High and low sensation seeking adolescents show distinct patterns of brain activity during reward processing

Anita Cservenka[a], **Megan M. Herting**[a], **Kristen L. Mackiewicz Seghete**[a], **Karen A. Hudson**[b], and **Bonnie J. Nagel**[a,b]

Anita Cservenka: cservenk@ohsu.edu; Megan M. Herting: hertingm@ohsu.edu; Kristen L. Mackiewicz Seghete: mackiewi@ohsu.edu; Karen A. Hudson: hudsonk@ohsu.edu; Bonnie J. Nagel: nagelb@ohsu.edu

[a]Department of Behavioral Neuroscience, Oregon Health & Science University, 3181 SW Sam Jackson Park Rd., Portland, OR, 97239-3098, U.S.A

[b]Department of Psychiatry, Oregon Health & Science University, 3181 SW Sam Jackson Park Rd., Portland, OR, 97239-3098, U.S.A

Abstract

Previous research has shown that personality characteristics, such as sensation seeking (SS), are strong predictors of risk-taking behavior during adolescence. However, the relationship between levels of SS and brain response has not been studied during this time period. Given the prevalence of risky behavior during adolescence, it is important to understand neurobiological differences in reward sensitivity between youth with high and low SS personalities. To this end, we used functional magnetic resonance imaging (fMRI) to examine differences in brain activity in an adolescent sample that included 27 high (HSS) and 27 low sensation seekers (LSS), defined by the Impulsive Sensation Seeking scale of the Zuckerman-Kuhlman Personality Questionnaire (Zuckerman et al., 1993). In the scanner, participants played a modified Wheel of Fortune decision-making task (Cservenka and Nagel, 2012) that resulted in trials with monetary Wins or No Wins. We compared age- and sex-matched adolescent HSS and LSS (mean age = 13.94 ± 1.05) on brain activity by contrasting Win versus No Win trials. Our findings indicate that HSS show greater bilateral insular and prefrontal cortex (PFC) brain response on Win vs. No Win compared to LSS. Analysis of simple effects showed that while LSS showed comparable brain activity in these areas during Wins and No Wins, HSS showed significant differences in brain response to winning (activation) versus not winning (deactivation), with between-group comparison suggesting significant differences in brain response, largely to reward absence. Group differences in insular activation between reward receipt and absence may suggest weak autonomic arousal to negative outcomes in HSS compared with LSS. Additionally, since the PFC is important for goal-directed behavior and attention, the current results may reflect that HSS allocate fewer attentional resources to negative outcomes than LSS. This insensitivity to reward

Corresponding Author: Bonnie J. Nagel, 3181 SW Sam Jackson Park Rd., Mail Code: DC7P, Portland, OR 97239-3098, U.S.A., Phone: 503-494-4612, Fax: 503-418-5774 nagelb@ohsu.edu.

absence in HSS may lead to a greater likelihood of maladaptive choices when negative consequences are not considered, and may be an early neural marker of decreased loss sensitivity that has been seen in addiction. This neurobiological information may ultimately be helpful in establishing prevention strategies aimed at reducing youth risk-taking and suggests value in further examination of neural associations with personality characteristics during adolescence.

Keywords

Adolescence; Sensation Seeking; Reward; fMRI

1. Introduction

Adolescence is a developmental period during which pubertal, cognitive, and affective maturation take place (Casey and Jones, 2010; Ernst and Fudge, 2009; Ernst et al., 2006; Scherf et al., 2012). This transitional period is marked by changes in physical (Susman et al., 2010) and brain (Sowell et al., 2002) maturity, as well as alterations in personality characteristics and behavior (Pharo et al., 2011). In particular, adolescence is considered a period of increased risk-taking, reflected by elevated alcohol and drug experimentation, unsafe sexual activity, and reckless driving (Eaton et al., 2010). While many risk factors are believed to increase susceptibility for engaging in maladaptive behavior, sensation seeking is one personality characteristic that is a strong predictor of such risk (Steinberg, 2004; Wills et al., 1994).

Sensation seeking has been defined as a trait that leads individuals to seek out novel and intense sensations and experiences (Zuckerman and Kuhlman, 2000). From an evolutionary perspective, sensation seeking during adolescence may be viewed as an adaptive mechanism for learning to gain independence from parents (Steinberg and Belsky, 1996); however, risky adolescent behaviors lead to especially high mortality rates (Institute of Medicine and National Research Council, 2011). High sensation seekers view novel activities as less risky compared to low sensation seekers (Horvath and Zuckerman, 1993), and thus, may be more prone to seek out exciting experiences without recognition/awareness of their potential adverse consequences (Zuckerman and Kuhlman, 2000). Along these lines, longitudinal analysis has shown that the increase in sensation seeking during adolescence, accompanied by concomitant rise of risk-taking behavior, is a significant predictor of elevated alcohol use (MacPherson et al., 2010). Other longitudinal studies have shown that sensation seeking predicts binge drinking onset and smoking behavior during adolescence, making this personality characteristic a potentially useful target for prevention strategies aimed at reducing the incidence of alcohol and substance abuse during this critical developmental period (Sargent et al., 2010). Given that sensation seeking is strongly associated with approach motivation (Zuckerman and Kuhlman, 2000), laboratory paradigms have begun to investigate the relationship between sensation seeking and risk-taking as they relate to reward/loss sensitivity in young adults. Results suggest that reward sensitivity may be an important marker for the relationship between personality and risk-taking, as individuals high in sensation seeking and impulsivity do not reduce the number of risky decisions they make in the face of high reward/loss magnitude trials (Bornovalova et al., 2009). This

suggests that sensation seeking may modulate sensitivity to reward, and that studying the neural correlates of this trait as a marker for reward sensitivity could help identify how this personality characteristic relates to risk-taking in adolescents.

To understand the underlying neural mechanisms of heightened approach behavior during adolescence, neuroimaging studies have been conducted to examine the relative rate of neural development across reward-related and higher-order cognitive control brain regions. These neurobehavioral models of adolescence propose that heightened approach behavior during this period, in the face of weak avoidance and still immature regulatory capacity by higher-order cognitive control systems, leads to the elevated risk-taking seen during this time (Ernst and Fudge, 2009; Ernst et al., 2009). For example, the triadic model of adolescent neurodevelopment (Ernst et al., 2006) has proposed that heightened approach behavior during adolescence may be linked to the earlier development of subcortical systems, such as the basal ganglia, relative to the more protracted maturation of prefrontal cognitive control brain regions (Casey and Jones, 2010). Some theories argue that heightened motivational drive is linked to increased ventral striatal response to rewards during adolescence (Galvan et al., 2006). However, others have proposed that it is a hyporesponsive subcortical system that leads adolescents to seek out exciting and novel experiences, a phenomenon that has been termed the reward deficiency hypothesis (Bjork et al., 2004). A number of different hypotheses have been reviewed that may explain discrepancies in the results of adolescent reward processing studies (Galvan, 2010). Differences in task design and analysis (including contrast specification) and variation in adolescent age samples are just a few examples that may account for disparate findings (Bjork et al., 2004; Bjork et al., 2010b; Ernst et al., 2005; Galvan, 2010; Galvan et al., 2006). Furthermore, individual variability in personality traits, such as sensation seeking, may be an important determinant of reward response that could have clouded past results. To identify youth who may be at greatest risk for maladaptive behavior, examining the neural correlates of sensation seeking during adolescence may hold promise.

Previous research examining the contribution of personality differences on brain structure and function has begun to examine the neurobiological basis of sensation seeking in adults. Using a probabilistic monetary reward task, Abler et al. (2006) found that thrill and adventure seeking was positively correlated with ventral striatal blood oxygen level-dependent (BOLD) response during the expectation of reward. Novelty seeking is another trait that has been closely associated with approach behavior and was found to correlate with medial prefrontal cortex activity during expectation of emotional relative to neutral pictures (Bermpohl et al., 2008). Furthermore, this trait has been examined in relation to brain morphology, with studies suggesting positive correlations between novelty seeking and grey matter volume in both prefrontal and parietal regions (Gardini et al., 2009; Van Schuerbeek et al., 2011).

While previous research has correlated personality traits with brain structure and function, few studies have stratified sensation seekers into high and low groups to examine differences in brain activity in relation to distinct sensation seeking profiles. Joseph et al. (2009) grouped young adults into high and low sensation seekers and measured BOLD response when viewing high- or low-arousing emotional pictures. The authors found that

high sensation seekers showed greater brain response to highly arousing stimuli compared to low sensation seekers in the insula and inferior frontal gyrus. Given other work implicating insular activity in response to appetitive stimuli (Ray et al., 2010), these results suggest an overactive approach system in high sensation seekers (Joseph et al., 2009). To date, only one study has examined neural response to monetary rewards in high and low sensation seekers and showed greater reward sensitivity in high sensation seeking adults in regions including the insula and nucleus accumbens (Kruschwitz et al., 2012). To our knowledge, no studies have examined the neural correlates of sensation seeking during adolescence, a period during which peak levels of this personality trait have been observed in the majority of individuals (Steinberg et al., 2008).

To this end, the current study stratified adolescents into those with above and below average sensation seeking profiles, using the Impulsive Sensation Seeking Scale of the Zuckerman-Kuhlman Personality Questionnaire (Zuckerman et al., 1993). Adolescents performed a probabilistic monetary reward-based decision-making task during fMRI (Cservenka and Nagel, 2012; Ernst et al., 2004b). Since we were interested in how personality may relate to reward sensitivity, we examined brain response during the reward feedback phase of the task. Overall, we hypothesized that adolescents would show a hyperresponsive pattern of brain activity in the ventral striatum in the presence vs. the absence of monetary rewards, in support of previous studies of adolescent reward sensitivity. In addition, based on the adult literature, we predicted that personality would further exacerbate this hyperresponsive pattern such that high sensation seeking youth would show greater activation to rewards compared with low sensation seeking youth in brain regions related to approach behavior and autonomic arousal, including the nucleus accumbens and insula.

2. Material and Methods

2.1 Participants

2.1.1 Inclusionary and Exclusionary Criteria—Participants included healthy adolescents, ages 12 to 16 years. All participants were recruited from the community and underwent comprehensive screening interviews as part of an ongoing study of adolescent neurodevelopment. Exclusionary criteria for youth included left handedness [Edinburgh Handedness Inventory (Oldfield, 1971)], DSM-IV psychiatric diagnoses (Lucas et al., 2001), inability of a parent to provide family history, serious medical problems, significant head trauma, mental retardation or learning disabilities, psychotic illness in a biological parent (e.g. schizophrenia or bipolar I), prenatal exposure to drugs or alcohol, MRI contraindications (e.g., irremoveable metal in the body), or pregnancy. In addition, all youth were free of heavy alcohol or substance use { 10 lifetime alcoholic drinks or > 2 drinks on any occasion, > 5 uses of marijuana, any other drug use, or > 4 cigarettes per day (Brief Lifetime version of the Customary Drinking and Drug Use Record (Brown et al., 1998)]}. Only participants who were classified as either a high or low sensation seeker, as defined below (section 2.1.2), were included. The study was approved by the Oregon Health & Science University (OHSU) Institutional Review Board.

2.1.2 Classification of Sensation Seeking Groups—94 adolescents (60 males) were administered the Impulsive Sensation Seeking (ImpSS) Scale of the Zuckerman-Kuhlman Personality Questionnaire (Zuckerman et al., 1993). This scale consists of 19 true-false statements to assess excitement and novelty seeking (e.g. "I like doing things just for the thrill of it"), as well as questions to assess impulsivity, including lack of planning (e.g. "I would like to take off on a trip with no preplanned or definite routes or timetables") and acting without forethought. The scale is then scored by summing items that are consistent with sensation seeking and impulsivity, and dividing by the total number of questions to get a subject's level of sensation seeking. This value was then multiplied by 100 to get a percentage score for each individual. When using the same method of calculation, the distribution of sensation seeking scores from all 94 subjects (mean: 46.7, standard deviation: 21.7, range: 0–95) was comparable to the ImpSS score distribution (mean: 44.8, standard deviation: 22.15) in a previous study of non-alcohol and tobacco using adolescents (Schepis et al., 2008). To dichotomize participants' ImpSS scores in the current study, we divided them into approximate thirds to get at the two distinct ends of the distribution, resulting in the classification of 27 below average ImpSS youth (LSS) (ImpSS scores < 32%) and 27 youth with above average ImpSS tendencies (HSS) (ImpSS scores > 63%).

2.1.3 Participant Characteristics—To provide an estimate of overall intellectual functioning, youth were administered the 2-subtest version of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). Self-assessment of puberty was collected using a modified line drawing version of the Tanner's Sexual Maturation Scale (SMS) (Taylor et al., 2001), with drawings ranging from stage 1 (pre-adolescent) through stage 5 (adult-like maturation). Socioeconomic status (SES) was assessed by administering the Hollingshead Index of Social Position to parents, a measure based on occupation and educational attainment of each parent (Hollingshead, 1957).

2.2 Wheel of Fortune Task

To assess reward-associated neural response, participants performed a previously published modified version of the Wheel of Fortune (WOF) Task (Cservenka and Nagel, 2012), adapted from the original WOF paradigm (Ernst et al., 2004b). In brief, during this two-choice computerized decision-making task (Figure 1), participants chose between different probabilities of winning various monetary amounts. Selecting the low probability/high magnitude portion of a wheel was considered a risky choice (10% or 30%), selecting the high probability/low magnitude portion of a wheel (70% or 90%) was considered a safe choice, and any response on a wheel with equal probabilities and magnitudes (50%) was considered a chance choice. A participant's choice that matched the computer's choice, based on the pre-defined probabilities, was a winning trial, while a choice that did not match resulted in no win. Participants were instructed to select the portion of the wheel they thought would win them money and to try to win as much money as possible, because they would receive a portion of their total earnings in the end. 72 trials were presented over two 10-minute runs. Each run included 12 "10/90" (Fig. 1A), 14 "30/70" (Fig. 1B), and 10 "50/50" (Fig. 1C) probability wheels. As this task was also designed to capture differences in risky vs. safe brain response, we included a greater number of 90/10 and 70/30 wheels than 50/50 wheels to have more power to model risky and safe selections (Cservenka and

Nagel, 2012). The number of trials for each condition were selected based on base rates of risky and safe responding in previous publications of this task (Ernst et al., 2004a; Ernst et al., 2004b). Further, the trials were programmed to most closely match probabilities of winning on the different types of wheels (e.g. 4 of the 14 wheels in which there was a 30% chance of winning the low probability/high magnitude option, resulted in wins when the smaller portion of the wheel was chosen, which approximates a 30% chance of winning). Trials were 10.5 seconds long and consisted of a selection (3 sec), anticipation (3.5 sec), and feedback (4 sec) phase, with intertrial fixation intervals jittered between 1–11 seconds. Given our current interest in how sensation seeking may influence reward processing, only the feedback phase of the trials was analyzed. During this phase, the screen indicated whether the participant won or did not win the amount of money attached to the option they selected, and participants were shown the cumulative dollar amount won up to that point. To ensure subjects were paying attention during this phase, they were also asked to button press "1" if they won (Win) or "2" if they did not win (No Win). For the feedback phase of each trial, Wins were categorized as money won after selecting any portion of a wheel presented during the task. No Wins were categorized as those trials in which no money was won following selection of a risky (10% or 30%) or chance (50%) portion of the wheel. To avoid including expectancy violations during No Wins (and associated brain response), any money not won after selecting a safe (70% or 90%) portion of a wheel (Safe No Win) was included as a regressor of non-interest in the hemodynamic response model (see below). Notably, Safe No Win trials modeled for HSS and LSS were few, with mean = 2.8 (standard deviation (SD) = 2.5), and mean = 4.2 (SD = 3.1) time repetitions (TRs), respectively, indicating that power for the fMRI analyses was not reduced substantially by excluding these trial types.

2.3 Imaging

2.3.1 Acquisition—Participants were scanned at OHSU's Advanced Imaging Research Center on a 3.0 Tesla Siemens Magnetom Tim Trio. Anatomical, high-resolution T1-weighted MPRAGE structural scans were collected in the sagittal plane (TR = 2300 ms, echo time (TE) = 3.58 ms, inversion time = 900 ms, flip angle = 10°, field of view (FOV) = 240×256 mm, voxel size = 1×1×1.1 mm, 160 slices, acquisition time = 9:14). Functional T2* weighted gradient echo-planar images were collected axially, parallel to the anterior commissure – posterior commissure line (TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 240 mm^2, voxel size = 3.75×3.75×3.8 mm, 33 slices, acquisition time = 2 runs of 300 TRs, lasting 10:00 minutes each).

2.3.2 Preprocessing—Analysis of Functional NeuroImages (AFNI) was used for preprocessing. To reduce artifacts, functional images underwent a series of preprocessing steps (Miezin et al., 2000). These processes included 1) removal of a central spike, 2) slice-timing correction, 3) correction for head movement within and across task runs, 4) spatial smoothing with a 6.0 mm full-width half-maximum Gaussian kernel, 5) within-run intensity normalization to a whole brain signal, and 6) co-registration of functional and anatomical images (Cox, 1996; Cox and Jesmanowicz, 1999). TRs during which participants moved more than 2.5 mm or 2.5° in any of the three displacement or rotational parameters were censored, and only runs with less than 1.5 mm root mean squared (RMS) of within-run

motion, across 6 motion parameters, were included in further analyses. There were no group differences in mean RMS (see Table 1) or mean TRs censored (HSS = 0.41, LSS = 0.89, U = 364.5, $Z = 0$, $p = 1$) in the current sample.

Regressors representing selection (risky, chance, or safe), anticipation (following risky, chance, or safe choices), and feedback phases (wins, no wins, or safe no wins) of the task were modeled. Stimulus times corresponded to the onset time of each phase, with duration of the event coded as the length of each phase convolved with a gamma-variate hemodynamic response function, while modeling delays in the hemodynamic response (Cohen, 1997). The estimated baseline model in this analysis was comprised of the mean BOLD signal from the entire timecourse of the task, linear drift, fixation periods, and regressors of no interest (e.g., motion parameters) (Cox, 1996). Contrast images for average percent signal change of Win vs. baseline, No Win vs. baseline, and Win vs. No Win were analyzed. Functional data were transformed into standard Talairach coordinates (Talairach and Tournoux, 1988) and resampled into 3 mm^3 voxels prior to group-level analyses.

2.4 Group Analyses

2.4.1 Demographic and Behavioral Data—Statistical analyses were performed in PASW (version 18.0, Chicago, IL). Demographic and behavioral data were analyzed using independent-samples t-tests and the appropriate nonparametric tests when data violated the assumption for normality. Chi-square tests were used to analyze nominal data.

2.4.2 Imaging Data—To ensure that there was no interaction between group status and the number of TRs modeled for each condition, a repeated measures ANOVA was used with Win and No Win outcomes as the within-groups variable and sensation seeking status as the between-groups variable. There was no significant interaction ($F_{1,52} = 0.003$, $p = 0.954$: mean number of TRs modeled for Wins: HSS = 30.6; LSS = 31.3; mean number of TRs modeled for No Wins: HSS = 35.5; LSS = 35.9). To best represent reward-related activity for both HSS and LSS, one-sample t-test maps for the Win vs. No Win contrast were corrected for multiple comparisons using AFNI's Monte Carlo simulation, which determined the number of voxels needed for correction at both a voxel ($p < 0.05$) and cluster threshold ($\alpha < 0.05$: HSS 233 voxels, LSS 212 voxels) (Cox, 1996; Forman et al., 1995). These voxel and cluster thresholded individual group maps were then combined to form a map of reward-related brain activity for the entire sample. Group differences were then examined within this reward-related activity map. AFNI's AlphaSim Monte Carlo simulation was performed to determine the number of voxels needed to correct the resulting group difference map for multiple comparisons at both a voxel ($p < 0.05$) and cluster threshold ($\alpha < 0.01$, 165 voxels) (Cox, 1996; Forman et al., 1995). Additionally, a regression analysis was performed with all 94 subjects to examine how SS scores predicted Win vs. No Win brain activation, controlling for sex, as there were more boys in the total sample than girls, and SS scores tended to be higher for males than females (mean SS boys: 49.82, mean SS girls: 41.21); $t_{(92)} = 1.87$, $p = 0.07$). Volumetric images of the results were displayed using AFNI, while Caret (Van Essen et al., 2001) was used to display task-related activity, as well as group differences, on surface-based brain maps.

3. Results

3.1 Demographic and Behavioral Data

Demographic and WOF behavioral data are presented in Table 1. HSS and LSS were not significantly different on age, pubertal status, ethnicity, or IQ. There was a trend for sex differences between HSS and LSS, with slightly more males among the HSS. There was also a trend for HSS to have lower SES than LSS, with each group falling into middle and upper middle class status, respectively. Covarying for these trends did not affect the imaging analyses presented below, so to conserve degrees of freedom the imaging results presented do not include these trend-level covariates. HSS and LSS were not different on the percentage of risky choices made on the WOF task when controlling for trend-level group differences in sex and SES ($p = 0.15$). There were no group differences on responses made to Wins ($p = 0.22$) and No Wins ($p = 0.67$) during reward outcome, suggesting that HSS and LSS were attending comparably to the feedback they received.

3.2 Functional Magnetic Resonance Imaging Data

3.2.1 Reward-related Brain Activity in HSS and LSS—Task-related brain activity during the reward outcome phase of the WOF task is displayed in Figure 2. Results for HSS and LSS were voxel and cluster thresholded at $p/\alpha < 0.05$ to display areas of brain response in the contrast of Win vs. No Win for each group. Increased brain activity to rewards was seen in both HSS and LSS in widely distributed brain areas, including prefrontal cortex, parietal lobules, as well as visual and temporal cortices. Both HSS and LSS showed greater subcortical brain response to rewards than non-rewards in the ventral striatum. There were no brain regions in the voxel and cluster corrected maps in which less brain response was seen in Wins compared with No Wins.

3.2.2 Group Differences in Reward-related Brain Activity in HSS and LSS—
There were two clusters in which reward-related brain activity was significantly different between HSS and LSS (Figure 3). Specifically, HSS showed greater Win vs. No Win brain activity in bilateral insula/prefrontal cortex (PFC) compared to LSS [cluster sizes and peaks: left: 226 voxels (x = −47, y = 29, z = 12); right: 187 voxels (x = 41, y = 44, z = 12)]. Both left and right clusters included anterior insula, dorsolateral prefrontal cortex (DLPFC), middle frontal, and inferior frontal gyri. To better understand group differences in brain response, we used a 2x2 mixed model ANOVA and included within-group factors of Win and No Win BOLD response (Reward) and between-group factors of HSS and LSS (Group). Both clusters showed a significant Reward×Group interaction (left insula/PFC: $F_{(1,52)} = 10.62$, MSE = 0.004, $p = 0.002$, partial $\eta^2 = 0.17$; right insula/PFC: $F_{(1,52)} = 10.92$, MSE = 0.004, $p = 0.002$, partial $\eta^2 = 0.17$), which was followed up with post-hoc t-tests to examine simple effects. On average, paired t-tests indicated that HSS had greater brain activity in these regions to Win than No Win outcomes (left insula/PFC: $t_{26} = 5.31$, $p < 0.001$; right insula/PFC: $t_{26} = 4.76$, $p < 0.001$), a distinction not present in LSS (left insula/PFC: $t_{26} = 0.46$, $p = 0.65$; right insula/PFC: $t_{26} = 0.61$, $p = 0.55$). Overall, HSS showed positive activation to Win outcomes and deactivation to No Win outcomes, while LSS showed positive BOLD response to both Win and No Win outcomes. Furthermore, two-sample t-tests showed that on average, HSS had significantly weaker brain response in bilateral

insula/PFC during No Win outcomes compared to LSS (left insula/PFC: $t_{52} = 2.81$, $p = 0.007$; right insula/PFC: $t_{52} = 2.38$, $p = 0.02$). There was also a main effect of Reward, such that greater brain activity was seen to Win than No Win (left insula/PFC: $F_{(1,52)} = 15.71$, MSE = 0.004, $p < 0.001$, partial $\eta^2 = 0.23$; right insula/PFC: $F_{(1,52)} = 16.63$, MSE = 0.004, $p < 0.001$, partial $\eta^2 = 0.24$), regardless of Group status. No main effect of Group was found.

Nucleus accumbens brain activity between HSS and LSS was examined by creating region of interest (ROI) masks of the left and right nucleus accumbens based on AFNI's whereami ROI tool and these masks were multiplied to the *t*-test of group differences in Win vs. No Win activation. Results indicated *t*-values of −0.3 and 1.2 for the left and right nucleus accumbens, suggesting mean voxel-wise group differences too liberal to warrant further cluster correction.

To examine whether group differences in brain response between HSS and LSS were affected by the questions included in the ImpSS targeting impulsivity (as opposed to sensation seeking alone), a secondary analysis was conducted using only the sensation seeking questions (11 items) from the ImpSS. 21 of the LSS and 22 of the HSS were identical subjects from the initial 94 participants when the highest and lowest sensation seeking individuals were grouped into approximate thirds as in the previous analysis. These participants did not differ significantly on any demographic or behavioral variables presented in Table 1 (all p's > 0.1), except SES ($t_{41} = −2.13$, $p = 0.04$), and sex ($X^2_1 = 4.56$, $p = 0.03$) were now significantly different between these groups, such that HSS included more males and had lower SES than LSS. To verify that group differences in bilateral insula/PFC activity remained significantly different between the 21 LSS and 22 HSS, defined by the sensation seeking questions alone, hierarchical linear regression was conducted in which sex and SES were entered as covariates in the model, followed by Group. Results showed that Group status significantly predicted differences in left and right insula/PFC brain response, above and beyond sex and SES (left insula/PFC: $R^2 = 0.23$, $F_{3,39} = 3.82$, $\beta = 0.39$, $t_{39} = 2.53$, $p = 0.02$; right insula/PFC: $R^2 = 0.26$, $F_{3,39} = 4.65$, $\beta = 0.36$, $t_{39} = 2.40$, $p = 0.02$).

Finally, when examining the relationship between continuous SS scores and brain activity during Win vs. No Win with regression analyses, there were no statistically significant clusters of related activation (multiple comparison correction of this analysis ($p/a = 0.05/0.05$)), although visual inspection of sub-threshold *t*-maps indicated trend-level similar patterns of brain response to the group-level analyses, such that higher SS scores were related to greater Win vs. No Win BOLD activity in insular and PFC regions.

4. Discussion

The purpose of the current study was to examine differences in reward-related brain response in high and low sensation seeking youth in an effort to understand the underlying neural correlates of a personality trait that has been linked to risky, reward-driven behavior during adolescence (Steinberg, 2004; Wills et al., 1994). The goal was to expand on the already existing literature of the triadic framework of adolescent neurodevelopment, in which hyperresponsive reward response and immature regulatory capacity may be a risk

factor for maladaptive adolescent behaviors. By examining sensation seeking, we were able to expand upon this framework by considering how personality during adolescence may be related to reward response. While previous research has examined reward-related brain response related to this trait in adults (Abler et al., 2006; Kruschwitz et al., 2012), neuroimaging studies of sensation seeking have been absent from the adolescent literature, despite adolescence being a time of heightened expression of this personality trait (Steinberg et al., 2008).

While no differences in task risk-taking behavior were seen between HSS and LSS, groups showed significant differences in brain response to reward feedback during the task. Specifically, within-group analyses showed that HSS had significant differences in bilateral PFC and anterior insula BOLD activity when comparing reward receipt and reward absence; this distinction was absent in the LSS, who showed comparable brain response to those two conditions. Furthermore, between-group analyses indicated comparable patterns of brain activity between HSS and LSS in response to reward receipt, while HSS showed a hyporesponsive pattern of brain response in the absence of reward compared to LSS. These results suggest that personality may be an important neural marker for reward response during adolescence. Thus, while previous studies of adolescent neurodevelopment and reward response have found both increased and decreased response to rewards (Bjork et al., 2004; Ernst et al., 2005; Galvan et al., 2006), the current findings indicate that differences in those studies may not only be due to variations in task paradigm, but also lack of consideration of personality differences and their relationship with reward presence/absence.

One of the brain regions in which group differences in Win vs. No Win brain activity were observed was the anterior insula. A previous study of reward processing also found significant differences in insular brain activity between high and low sensation seeking adults and showed that compared with LSS, HSS deactivated the insula in response to large losses, but showed similar patterns of brain response to the largest magnitude of reward outcome (Kruschwitz et al., 2012). While large reward loss cannot be equated to reward absence, the pattern of activity between HSS and LSS in the current study parallels what has previously been seen in adults. This suggests that despite adolescence being a period of heightened sensation seeking compared with adulthood (Steinberg et al., 2008), brain response to reward could be more dependent on individual differences in personality, rather than adolescent age. Since different measures were used between the current and adult study, these results are likely not measure-specific. In support of this notion, other studies have found differences in insular brain response between high and low sensation seeking adults in response to high-arousal emotional pictures, but not low-arousal ones (Joseph et al., 2009). Thus, sensation seeking personality may relate to insular brain activity during various tasks that incorporate stimuli that capture attention, including both monetary rewards and emotional pictures. Furthermore, in a study of adolescents with and without externalizing symptomology, insular activity was present during loss notification, independent of group classification (Bjork et al., 2010a). However, in the current study, LSS recruited bilateral anterior insula activity during notification of No Wins, while HSS showed deactivation in anterior insula during reward absence. The difference in these findings may in part be explained by studies suggesting that externalizing disorders, such as attention deficit hyperactivity disorder, are associated with a different personality profile than

substance use disorders. For example, impulsivity is a strong predictor of externalizing behavior, such as conduct disorder, while SS is more closely related to binge drinking (Castellanos-Ryan and Conrod, 2011; Castellanos-Ryan et al., 2011). Thus, it is plausible that HSS may have a very different neural response to reward absence in the insula than youth with externalizing disorders, whose personality is associated with heightened impulsivity.

Group differences in reward processing were seen also in the DLPFC. Between-group differences in brain response again showed that HSS youth had significant deactivation in the DLPFC during No Wins compared to LSS, indicating distinct responses to *reward absence* in these groups. Primate studies have shown that the DLPFC is important for goal-directed behavior in the presence of reward processing (Wallis and Miller, 2003). Thus, decreased brain activity in the DLPFC in HSS while responding to reward absence could indicate a lack of attention during goal-directed behavior when feedback is negative. This insensitivity, or hyporesponsive pattern of brain activity, to reward absence in HSS may result in increased engagement with maladaptive behaviors when negative consequences are not considered. This pattern of brain response has been seen in pathological gamblers, who show reduced middle PFC and insular activity during reward loss compared to controls (Balodis et al., 2012). Similarly, atypical ventrolateral PFC activity is seen in problem gamblers and smokers compared with healthy controls (de Ruiter et al., 2009), but it is uncertain whether personality characteristics, such as sensation seeking, prior to gambling addiction, may have been predictive of hyporesponsivity to reward loss in these groups. However, these studies suggest that both insular and prefrontal cortical brain regions have been implicated in reduced brain response to reward loss in addiction. Since this type of deactivation in the presence of reward loss has been suggested to reflect decreased loss sensitivity (Dong et al., 2011), the current findings of deactivation to reward absence in HSS could be an important risk marker for future maladaptive behavior and warrants further exploration.

Contrary to hypotheses, the current study did not find subcortical (e.g. nucleus accumbens) differences in brain activity between HSS and LSS. Lack of differences in BOLD response in this region may be due to the already heightened activity of the ventral striatum in response to rewards during adolescence (Ernst et al., 2005; Galvan et al., 2006), which may be common neurobiology in most youth, regardless of personality differences. On the contrary, sensation seeking differences may not be related to nucleus accumbens brain response. Rather, other personality characteristics associated with risky adolescent behaviors, such as extraversion (Nees et al., 2012) or aggression (Prinstein and La Greca, 2004), may better dissociate differences in subcortical brain response to rewards.

While this was the first study to stratify high and low sensation seeking adolescents and examine differences in brain activity during a reward-based decision-making task, limitations should be noted. First, while the trend in sex differences between HSS and LSS did not affect results of the current study, our results are consistent with findings showing that males have higher scores on impulsive sensation seeking than females (Zuckerman and Kuhlman, 2000), so disparities in the relative contribution of sex to sensation seeking personality should be further explored. This could provide important sex-specific

information to aid the focus of prevention strategies targeting high-risk youth during adolescence.

Second, HSS did not exhibit greater risk-taking behavior on the WOF task than LSS. While one might expect HSS to show heightened risk-taking compared to LSS, it is possible that the WOF task is not salient enough to drive heightened risk-taking behavior during monetary decision-making in HSS. Similar lack of behavioral differences has been observed in a previous study of decision-making on the WOF task when at-risk youth with familial history of alcoholism were compared to their control peers (Cservenka and Nagel, 2012). Thus, it is plausible that vulnerable populations including high sensation seeking youth, as well as those at high familial risk for alcoholism, may show greater behavioral differences from their control peers when real-life, high-risk behaviors are examined (Malmberg et al., 2010; Sher et al., 1991). Another possibility may be that riskier behaviors in HSS may be better observed in the presence of peers during adolescence, a time when most risk-taking behavior is highly influenced by social groups (Steinberg, 2008). Thus, it will be essential for future studies to incorporate tasks that examine peer influence on risky behaviors (Chein et al., 2011) when different personality traits are considered. An alternative interpretation for lack of behavioral differences is that deactivation to reward absence may allow HSS to have comparable risk-taking behavior to LSS. Perhaps reduced activation during reward absence in the insula, known for its role in affective processing, elicits a weaker emotional reaction in HSS, which may suggest less frustration with reward absence. This could protect HSS from affect-driven decisions, resulting in comparable risk-taking levels to LSS. However, given the non-significant ($p = 0.15$), but higher risk-taking in HSS compared with LSS, we believe the former interpretations may better explain neural differences between the groups.

Third, we did not find a significant continuous relationship between SS scores and brain response when all 94 adolescents were included in the sample. It is possible that the distinct brain response profiles of high vs. low sensation seekers was masked by the increased variability in sensation seeking values that fall in the middle percentile range. Thus, polarizing youth by high and low sensation seeking may be a more powerful approach for detecting distinct neural profiles of personality differences.

Lastly, the measure of sensation seeking personality used in the current study also included questions related to impulsivity, such as those assessing lack of forethought and decreased inhibitory capacity. However, careful inspection of the data showed comparable behavioral and imaging results in the sample dichotomized into HSS and LSS by the sensation seeking questions alone, suggesting that the ImpSS may be used to distinguish adolescents by individual differences in sensation seeking personality. Furthermore, the findings in the current study are comparable to adult neuroimaging studies of sensation seeking that used different personality measures.

Despite lack of behavioral differences in decision making, the evaluation of reward outcome at the neural level differed between the groups. LSS did not show decreased brain response in prefrontal cortex and insula to lack of rewards, suggesting that their sensitivity to reward absence may indicate an ability to evaluate the negative outcomes of their decisions, a sensitivity that is not present in high sensation seeking youth. This insensitivity in HSS may

then result in poor evaluation of behavior, which may be especially dangerous in real-life risky behaviors, where stakes may be higher than in a laboratory setting. Additionally, to determine the predictive power of the current results, future longitudinal prospective studies will be necessary to assess whether HSS are more prone for risky behaviors, such as early alcohol or substance use during adolescence, compared to LSS, and whether this potential biomarker of reduced neural sensitivity to reward absence is predictive of such behavior.

5. Conclusions

The current study is the first to examine the underlying neural correlates of sensation seeking in an adolescent sample, and suggests value in examining personality traits during adolescence as they relate to approach behavior and reward response. Recent evidence suggests that personality variables, including sensation seeking, explain more variance in adolescent alcohol use than behavior or brain response alone (Nees et al., 2012). Thus, the current research will ultimately aid in better understanding neurobiological underpinnings of personality traits during adolescence that have been linked to risky, maladaptive outcomes, including alcohol and drug experimentation. This information may prove helpful in establishing future prevention strategies aimed at reducing the incidence of high-risk adolescent behaviors.

Acknowledgments

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Highlights

- Sensation seeking relates to brain activity during reward in adolescents.

- High sensation seekers show hypoactivity in the insula in the absence of reward.

- Sensation seeking personality may be an important marker for risky behavior.
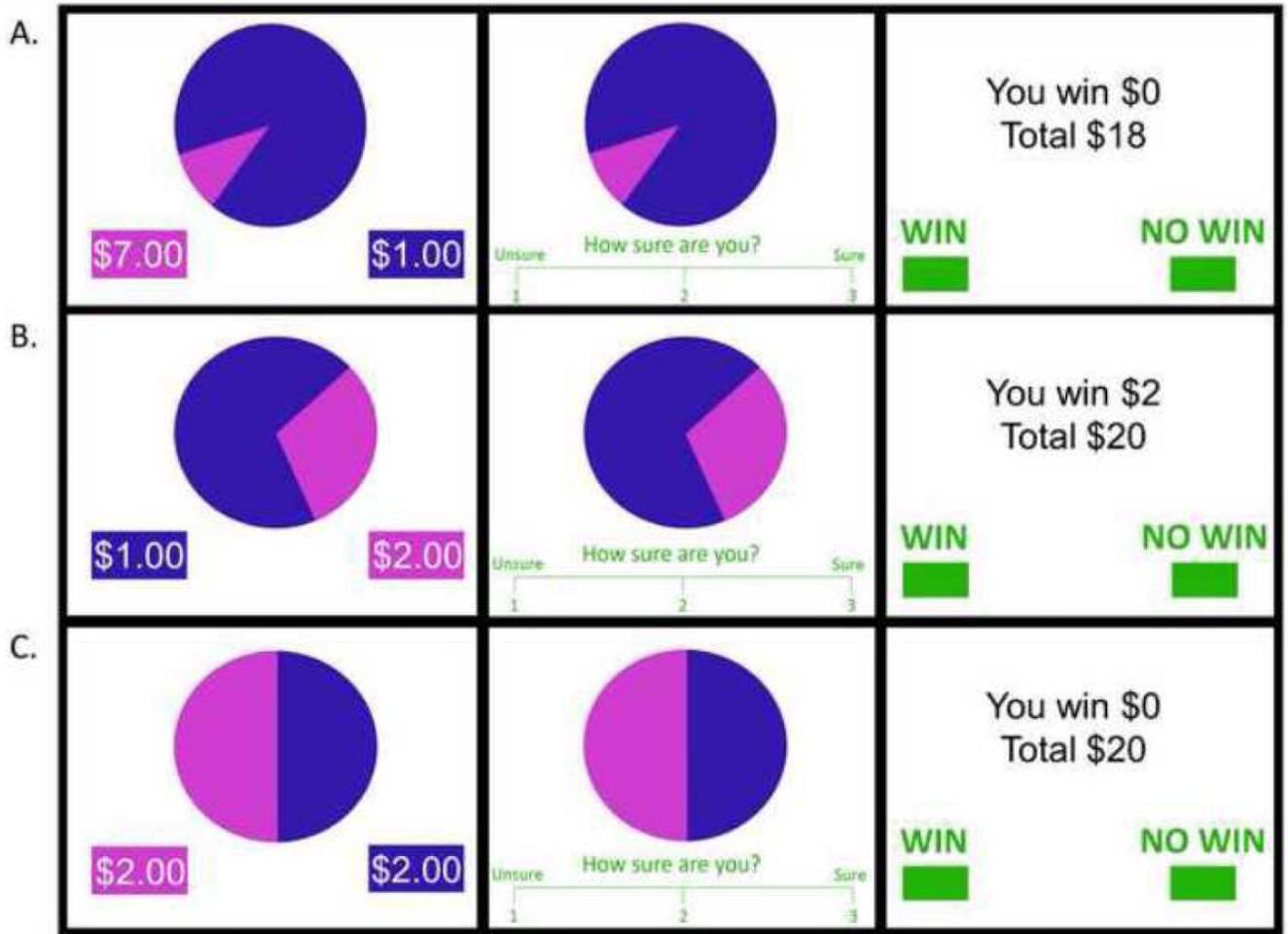
Figure 1. Wheel of Fortune Task

(A) Example of not winning when selecting the low-probability / high-reward option instead of the high-probability / low-reward option (10%—$7.00 vs. 90%—$1.00). During the selection phase of the trial, participants chose which portion of the wheel they thought would win them money, during anticipation they responded to how sure they were of winning, and during feedback they responded to whether or not they won money during that trial, in addition to being shown their total earnings. The imaging analyses were limited to the feedback phase of the trials to examine brain response to reward receipt. (Trials were 10.5 seconds long and consisted of a selection (3 seconds), anticipation (3.5 seconds), and feedback (4 seconds) phase. (B) Example of winning after selecting the 30% portion of the wheel in the 30%—$2.00 versus 70%—$1.00 wheel. (C) Example of not winning after selecting a chance portion of the wheel.
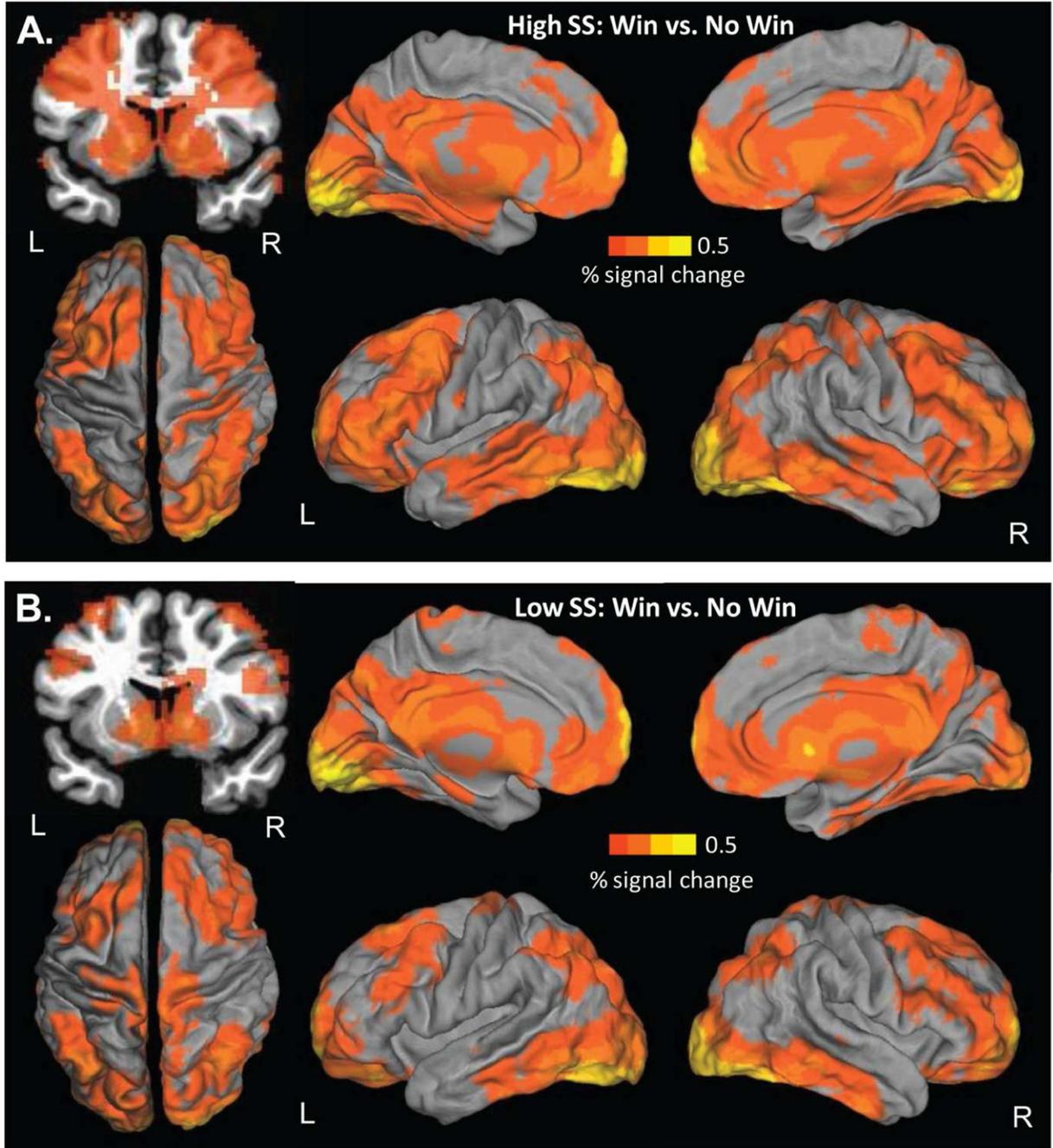
Figure 2. Win vs. No Win Whole-Brain Activity in High and Low Sensation Seekers
HSS (A) and LSS (B) brain activity during Win vs. No Win surface mapped onto Caret's anatomical template image in the sagittal and axial views. Coronal view is mapped onto AFNI's anatomical template image to illustrate expected ventral striatal brain activity in each group (Win > No Win). For each group, areas in red correspond to brain regions where Win > No Win BOLD response. There were no regions that survived multiple comparison correction in which No Win > Win BOLD response was observed. Whole-brain activity is voxel and cluster thresholded at $p/\alpha < 0.05$. SS = sensation seekers L = left, R = right.
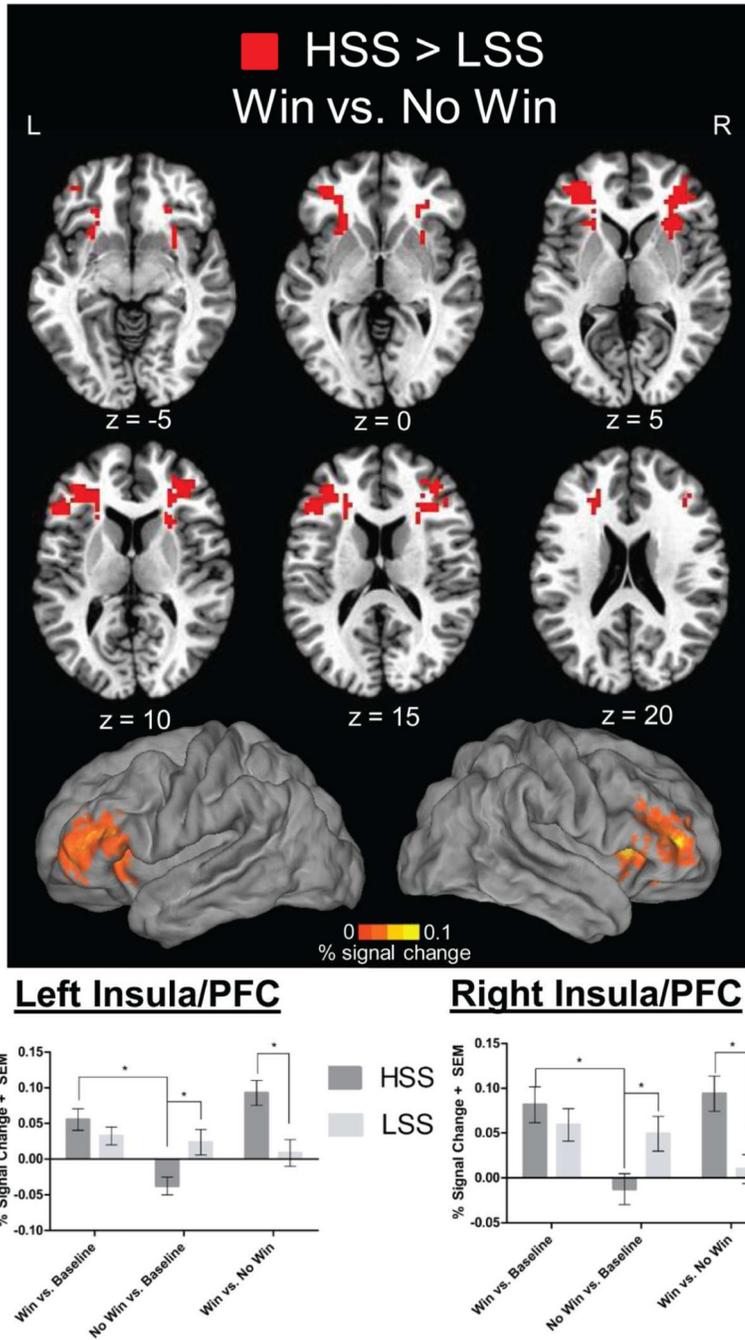
Figure 3. Group Differences in Win vs. No Win Brain Activity in High and Low Sensation Seekers

Significant group differences (voxel/clusterwise corrected, $p < 0.05/\alpha < 0.01$, minimum cluster size: 165 voxels) in reward-related brain activity between HSS and LSS are seen in bilateral insula/PFC surface mapped onto Caret's anatomical template in the sagittal view. Axial views are illustrated with AFNI's anatomical template as the underlay to display the extent of activation in the left and right insula/PFC clusters, with corresponding Talairach coordinates below each axial plane. Results indicate greater bilateral insula/PFC activity in HSS compared to LSS, which is illustrated in the bar graphs of percent signal change below

each of the clusters. *$p<0.05$. HSS = high sensation seekers, LSS = low sensation seekers, L = left, R = right.

Table 1

Participant characteristics and task performance

Means are presented in each column, with standard deviation for each group presented in parentheses. There were no significant group differences on any of the measures presented.

	High Sensation Seeking	Low Sensation Seeking	Statistic
Age	14.12 (0.96)	13.75 (1.12)	$t_{52} = 0.19$
Sex (Male/Female)	21/6	15/12	$X^2_{1,54} = 3.00^{†}$
Puberty[a]	3.77 (1.19)	3.44 (0.97)	$U_{52} = 288.5, Z = -1.37$
IQ[b]	109.48 (12.33)	111.48 (11.16)	$t_{52} = 0.54$
SES[c]	32.26 (14.88)	25.67 (11.59)	$U_{52} = 267.5, Z = -1.69^{†}$
Movement (RMS)	0.25 (0.18)	0.29 (0.21)	$U_{52} = 316, Z = -0.84$
Sensation Seeking (%)[d]	73.52 (10.13)	21.59 (9.87)	
Performance on WOF task			
Risky Selections (%)	71.44 (23.34)	64.26 (21.01)	$U_{52} = 287.5, Z = -1.33$
Accuracy on Win Trials (%)	98.64 (3.54)	99.56 (1.58)	$U_{52} = 321.5, Z = -1.15$
Accuracy on No Win Trials (%)	95.82 (7.04)	93.82 (19.37)	$U_{52} = 342, Z = -0.43$

[a]Tanner's Sexual Maturation Scale; scores range 1–5, with higher scores reflecting greater maturity (Taylor et al., 2001)

[b]Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999)

[c]Hollingshead Index of Social Position; higher scores indicate lower socioeconomic status; mean scores here are commensurate with middle (High Sensation Seeking) and upper-middle class (Low Sensation Seeking) status (Hollingshead, 1975)

[d]Impulsive Sensation Seeking Scale of the Zuckerman-Kuhlman Personality Questionnaire (Zuckerman et al., 1993)

WOF = Wheel of Fortune Task, RMS = root mean square

[†]$p < 0.1$