psychopathy and impulsivity; Lejuez et al., 2002, 2003b). The BART has strong split-half reliability ($r = 0.82$; Lejuez et al., 2002) and test/retest reliability ($r = 0.62$ – 0.82 across 3 administrations on the same day,

Lejuez et al. (2003b); $r=0.77$ across a span of two weeks, White, Lejuez, & de Wit (2008)). BART data were collected approximately 6 months prior to imaging.

Working Memory Task—An fMRI Verbal and Visuospatial Recognition Task was administered to assess working memory (see Figure 1).

The verbal condition comprised of 138 three- to six-letter monosyllabic English words, whereas the visuospatial condition consisted of 138 non-verbal stimuli comprising of South-Asian characters. It was assumed that these characters would be coded as complex geometric patterns for participants who do not speak South-Asian languages (no participant spoke South-Asian languages in the present sample). Both verbal and visuospatial conditions consisted of four stages: (1) rest, (2) encoding, (3) rehearsal, and (4) recognition, each lasting for twenty seconds. It began with the *rest* stage where participants waited for the beginning of the trial. During the *encoding* stage, stimuli were consecutively presented to participants. Then, during the *rehearsal* stage, there was a delay during which participants were asked to keep them in mind and rehearse. Finally, during the *recognition* stage, six stimuli were presented consecutively. Participants indicated by a button press whether the stimuli were previously seen or not during the encoding stage: three stimuli were always from the original stimulus set and three stimuli were new to the condition. This sequence was repeated four times within a run; two sequences contained verbal stimuli and two sequences contained visuospatial stimuli. There were six runs in total, and therefore twelve trials of verbal working memory and twelve trials of visuospatial working memory.

After all six runs were completed, a *delayed recognition* block of trials was presented. This block consisted of rest and a delayed recognition task. The task could contain verbal or visuospatial information, and six stimuli were presented: three were old stimuli (presented during encoding but not early recognition) and three were new stimuli. During the delayed recognition block, there were ten trials of the verbal task, and ten trials of the visuospatial task (randomized). Responding during the task was recorded; however, these behavioral data were lost, and thus analyses focus on the neuroimaging data. All participants completed a mock scan prior to data collection to reduce anxiety associated with scanning and to ensure their clear understanding of the task. Further, immediately after scanning, all participants were queried regarding strategies used to remember verbal and nonverbal stimuli. This allowed a manipulation check to ascertain the type of strategies participants were employing during the task. No participant reported use of comparable strategies for the verbal and visuospatial conditions.

FMRI Image Acquisition

Data were collected using a 3.0 Tesla Siemens Trio MRI system with a standard quadrature head coil. Before scanning, participants underwent a mock scanner training session where they performed the task. This practice session was comparable to the actual scanning experience and was conducted to familiarize the participants with the scanner. The stimuli used differed from the stimuli used in imaging runs. Foam padding and a forehead-restraining band were used to prevent head motion.

Functional data were acquired using a single-shot, gradient echo-pulse sequence with the following parameters: echo time (TE) = 30 ms, repetition time (TR) = 2000 ms, flip angle (FA) = 80°, imaging matrix = 64mm², field of view (FOV) = 20cm², axial oblique plane with 25 slices, 5mm slice thickness, voxel size 3.125mm³ × 3.125mm³, 1 average (AVG). Anatomical images of two types were obtained: T1 weighted anatomic scan and High-Resolution anatomic scan. The prior was acquired using a FLASH sequence with the following parameters: TR = 300ms, TE = 2.47 ms, FA = 60°, FOV = 20cm², imaging matrix = 256mm², axial oblique plane with 25 slices, slice thickness = 5mm, voxel size of 0.781mm³ × 0.781mm³, 2 AVG. Magnetization-prepared rapid acquisition with gradient echo (MPRAGE) was used to acquire high-resolution anatomic scans. It had the following parameters: TE = 2.77 ms, TR = 2530ms, FA = 7°, FOV = 256×256, sagittal plane with 176 slices, slice thickness = 1mm, voxel size of 1mm³ × 1mm³, 1 AVG.

FMRI Analysis

Whole-brain fMRI analyses were conducted. Functional data were preprocessed and analysed using Bioimage Suite analysis package (www.bioimagesuite.org). The data for each participant were corrected for slice time acquisition using sinc interpolation and corrected for motion using SPM99. Images were excluded from analysis if their displacement exceeded 1.5mm and the rotation exceeded 2°. Smoothing was carried out using a Gaussian filter of full width at half maximum (FWHM) of 6.25mm. The preprocessed data were then aligned with the high-resolution anatomic scan followed by normalization. The data were spatially normalized to the Montreal Neurological Institute (MNI) Template using nonlinear spatial normalization. As described above, data from 3 participants were excluded owing to excessive head motion, leaving a sample of 18 adolescents in the present analyses.

Eight individual maps of activation were generated for each subject by modelling blocks using regression-based methods implemented with the general linear model (GLM). Effects were modelled by convolving the gamma function with block-length (20sec) box-car function for each task within each run. To assess the group effects, each of these eight maps was combined across subjects to generate group t-test maps. Individual scores on the BART and BIS-11 measures were correlated with each voxel of the individual maps. For all analyses, the obtained maps were checked at a threshold of $p=.05$ corrected for multiple comparisons using the AFNI AlphaSim program to establish a family-wise error (FWE) correction. A cluster of 251 voxels (6777mm³) was considered to be significantly activated in the whole-brain analysis. The rationale for using a large cluster size is twofold. First, as this is a preliminary study, our goal was to identify broad regions of activity associated with working memory, impulsivity and risk-taking. Second, conducting numerous correlations with a relatively small sample size increases the likelihood of Type-1 error. Thus a large cluster size (one that corrects for multiple comparisons at a whole-brain level) was used to control for false positives.

Results

Psychometric and Behavioral Measures

From the 18 participants that underwent scanning, 16 participants completed the BIS-11A. However, one participant did not respond to all items on the motor subscale but their data was included for all other analyses. The mean total impulsivity score was 63.13 ($SD=8.36$). The total score was broken down into its three factors: Attention Impulsivity ($M=15.13$, $SD=3.5$), Motor Impulsivity ($M=23.3$, $SD=2.38$) and Non-Planning Impulsivity ($M=24.00$, $SD=5.21$). All 18 participants completed the BART. The mean average adjusted pumps across the 30 trials were 27.98 ($SD=15.15$; range=7.76–54.94). No statistically significant correlations were found between BART performance and the BIS-11A total score, or its three subscales ($p's>.42$). Furthermore, no relationship was found between participant age and the scores on the BIS-11A (total score or subscales) or BART ($p's>.08$).

Neural Correlates of Working Memory

Whole-brain analyses first examined the differences in activity during each of the encoding, rehearsal, and recognition cycles for verbal and visuospatial working memory tasks relative to the rest cycle. Family-wise error correction for multiple comparisons was set at $p<.05$ with a cluster threshold of 6777 mm³ for each of the 8 maps. Table 1 presents the coordinates, sizes and mean activation values of the cluster of brain regions for the verbal and visuospatial conditions.

Encoding—Regional activity during verbal encoding recruited a number of regions, including DLPFC, vmPFC, striatum and insula. During visuospatial encoding, regions such as the cerebellum and intraparietal sulcus were recruited. Common activations across both verbal and visuospatial encoding included the ACC, fusiform gyrus, parahippocampus and extrastriate area. Adolescent age was found to be associated with the neural activity during encoding of both verbal (cluster 4 comprising DLPFC and motor cortex; $r(16) = 0.47$, $p < .05$) and visuospatial stimuli (cluster 6 comprising ACC and motor cortex; $r(16) = 0.59$, $p < 0.01$).

Rehearsal—Verbal rehearsal evidenced differential regional activity in the supplementary motor area, ACC, left DLPFC, vmPFC, and IFG. Common regional activations across both verbal and visuospatial rehearsal occurred in the PCC, insula, primary motor cortex, extrastriate, putamen and thalamus. No additional regions were recruited during the rehearsal of visuospatial information. Notably, adolescent age was associated with rehearsal of verbal stimuli (cluster 3 comprising left DLPFC $r(16) = 0.55$, $p < 0.01$).

Recognition—Common activation was found in the ACC, PCC, striatum, thalamus, insula, cerebellum and motor cortex during the recognition of verbal and visuospatial information. Unique activations were seen in bilateral DLPFC during the verbal recognition condition and in bilateral intraparietal sulcus during the visuospatial recognition condition. Adolescent age was not associated with activity during verbal or visuospatial recognition.

Delayed Recognition—The ACC, parietal cortex, insula, putamen, fusiform gyrus, and extrastriate areas were activated during the delayed recognition of both verbal and visuospatial information. In addition, the verbal condition also recruited the caudate, thalamus and right DLPFC and IFG areas, while the visuospatial condition additionally activated bilateral temporal gyri and the intraparietal sulcus. There were no age-associated effects in the delayed-recognition conditions.

Differential Brain Activation Across Verbal and Visuospatial Working Memory

Differential brain activation across verbal and visuospatial working memory was assessed using t-tests at a cluster threshold of 6777 mm^3 . Contrasts were generated across each working memory condition by comparing the verbal to its visuospatial counterpart (e.g., Verbal Encoding versus Visuospatial Encoding). Statistically significant differences were found between the encoding, recognition and delayed recognition conditions at a threshold of $p < .05$ FWE-corrected: Similar differences in brain activity were found across the three conditions such that increased activation in the left VLPFC, DLPFC and insula was found for the verbal conditions while activation in the right parietal regions was found for the visuospatial conditions (see Fig. 2). Coordinates, sizes and mean activation values of the activation changes of difference across the encoding, recognition and delayed recognition conditions are presented in Table 2.

Brain and Behavior Correlations: BART and Working Memory

To determine the relationship between the working memory-related brain activity and the scores on the BART, a voxel-based whole-brain correlation analysis was conducted between BART scores and the 8 individual maps of working memory; i.e., encoding, rehearsal, recognition and delayed recognition across both verbal and visuospatial conditions conducted at voxel-level threshold of $p < .05$ and a conjoint cluster threshold of 6777 mm^3 . Coordinates, size of the cluster and the correlation values of the cluster of brain regions that reached statistical significance for correlations with the BART are presented in Table 3.

Verbal and Visuospatial Rehearsal and BART—A positive correlation was found between scores on the BART and the subcortical regions activated during the rehearsal of verbal stimuli, $r(16) = .56, p < .05$ (Fig. 3, Panel A, cluster 1). These regions comprise the cluster including the thalamus and dorsal striatum. An inverse correlation was found between average adjusted pumps and cortical regions activated during the rehearsal of visuospatial stimuli, $r(16) = -0.55, p < 0.05$ (Fig. 3, Panel B, cluster 3). These regions comprise the right ACC, PCC, parietal regions, temporal regions and supplementary motor cortex.

Verbal Recognition and BART—A positive correlation was found between BART scores and activity in subcortical regions, namely the thalamus and right dorsal striatum, $r(16) = .58, p < .05$, corrected during verbal recognition (Fig. 3, Panel C, cluster 2). An inverse correlation was found between BART scores and activity in cortical regions comprising the parietal and temporal regions, $r(16) = -.56, p < .05$ (Fig. 3, Panel D, cluster 1).

Brain and Behavior Correlations: BIS-11A and Working Memory

To determine the relationship between the working memory-related brain activity and the scores of BIS-11A, a voxel-based whole-brain correlation analysis was conducted at $p < .05$ and a cluster threshold of 6777 mm^3 . Coordinates, sizes and the correlation values of the cluster of brain regions showing statistically significant correlations are presented in Table 4.

Verbal Encoding and Motor Impulsivity—There was a positive correlation between motor impulsivity and activity during verbal encoding in cluster 2, table 4A, comprising the left IFG, insula, DLPFC, Broca's area and the premotor cortex, $r(13) = 0.58, p < .05$.

Verbal and Visuospatial Rehearsal and Motor Impulsivity—There was also a positive correlation between activity in the left IFG, insula, DLPFC, putamen and premotor cortex with motor impulsivity during the rehearsal of verbal information, $r(13) = 0.61, p < .05$ (Fig. 4 panel A, table 4B cluster 1). In contrast, an inverse correlation was found between scores on the motor impulsivity subscale and brain regions activated during rehearsal of visuospatial information, $r(13) = -0.58, p < .05$ (Fig. 4 panel B, table 4C cluster 1). These neural substrates comprise the bilateral posterior parietal cortex, premotor cortex, primary motor cortex, primary sensory cortex and sensory association areas.

Visuospatial Recognition, Motor Impulsivity, and Non-Planning Impulsivity—There was a positive correlation between motor impulsivity and activity in the cortical and subcortical brain regions activated during the recognition of visuospatial information, $r(13) = .59, p < .05$ (Fig. 4 panel C, table 4E cluster 2). These cortical regions comprise the left anterior parietal cortex and primary sensory cortex while the subcortical regions include the left thalamus, striatum and brainstem. A positive correlation was found between the non-planning impulsivity subscale and the PCC, primary visual cortex and extrastriate cortex, $r(13) = .57, p < .05$ (Fig. 4 panel D, table 4F cluster 1).

Verbal Recognition, Attention Impulsivity and Non-Planning Impulsivity—There was an inverse correlation between the subscale of attention impulsivity and activity in the right primary motor cortex, primary sensory cortex and the premotor cortex during the recognition of verbal information, $r(13) = -.58, p < .05$ (table 4D cluster 1). The non-planning impulsivity subscale correlated positively with the extrastriate area and primary visual area during the delayed recognition of verbal information, $r(13) = .60, p < .05$ (table 4G cluster 1).

Discussion

Adolescence represents a critical period of development that is associated with increased levels of impulsivity and risk-taking behavior. These adolescent characteristics may have detrimental consequences in respect of morbidity and mortality, with there being particular interest in the contribution of impulsivity and risk-taking to addictive behaviors. To date, several studies have examined the relationships between these constructs and adolescent sensitivity to reward and socioemotional processes; however, fewer studies have examined the relationships between impulsivity and risk-taking with other cognitive processes.

Therefore, the purpose of this study was to investigate the neural correlates of working memory and their relationship to risk-taking and impulsivity in an adolescent sample.

Neural Correlates of Working Memory

Prior to considering the relationships between impulsivity, risk-taking and neural correlates of working memory, we will review our findings related to the neural correlates of working memory. The working memory task that we employed provided an opportunity to (1) parse the distinct neural correlates of the different stages of working memory (specifically, encoding, rehearsal, recognition and delayed recognition); and (2) examine both visuospatial and verbal working memory processes. Our findings were largely consistent with existing research in this area, confirming the presence of overlapping as well as distinct neural correlates of the different stages of working memory in respect of visuospatial and verbal stimuli.

In our first analysis, we found that multiple regions were recruited during the *encoding* of both verbal and visuospatial stimuli, including the ACC and parahippocampus. The ACC has previously been identified as being involved with encoding information into working memory, as has the DLPFC (Narayanan et al., 2005; Nyberg et al., 1996). However, we only found the DLPFC to be recruited during verbal encoding, despite prior work implicating DLPFC in the encoding of visuospatial information as well (Rothmayr et al., 2007). Interestingly, while other studies have confirmed ACC involvement in verbal encoding (Rypma & D'Esposito, 1999; Rypma & D'Esposito, 2000), there is also a suggestion that the ACC and left DLPFC are both involved in long-term encoding of verbal information as well (Buckner & Koutstaal, 1998; Kaneda & Osaka, 2008). Thus, there is accumulating evidence of potential overlapping neurocircuits for working memory and long-term memory.

Second, we only found evidence for distinct neural correlates underscoring rehearsal of verbal stimuli relative to the rest condition, which included the supplementary motor area, ACC, left IFG, DLPFC and vmPFC. No additional regions were recruited during the rehearsal of visuospatial stimuli. The regions recruited during verbal rehearsal are consistent with previously published research in this area (Jonides et al., 1998; Narayanan et al., 2005; Olesen et al., 2007). Moreover, activity in left IFG/Broca's area has also been implicated in subvocal rehearsal (Smith, Jonides, Marshuetz, & Koeppel, 1998), and activity in left premotor cortex has been implicated in storage of verbal information (Henson, Burgess, & Frith, 2000; Romero, Walsh, & Papagno, 2006). Therefore, the findings from the present study are consistent with studies documenting the broader neurocircuitry of verbal rehearsal.

Third, as has been previously reported (Leung, Gore, & Goldman-Rakic, 2005; Narayanan et al., 2005; Nyberg et al., 1996), during *recognition* and *delayed recognition* of verbal and visuospatial information, the ACC was again recruited. Activity in bilateral DLPFC was also observed during both recognition and delayed recognition for verbal information. However, activity in left DLPFC was observed only during the delayed recognition of visuospatial information. The activation of DLPFC during retrieval of verbal and visuospatial information is consistent with the account that DLPFC is involved in processing of multimodal information (Funahashi, 2006). Previous studies measuring verbal working memory have shown activation of bilateral DLPFC similar to the present study (Mottaghy et

al., 2000; Smith & Jonides, 1998). However, left DLPFC activation during delayed recognition in the visuospatial task differs from previous reports of increased activity in the right DLPFC or bilateral DLPFC during these types of task (Opitz, Mecklinger, & Friederici, 2000; Smith, Jonides, & Koeppel, 1996). Recent evidence has suggested that the left DLPFC may be involved in the retrieval of information from long-term memory when participants are not using any intended strategy (Manenti, Cotelli, Calabria, Maioli, & Miniussi, 2010). Thus, our finding of left DLPFC activity suggests that adolescents in the present study may have been drawing on long-term memory during this delayed recognition task.

In addition to investigating the neural correlates of working memory, we also sought to understand whether there were differences in the processing of verbal and visuospatial information. Differential activity in the left VLPFC was found during encoding, recognition and delayed recognition of verbal information. This is consistent with prior research (Rottschy et al., 2012; Smith & Jonides, 1998) and further supports the role of left VLPFC in processing verbal material. We also found differential activity in the right parietal regions during encoding, recognition and delayed recognition of visuospatial information. The literature is less consistent in this regard, with roles for right frontal regions (Courtney, Petit, Haxby, & Ungerleider, 1998), dorsal and medial premotor cortex (Rottschy et al., 2012), and parietal regions (McCarthy & Warrington, 1994; Pochon et al., 2001; Postle, Berger, Taich, & D'Esposito, 2000; Smith & Jonides, 1997) during encoding and recognition of visuospatial information. Nevertheless, these findings are consistent with the notion that there may be hemispheric lateralization in processing verbal and visuospatial information in the brain (Kelley et al., 1998; Smith & Jonides, 1997; Smith et al., 1996).

Working Memory and Risk-Taking

Central to the current study was to investigate the relationship between working memory and risk-taking. To achieve this, we examined the neural correlates of each stage of working memory as related to measures of risk-taking behavior as assessed by the BART (Lejuez et al., 2002). We found during verbal rehearsal, higher levels of risk-taking were associated with increased activity in a regional cluster involving the dorsal striatum (caudate and putamen) and thalamus. Other studies have also implicated the thalamus during the rehearsal of verbal materials (Awh, Smith, & Jonides, 1995; Koelsch et al., 2009). While few studies have implicated the caudate and putamen in the neural correlates of working memory, there is some suggestion that these regions, primarily the caudate, may be recruited during working memory tasks (Braver et al., 1997). For instance, one study reported that the caudate is important for the manipulation of information in working memory (Lewis, Dove, Robbins, Barker, & Owen, 2004). Furthermore, increased activity in the caudate has been found after working memory training (Olesen, Westerberg, & Klingberg, 2004). Finding a positive correlation between activity in the dorsal striatum and thalamus and risk-taking behavior is informative given the broader framework of adolescent risk-taking behavior and our understanding of the neurobiology that may contribute to risky behavior during the developmental period. Indeed, increasing activity in the dorsal striatum and its association with higher levels of risk-taking is consistent with the role of this region in driving behavior during adolescence according to the dual systems model (Casey et al., 2008), but is also

consistent with motivational accounts of adolescent risky behavior, and the additional role of the thalamus in this regard (Chambers et al., 2003).

We also found during the rehearsal of visuospatial information, higher levels of risk-taking were associated with reduced activity in temporal and parietal regions. These regions have previously been associated with the storage of non-verbal information (Jonides et al., 1993; Rothmayr et al., 2007) as well as working memory capacity (Olesen et al., 2004). Moreover, the right parietal cortex more generally has been implicated in a variety of attentional processes (Coull, Frith, Frackowiak, & Grasby, 1996; Posner & Peterson, 1990; Rushworth, Ellison, & Walsh, 2001). Thus, this inverse relationship between risk-taking and activity in temporal and parietal regions may suggest that higher levels of risk-taking are associated with poorer recruitment of cortical regions involved in maintaining attention to task-relevant information during visuospatial rehearsal. In support of this hypothesis, we also found that during the recognition of verbal information, higher levels of risk-taking were associated with increased activity in the dorsal striatum and thalamus and lower levels of activity in temporal and parietal regions. This finding resonates with neurobiological accounts underscoring risk-taking behavior during adolescence and the imbalance between cognitive and affective systems during this developmental period (Casey et al., 2008; Steinberg et al., 2008). Finally, it is worth noting that taking these data together, they support the importance of examining individual differences in adolescent risk-taking and how they pertain to cognition and behavior (Somerville, Jones, & Casey, 2010).

Working Memory and Impulsivity

A second central tenant of this investigation was to examine the relationship between working memory and impulsivity. To achieve this, we examined the neural correlates of each stage of working memory to the different dimensions of impulsivity assessed using the BIS-11A (Fossati et al., 2002). The BIS-11A is valuable as a measure to employ when investigating impulsivity owing to the different dimensions of impulsivity that it assesses. As predicted, we found a positive correlation between motor impulsivity and left IFG and premotor cortex activity during encoding and rehearsal of verbal information. Other regions showing a similar association included the left insula, DLPFC and Broca's area. The role of right IFG has been well established in response inhibition (Aron et al., 2004; Chambers et al., 2006). However, a recent neurophysiological study has also implicated the left IFG and insula in response inhibition (Swick et al., 2008). Moreover, these findings are consistent with other studies that report common neural correlates underlying working memory and response inhibition in the left IFG, DLPFC and premotor cortex (Hester et al., 2004; Kelly et al., 2006). Indeed, inhibition may be important to working memory in preventing distraction from task-irrelevant stimuli (McNab et al., 2008). The DLPFC, also present in this cluster, has been implicated in attentional control (Milham, Banich, Claus, & Cohen, 2003), temporary coding, maintenance and manipulation of stored information (Smith & Jonides, 1999). Furthermore, the left IFG and premotor cortex have been implicated in subvocal rehearsal, maintenance and storage of encoded verbal information in working memory (Paulesu, Frith, & Frackowiak, 1993; Smith et al., 1998). Taken together, these findings suggest that elevated activity observed in adolescents higher on the dimension of motor

impulsivity during this task is associated with increasing activity in regions associated with response inhibition and attentional control.

During rehearsal of visuospatial material, we found an inverse correlation between motor impulsivity and activity in the premotor cortex, a region previously implicated in visual attention and memory (Simon et al., 2002). A similar relationship was found between motor impulsivity and activity in the posterior parietal lobe. The parietal cortex has been implicated in the storage of spatial working memory (Awh et al., 1999). Recent evidence has also shown it contributes to sustained attention (Thakral & Slotnick, 2009). Furthermore, increased activity in the frontoparietal regions has been associated with better visuospatial task performance (Pessoa et al., 2002). Thus, one interpretation of the observed inverse correlation between motor impulsivity and activity in premotor and parietal regions may be that adolescents high on motor impulsivity have a reduced capacity for maintaining attention to task relevant information during rehearsal, although further work is needed to test this possibility. This finding was unexpected given the positive relationship between motor impulsivity and activity in regions associated with response inhibition and attentional control reported above, but may represent an important distinction in the neural correlates of verbal and visuospatial memory tasks and their relationship to impulsivity.

There was also a positive correlation between motor impulsivity and activity in the left anterior parietal cortex, primary sensory cortex, striatum and thalamus during the recognition of visuospatial information. The thalamus has been implicated in selectively attending to task relevant stimuli by filtering out irrelevant information (LaBerge & Buchsbaum, 1990). This region has connections with cortical areas and is crucial for shifting attention during object recognition (LaBar, Gitelman, Parrish, & Mesulam, 1999). The observed positive correlation suggests that adolescents higher on motor impulsivity may be more effortful in inhibiting distraction by selectively attending to task relevant information during the retrieval of previously learned information, and this hypothesis warrants additional investigation.

It was hypothesized that the attention impulsivity subscale would be associated with activity in the right frontal and parietal cortices, regions which contribute to selective and sustained attention (Coull et al., 1996). However, we instead found that attention impulsivity was associated with activity in the primary motor cortex, primary sensory cortex, and premotor cortex during verbal recognition, suggesting a more significant role for attention impulsivity in processes underscoring working memory. A positive correlation was seen between non-planning impulsivity and brain regions recruited during the recognition of visuospatial material (e.g. PCC, primary visual and extrastriate areas). An association was also observed between non-planning impulsivity and activity in primary visual and extrastriate areas during delayed verbal recognition processing. These areas have previously been reported as being involved in visual processing of diverse information content (Hotson, Braun, Herzberg, & Boman, 1994; Pitcher, Charles, Devlin, Walsh, & Duchaine, 2009). Additionally, a positive association in the PCC was seen during the recognition of visuospatial information. Previous studies have implicated the PCC in spatial working memory and orientation (Vogt, Finch, & Olson, 1992). Furthermore, this region has also shown activation during tasks measuring choice impulsivity such that heightened activity is

observed during selection of smaller immediate rewards over larger delayed rewards (McClure, Laibson, Loewenstein, & Cohen, 2004; Xu, Liang, Wang, Li, & Jiang, 2009), suggesting a role for the PCC in impulsive decision-making.

In summary, the motor impulsivity dimension was associated with brain activity during encoding, rehearsal and recognition phases of working memory, suggesting an important role for motor impulsivity in working memory more generally. Notably, attention and non-planning impulsivity were only associated with brain activity during the recognition and delayed recognition phases of our working memory task. These findings support the potential for a relationship between the neural correlates of working memory and impulsivity, but critically highlight the value of examining different dimensions of impulsivity and working memory, rather than treating these as more global constructs.

Working Memory, Risk-Taking and Impulsivity

This study has evidenced that the neural correlates of the different stages of working memory show associations with both risk-taking and impulsivity. It was noteworthy that during visuospatial and verbal rehearsal stages, there was a differential pattern of relationships between brain activity and these two constructs. Specifically, during verbal rehearsal, higher levels of risk-taking and impulsivity were associated with increasing brain activity, but in different brain regions: the positive relationship between risk-taking and brain activity during rehearsal was in subcortical regions (e.g., thalamus), whereas this positive relationship between motor impulsivity and brain activity during rehearsal was in more cortical regions, namely the left IFG and, DLPFC and VLPFC. There was more consistency in the visuospatial domain, whereby an inverse relationship between risk-taking and brain activity during rehearsal was found in the right parietal cortex, and this same pattern of association for motor impulsivity was associated with reduced activity bilaterally in the postsuperior parietal lobe. This finding in the verbal domain is noteworthy because it suggests that individual difference as they relate to risk-taking and impulsivity may have distinct correlates with neural processing underscoring working memory. While it may be parsimonious to consider that impulsivity and risk-taking exert a comparable influence on aspects of cognition, these results suggest that this may not always hold true. Indeed, understanding the subtleties of these relationships may be helpful in the development of interventions for at-risk adolescents.

Limitations and Directions for Future Research

Although preliminary, the findings from the present study provide support for there being a relationship between the neural correlates of working memory and risk-taking and impulsivity. However, it is important to consider the present study in light of its limitations and directions for future research. While we were able to assess the neural correlates of each stage of working memory and their relationship to impulsivity and risk-taking, we were not able to address this relationship in the context of working memory performance. This will prove important in future studies to determine whether the underlying neural activity is associated with working memory performance, as well as how working memory capacity more generally relates to adolescent risk-taking and impulsivity. Moreover, it will be important to understand the implications of the current findings for addictive behaviors.

Specifically, examining the extent to which the observed neural correlates of working memory may relate prospectively to substance use will be a valuable goal for future research.

From a methodological perspective, although the BIS-11A was valuable in providing indices of the different dimensions of impulsivity, it is a self-report measure, and may be limited by the potential for response bias and the ability of an individual to report their own behavior (de Wit, 2009). Thus, employing behavioral tasks (such as the BART) to accompany self-report measures of impulsivity may be valuable in moving forward with this work. Notably, a limitation in relation to these measures was that the impulsivity and risk-taking assessments were obtained at different time points across a year-long period. While we found evidence that these measures were related to neural activity within some conditions, our measures may have been more tightly coupled if they had been administered at the same time-point, and future studies should investigate this possibility directly.

Our adolescent sample was broad in their chronological age-range (13-18 years), and this may contribute to some of the variance in our assessments owing to potential changes across this period of brain development (Crews, He, & Hodge, 2007; Giedd et al., 1999), impulsivity (Leshem & Glicksohn, 2007) and working memory (Luciana, Conklin, Hooper, & Yarger, 2005). Although we found that age was not associated with our measures of impulsivity (BIS-11A) and risk-taking (BART), age was associated with the brain activations during encoding of both verbal (e.g., DLPFC) and visuospatial/nonverbal (e.g., ACC) stimuli, as well as the rehearsal of verbal stimuli (e.g., DVPFC), in our task. Thus age may contribute to the results reported here. However, it is worth noting that our results are more generally consistent with the broader literature of working memory that describes activation of DLPFC and ACC during encoding (Narayanan et al., 2005; Nyberg et al., 1996) and prefrontal cortical involvement/left VLPFC during rehearsal (Jonides et al., 1998; Olesen et al., 2007; Smith et al., 1998a). Thus, despite these age-related associations across adolescents, our results converge with previously published studies in this area. These findings also converge with prior research evidencing increasing recruitment of prefrontal working memory regions across developmental ages (Bunge & Wright, 2007; Scherf, Sweeney, & Luna, 2006).

It is important to note that the current study was also limited by a small sample size, which is noteworthy in terms of both the power of the statistical analyses as well as the generalizability of the results. Moreover, conducting numerous correlations with a relatively small sample size increases the likelihood of Type-1 errors. Future work with a larger sample size is necessary to replicate the present findings in a less exploratory and more hypothesis-driven and independent fashion.

In summary, the purpose of this study was to investigate the neural correlates of working memory and explore their relationship with impulsivity and risk-taking in an adolescent sample. We found preliminary evidence for relationships between our measures of impulsivity and risk-taking and the neural correlates of working memory. These findings are important in considering the role of working memory to risk-taking and impulsivity and suggest important directions for future research in this area.

Acknowledgments

We would like to thank Leslie Jacobsen, Ph.D., for her contribution to the design and implementation of this study. This work was supported by the Anna Freud Centre-Yale Bridge Programme, NIH R21 DA024232, NIH (R01 DA018647, P20 DA027844, RL1 AA017539), the Connecticut State Department of Mental Health and Addictions Services, the Connecticut Mental Health Center, an unrestricted research gift from the Mohegan Sun casino, the Yale Gambling Center of Research Excellence Award grant from the Institute for Research on Gambling Disorders of the National Center for Responsible Gaming, and CTSA Grant Number UL1 RR024139 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. The findings do not necessarily reflect those of the funding agencies and the funding agencies did not review or provide input into the content of this manuscript.

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Highlights

- Examined in adolescents the relationships between self-reported impulsivity, behavioral risk-taking and brain function underlying working memory.
- Similarities and differences were observed in the neural correlates of aspects of verbal and visuospatial working memory.
- Risk-taking was positively associated with subcortical activations and motor impulsivity with cortical activations during verbal rehearsal.
- Findings suggest differential relationships between working-memory-related brain function and tendencies linked to addictive behaviors.

Figure 1.

Schematic representation of the visuospatial and verbal working memory task employed in the current study.

Figure 2. Differential brain activity between verbal > visuospatial working memory during encoding (Upper Panel) and recognition (Lower Panel). Regions in orange/yellow show greater activation in the verbal condition while regions in blue/purple show greater activation in the visuospatial condition.

Panel A

Panel B

Panel C

Panel D

Figure 3.

Axial views of the neural regions that are correlated with risk-taking behavior (as measured by the BART and shown in the scatterplot) and verbal rehearsal (Panel A), visuospatial rehearsal (Panel B), and verbal recognition in subcortical (Panel C) and cortical (Panel D) regions.

Panel A

Panel B

Panel C

Panel D

Figure 4.

Scatter plots and axial views of the neural regions that are correlated with verbal rehearsal and motor impulsivity (Panel A), visuospatial rehearsal and motor impulsivity, (Panel B), visuospatial recognition and motor impulsivity in subcortical regions (Upper Panel C) and

cortical regions (Lower Panel C), and visuospatial recognition and non-planning impulsivity (Panel D).

Table 1

Brain Activation during the Working Memory Task

Regions of Activation	Coordinates					t
	X	Y	Z	Size (voxel)		
	Lat	Verbal Encoding				
Insula, Temporal gyri (BA 20, 21, 38), Parietal cortex (BA 39, 40), Anterior Entorhinal cortex (BA 34), Amygdala, Primary Motor area (BA 4), Primary Auditory area (BA 41), Primary sensory area (BA 5)	L	48	19	6	1510.74	-3.04
Dorsolateral Prefrontal Cortex	R	9	42	13	1063.19	-2.679
Anterior Cingulate Cortex (BA 32), Ventromedial Prefrontal Cortex (BA 10), Orbitofrontal area (BA 11), Supplementary Motor Area (BA 8)	M					
Insula, Temporal gyri (BA 20, 21, 38), Parietal cortex (BA 39, 40), Anterior Entorhinal cortex (BA 34), Amygdala, Primary Motor area (BA 4), Primary Auditory area (BA 41), Primary sensory area (BA 5)	L	48	19	6	1510.74	-3.04
Dorsolateral Prefrontal Cortex	R	9	42	13	1063.19	-2.679
Anterior Cingulate Cortex (BA 32), Ventromedial Prefrontal Cortex (BA 10), Orbitofrontal area (BA 11), Supplementary Motor Area (BA 8)	M					
Visuospatial Encoding						
Parietal Cortex(BA7,39,40), Fusiform (BA37), Extrastriate area, Parahippocampus	R	33	62	3	2066.63	3.37
Cerebellum	B					
Hippocampus	L					
Anterior Cingulate Cortex (BA32), Motor cortex (BA6,8)	M	0	16	45	447.19	2.928
Parietal Cortex (BA7,39,40)	L	33	48	41	427.63	2.804
Parahippocampus, Fusiform, Extrastriate area	L	36	70	3	1111.19	3.678
Temporal gyri (BA21,22), Parietal Cortex (BA39,40), Insula (BA13), Fusiform (BA37), Primary Auditory Cortex (BA41), Extrastriate cortex (BA19)	R	51	43	16	1322.74	-2.844
Anterior Cingulate Cortex (BA24,30), Posterior cingulated cortex (BA23,31), Extrastriate Area (BA18,19)	M	0	57	22	4358.19	-3.144
Superior Parietal Lobe (BA7), Fusiform (BA37), Parahippocampus	L					
Parietal cortex (BA39,40), Temporal gyri (BA21,22), Insula, Primary auditory cortex (BA41), Extrastriate Area (BA19)	L	49	42	19	1046.3	-2.756
Verbal Rehearsal						
DLPFC (BA9,46), Ventrolateral Prefrontal Cortex (BA44,45,47), Ventromedial Prefrontal Cortex (BA10), Orbitofrontal area (BA11), Insula (BA13)	L	29	30	9	390.85	2.619
Anterior Cingulate Cortex (BA24,32), Motor Cortex (BA6,8)	M	-2	17	38	490	2.749
Parahippocampus, Fusiform, Extrastriate area (BA18,19), Primary Auditory Area (BA41)	B	17	39	22	4462.48	-2.82
Parietal cortex (BA7,39), Thalamus, Superior Temporal gyrus (BA22), Primary Motor Area (BA 4), Primary Sensory Area (BA5)	R					
Hippocampus	L					

Regions of Activation	Coordinates					t
	X	Y	Z	Size (voxel)		
	Lat	Verbal Encoding				
Posterior and anterior cingulated cortex (BA23,24,31)	M					
Temporal gyri (BA21,22,38), Inferior Parietal Lobe (BA40), Insula (BA13), Amygdala, Premotor cortex (BA6), Anterior Entorhinal cortex (BA34), Primary Motor area (BA4), Primary Auditory Area (BA41)	L	46	15	7	739.56	
Parietal Cortex (BA7,39), Extrastriate Area (BA18,19)	L	41	66	25	285.67	
					-2.545	

Regions of Activation	Coordinates				t	
	X	Y	Z	Size (voxel)		
	Lat	Verbal Encoding				
Anterior Cingulate Cortex (BA 24, 31), Superior Parietal Lobe (BA7), Parahippocampus, Fusiform (BA37), Extrastriate Area (BA18,19)	M	-1	50	31	3492.56	-3.021
Thalamus	R					
Angular gyrus (BA39)	L					
Striatum (Caudate, Nucleus Accumbens), Ventromedial Prefrontal Cortex (BA11,25), Orbitofrontal area (BA11), Anterior Cingulate Cortex (BA32)	M	0	32	-1	632.63	-3.015
Temporal gyri (BA22,37), Parietal Cortex (BA39, 40), Insula (BA13), Primary Sensory Area (BA5), Primary Auditory Area (BA41), Extrastriate cortex (BA18,19)	R	48	48	21	651.52	-2.94
Verbal Delayed Recognition						
Anterior Cingulate Cortex (BA24,32), Motor Cortex (BA6,8)	M	25	1	29	3881.22	3.224
Dorsolateral Prefrontal Cortex (BA9, 46), Parietal Cortex (BA7,39, 40), Motor cortex (BA6,8), Ventrolateral Prefrontal Cortex (BA44,45), Insula (BA13), Thalamus, Dorsal Striatum (Caudate, putamen), Primary Sensory Area (BA5)	L					
Dorsolateral Prefrontal Cortex (BA9,46)	B					
Ventrolateral Prefrontal Cortex (BA44,45,47), Motor cortex (BA6), Insula (BA13), Putamen	R	36	12	4	452.26	3.194
Dorsolateral Prefrontal Cortex (BA9,46), Ventrolateral Prefrontal Cortex (BA44), Ventromedial Prefrontal Cortex (BA10), Motor Cortex (BA6)	R	45	26	25	255.04	2.7
Cerebellum, Fusiform, Extrastriate area (BA18,19)	R	28	73	-8	1601	3.329
Cerebellum, Fusiform, Extrastriate area (BA18,19)	L	33	75	-3	1307.07	3.649
Visuospatial Delayed Recognition						
Parietal Cortex (BA7,39,40)	R	31	54	39	452.26	3.052
Anterior Cingulate Cortex (BA32), Motor Cortex (BA6,8)	M	0	16	38	347.19	3.257
Ventrolateral Prefrontal Cortex (BA45,47), Putamen, Insula (BA13)	L	28	13	3	251.11	2.977
Dorsolateral Prefrontal Cortex (BA9,46), Parietal Cortex (BA7,39,40), Motor Cortex (BA6,8), Primary Motor Area (BA4), Primary Sensory Area (BA5)	L	39	28	42	1238.33	3.009
Fusiform (BA 37), Extrastriate Area (BA18,19)	L	37	69	-4	1583.22	3.891
Parahippocampus, Fusiform (BA37) Extrastriate Cortex (BA18,19)	L	35	72	-2	1379.33	3.93
Posterior Cingulate Cortex (BA23,30,31), Premotor cortex (BA6), Primary Motor Area (BA 4), Extrastriate area (BA19), Superior Parietal Lobe (BA7)	M	11	50	23	6898.63	-3.682
Parietal Cortex (BA39,40), Temporal gyri (BA21,22), Insula, Primary Sensory area (BA5)	L					
Parahippocampus	B					
Dorsolateral Prefrontal Cortex (BA9), Ventromedial Prefrontal Cortex (BA10), Orbitofrontal area (BA11), Anterior Cingulate Cortex (BA24,32)	M	1	34	-1	962.48	-3.175
Dorsolateral Prefrontal Cortex (BA9,46), Supplementary Motor Area (BA8)	R	23	31	36	320.89	-2.705

Regions of Activation	Coordinates					t
	X	Y	Z	Size (voxel)		
				Lat	Verbal Encoding	
Cerebellum	L	0	80	24	575.04	-3.059

Significant Activations at $p<0.05$ (whole brain family wise error corrected). Talairach Coordinates were used. Lat. Laterality; B, Bilateral; M, Medial; L, Left; R, Right; BA, Brodmann's area.

Table 2

Differential activation across the Verbal and Visuospatial encoding, recognition and delayed recognition conditions.

G H	Regions of Activation	Lat	Coordinates			t	
			X	Y	Z		size (voxels)
			Verbal Encoding>Visuospatial Encoding				
	Ventrolateral Prefrontal Cortex (BA44,45,47), Temporal gyri (BA22,38), Insula (BA13), Premotor cortex (BA6)	L	48	16	5	407.63	2.59
	Temporal gyri (BA21,22), Angular gyrus (BA39)	L	53	44	9	339.44	2.91
	Parietal Cortex (BA7,39), Extrastriate area (BA18,19), Fusiform (BA37), Parahippocampus,	B	11	60	16	4204.22	-3.21
	Hippocampus	L					
	Inferior Parietal Lobe, Caudate, Inferior Temporal area (BA20)	R					
			Verbal Recognition > Verbal Recognition				
	Dorsolateral Prefrontal Cortex (BA46), Ventrolateral Prefrontal Cortex (BA44,45,47), Ventromedial Prefrontal Cortex (BA10), Insula (BA13)	L	42	18	10	518.63	2.68
	Parietal Cortex (BA7,39,40), Temporal gyri (BA20,21,37), Parahippocampus Extrastriare area (BA18,19), Hippocampus	R	35	59	10	2018.04	-2.89
	Extrastriate Cortex (BA18,19), Fusiform (BA37)	L	41	62	-1	318.93	-3.04
			Verbal Delayed Recognition > Visuospatial Delayed Recognition				
	Cerebellum	B	12	78	25	740.48	2.89
	Tempral gyri (BA20,21,22,37)	R	51	34	-3	689.56	2.67
	Parietal Cortex (BA7,39,40), Temporal gyri (BA20,37), Extistriate cortex (BA18,19), Hippocampus, Parahippocampus	R	34	59	13	1741.56	-2.99
	Temporal gyri (BA20,21,22,37), Parietal Cortex (BA39,40)	L	50	46	16	1403	2.85
	Dorsolateral Prefrontal Cortex (BA9,46), Thalamus, Ventromedial Prefrontal Cortex (BA10), Dorsal Striatum (Caudate, Putamen), Supplementary motor area (BA8)	B	23	20	18	2136.33	2.69
	Ventrolateral Prefrontal Cortex (BA44,45,47), Insula (BA13), Global Palidus, Premotor cortex (BA6), Temporal area, Orbitofrontal area (BA11)	L					
	Ventrolateral Prefrontal Cortex (BA 44, 45, 47), Temporal gyri (BA22,38), Premotor area (BA6), Insula (BA13)	R	47	13	0	380.22	2.55
	Anterior and posterior cingulated cortex (BA23,24,31)	M	0	16	20	2129.85	2.55
	Thalamus	L					
	Supplementary Motor Area (BA8)	R					
	Superior Parietal Lobe (BA7), Extrastriate Area (BA18,19)	B					
	Fusiform (BA37), Extrastriate Area (BA19)	L	42	71	5	336.07	-2.97

G	Coordinates				t
	X	Y	Z	size (voxels)	
H					
Regions of Activation	Lat	Verbal Encoding>Visuospatial Encoding			
	R	51	54	30	290.3
Angular gyrus (BA39), Extrastriate Area (BA19)					2.48

Angular gyrus (BA39), Extrastriate Area (BA19)

Significant Activations at p<0.05 (whole brain family wise error corrected). Talairach Coordinates were used. Lat. Laterality; B. Bilateral; M. Medial; L. Left; R. Right; BA, Brodmann's area.

Table 3

Brain regions correlated with between Working Memory and BART.

G	Coordinates				
	X	Y	Z	size (voxels)	
H					
Regions of Activation	Lat	Verbal Rehearsal and BART			r
	B	3	19	4	800.7
Thalamus, Dorsal striatum (caudate, putamen), Parahippocampus, Cingulate Cortex (BA 30), Cerebellum					0.56
Hippocampus	L				
Visuospatial Rerearsal and BART					
Temporal gyri (BA21,37), Parietal cortex (BA39), Hippocampus, Cingulate cortex (BA30) and Extrastriate cortex (BA18, 19)	L	39	55	5	517.63
Posterior cingulate cortex (BA23,30,31), Extrastriate cortex (BA18,19), Parahippocampus, Primary visual area (BA17)	M	10	63	12	274.26
Anterior Cingulate Cortex (BA24,31,32) and premotor cortex (BA6)	M	32	26	37	1284.48
Parietal cortex (BA7,39,40), Temporal cortex (BA21, 22), Insula (BA13), Primary sensory cortex (BA5) and sensory association area (BA1)	R				
Superior Temporal Gyrus (BA22), Inferior Parietal lobe (BA40), Premotor area (BA6), Insula (BA13), Primary auditory area (BA41), Primary motor area (BA4)	L	42	20	33	947.52
Verbal Recognition and BART					
Temporal gyri (BA21,22,37), Parietal cortex (BA39)	L	-51	48	9	362.11
Thalamus, Posterior cingulate cortex (BA23)	B	2	16	13	449.07
Dorsal Striatum (caudate, putamen)	R				0.58

Significant Activations at p<0.05 (whole brain family wise error corrected). Talairach Coordinates were used. Lat, Laterality; B, Bilateral; M, Medial; L, Left; R, Right; BA, Broadmann's area.

Table 4

Brain regions correlated with between Working Memory and Impulsivity.

G	H	Regions of Activation	Lat	Coordinates			r
				X	Y	Z	
				Verbal Encoding and Motor Impulsivity			
		Cerebellum, Fusiform gyrus (BA37), Extrastriate cortex (BA18,19)	B	8	-59	-15	0.59
		Inferior Frontal Gyrus (BA47), Insula (BA13), DLPFC (BA 9,46), VLPFC (BA44,45) and Motor cortex (BA6, 8)	L	-41	14	17	0.62
		Primary Visual Area (BA17) and Extrastriate cortex (BA18, 19)	M	-4	-77	13	0.6
				Verbal Rehearsal and Motor Impulsivity			
		Inferior Frontal Gyrus (BA47), Insula (BA13), DLPFC (BA9,46), VLPFC (BA44,45), Putamen and motor cortex (BA6)	L	-39	-14	11	0.61
				Visuospatial Rehearsal and Motor Impulsivity			
		Superior Parietal Lobe (BA7), Premotor cortex (BA6), Primary motor area (BA4), Primary Sensory Area (BA5), Sensory Association Area	B	-1	-32	60	-0.58
				Visuospatial Recognition and Motor Impulsivity			
		Dorsal posterior cingulate (BA31), Cerebellum	M	22	-54	-4	0.59
		Posterior cingulate cortex (BA23), Fusiform gyrus (BA37) and Parahippocampus	R				
		Thalamus, Dorsal striatum (putamen, caudate), Inferior parietal lobule (BA40), Insula (BA13), Primary sensory area (BA5)	L	-23	-18	12	0.59
		DLPFC (BA9, 46), Motor cortex (BA6, 8), VLPFC (BA44), ACC	B	3	19	31	0.59
				Visuospatial Recognition and Non-planning Impulsivity			
		Posterior Cingulate Cortex (BA23), Extrastriate area (BA18,19), Primary Visual Area (BA17)	M	4	-74	11	0.57
				Verbal Recognition and Attention Impulsivity			
		Inferior parietal lobe (BA40), Motor cortex (BA6), Primary Sensory Area (BA5)	R	32	14	52	-0.58
				Verbal Delayed Recognition and Non-planning Impulsivity			
		Extrastriate area (BA18,19), Primary Visual Area (BA17)	M	10	-74	14	0.6

Significant Activations at p<0.05 (whole brain family wise error corrected). Talairach Coordinates were used. Lat, Laterality; B, Bilateral; M, Medial; L, Left; R, Right; BA, Broadmann's area.