White Matter Integrity and Behavioral Activation in Healthy Subjects

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Abstract

Individual differences in behavioral inhibition and behavioral activation may place certain people at greater risk for neuropsychiatric disorders and engagement in risky behaviors. Therefore, studying the neural correlates of behavioral inhibition and activation may help us understand neural mechanisms underlying risk behaviors in both clinical and non-clinical populations. To investigate, we assessed the relationships between white matter integrity and measures of behavioral inhibition and behavioral activation in 51 healthy participants using diffusion tensor imaging (DTI) and the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) scale. Scores on the Fun-Seeking subscale of the BAS positively correlated with DTI fractional anisotropy (FA) in the left corona radiata and adjacent superior longitudinal fasciculus, and with mean diffusivity (MD) in the left inferior longitudinal fasciculus and inferior fronto-occipital fasciculus after controlling for age, gender, and education. These findings suggest that the integrity of white matter connecting extensive brain regions implicated in self-control and the processing of rewards and emotions are associated with individual differences in the motivation for seeking and participating in fun and novel experiences.

Keywords

Behavioral Activation; Behavioral Inhibition; Neuroimaging; DTI; Self-Control; Cognitive Control

Introduction

Gray proposed that a behavioral inhibition system (BIS) and a behavioral activation system (BAS) underlie propensities to engage in motivated behaviors (Gray 1982; Gray 1987). According to Gray’s theory, the BIS is sensitive to cues of loss, punishment, conflict, or novelty, and inhibits behaviors leading to negative results. Its activation is associated with negative affective states (like anxiety), and its neural correlates include amygdala and septo-hippocampal systems (Gray 1987; Gray 2000). The BAS is sensitive to rewarding cues and

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promotes approach behaviors to potential rewards. Its activation is associated with positive affective states (like happiness), and its neural correlates include the mesolimbic dopaminergic system (Depue & Collins 1999; Gray 1987; 1990).

Although the theory proposing separate systems for behavioral inhibition and activation is mainly based on animal research (Fowles 1987; Gray 1987), human studies have demonstrated distinct roles for these systems in clinical and non-clinical populations. It has been demonstrated that high BIS and BAS function may predispose individuals to internalizing and externalizing disorders, respectively (Bijttebier et al 2009; Colder & O'Connor 2004; Hundt et al 2008). For example, increased BIS activation is associated with anxiety and/or depression among community populations (Carver & White 1994; Hundt et al 2007; Johnson et al 2003; Shackman et al 2006), while increased BAS activation is associated with conduct-related disorders, eating disorders, and alcohol and drug use (Johnson et al 2003; Knyazev 2004; Loxton & Dawe 2006; Quay 1993). Further, patients with depression and/or anxiety consistently report higher BIS scores compared to healthy adults, while patients with bipolar, substance use, or attention deficit hyperactivity disorders report higher BAS scores (Alloy et al 2009; Bijttebier et al 2009; Franken et al 2006). Taken together, these data suggest that BIS and BAS are associated with negative and positive affect, respectively, and with the development of distinct forms of psychopathology.

The neural correlates of BIS and BAS have been examined in structural brain imaging studies. For example, two voxel-based morphometry (VBM) studies assessed the structural correlates of BIS and BAS in 50 male college students using the Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ) (Torrubia et al 2001). Consistent with Gray's theory, sensitivity to Punishment (SP) scores correlated positively with volumes of gray matter (GM) in the amygdala and hippocampal formation (Barros-Loscertales et al 2006a), and Sensitivity to Reward (SR) scores correlated negatively with GM volumes in the dorsal striatum and right superior frontal gyrus (Barros-Loscertales et al 2006b). Another VBM study assessed personality traits of 85 young adults using the Tri-dimensional Personality Questionnaire (TPQ) (Cloninger 1987). Scores on harm avoidance, which are thought to reflect BIS function, correlated negatively with GM volumes in the prefrontal, parietal, and occipital cortices, and scores on reward dependence, which are thought to reflect BAS function, correlated negatively with GM volumes in the caudate and frontal rectal gyrus (Gardini et al 2009). A separate study assessed the volumes of amygdala and hippocampal formation in 430 community adults using manual tracing on T1 magnetic resonance image (MRI) and correlated these measures with scores on the BIS/BAS scale (Carver & White 1994) and found that BIS scores correlated positively with hippocampal volume (Cherbuin et al 2008). Taken together, these, but not all, studies provide initial evidence indicating that GM volumes in the hippocampus, amygdala, striatum, and PFC may be associated with aspects of BIS and/or BAS function.

Although prior studies have linked BIS/BAS function to GM volumes, the role of white matter (WM) in BIS/BAS function is not clear. The WM may influence BIS/BAS function because WM connections mediate communications between different brain regions and are essential for integrated brain function. Diffusion tensor imaging (DTI) assesses WM integrity by measuring directional water diffusion (Alexander, 2007; Assaf, 2008). Recently, DTI has been used to assess WM integrity as related to brain function and behavior in healthy subjects and those with neuropsychiatric disorders (Agarwal et al 2010; Sexton et al 2009). The commonly used DTI parameters include fractional anisotropy (FA), mean diffusivity (MD), longitudinal eigenvalue ($\lambda_1$), and perpendicular eigenvalue ($\lambda_T$). FA is a normalized standard deviation of eigenvalues (Pierpaoli and Basser, 1996), and decreased FA value in the WM is regularly interpreted as reflecting impaired WM integrity. MD is calculated as the mean of all eigenvalues. Increases in tissue water (e.g., edema) and/or in
inter-membrane space in the WM can increase MD values (Alexander, 2007). There are data indicating that axonal degeneration is associated with decreased $\lambda_1$ values (Concha et al. 2006; Sidaros et al. 2008), while demyelination is associated with increased $\lambda_T$ value (Song et al. 2002). However, the cellular mechanisms underlying the changes of either eigenvalues have not been fully revealed, and several other factors, including directions and patterns of crossing fibers, may also influence eigenvalues (Jbabdi et al. 2010; Wheeler-Kingshott & Cercignani 2009).

To our best knowledge, no published studies have used DTI to assess the relationship between white matter (WM) integrity and BIS/BAS measures. Given the role of BIS and BAS in affect and in the development of psychopathology, understanding their neural correlates, including WM, may have broad applicability. To investigate, we analyzed the relationships between WM integrity assessed by DTI and scores on the BIS/BAS scales and subscales in 51 healthy participants (HPs). We predicted that: 1) poorer integrity of WM interconnecting striatum and PFC would correlate with greater scores on BAS, because previous studies reported negative correlations between measures on BAS and GM volumes in the striatum and PFC (Barros-Loscertales et al. 2006b; Gardini et al. 2009); and, 2) better integrity of WM connecting limbic regions would correlate with higher scores on BIS, because previous studies reported positive correlations between measures on BIS and GM volumes of hippocampus and amygdala (Barros-Loscertales et al. 2006a; Cherbuin et al. 2008).

Methods

Participants

We acquired both DTI and self-reported data on the BIS/BAS scale from 56 HPs. Subjects were recruited by media ads and provided written informed consent approved by the Yale Human Investigations Committee. Participants were screened using the Structured Clinical Interview (SCID) (First et al. 1997; First et al. 1996) and had urine samples tested for metabolites of cocaine, opioids, amphetamines, marijuana and benzodiazepines. Participants were excluded if any metabolites of these substances were positive in their urine samples. Handedness was assessed by asking participants which hand they usually use for tasks like writing or throwing, and left-handed individuals were not invited to participate. Exclusion criteria included pregnancy, color blindness, a current Axis I disorder, or an unstable medical condition. Two independent neuroimaging researchers, who were blind to the identity of DTI images, independently examined the quality of each image in the original space. Images from five participants were rated as excessively noisy by both investigators and were excluded from further analysis. The excessive noise might due to one or more possible factors including motion, scanner instability, and static interference from electronic equipments in the scanning room. The final sample included 51 HPs with a mean age of 29.6 (standard deviation (SD) = 10.0, range: 18 - 54) years, and mean education of 15.0 (SD = 2.0, range: 12 - 20) years. Twenty-one participants were female.

BIS/BAS Assessment

The BIS/BAS scale is a valid and reliable 20-item questionnaire (Carver & White 1994; Heubeck et al. 1998). Seven items measure sensitivity to signals of punishment, non-reward, or conflicts, and comprise a BIS scale. The remaining 13 items comprise a BAS scale measuring sensitivity to signals of reward or non-punishment, with subscales for Drive (BAS-Drive), Fun-Seeking (BAS-Fun), and Reward-Responsiveness (BAS-Reward), which measure the propensities of pursuing goals, seeking out new potentially rewarding experiences, and reward response tendencies, respectively (Carver & White 1994; Heubeck
et al. 1998). The correlations between scores on the BIS/BAS subscales were analyzed using SPSS16.

Scanning Procedures

DTI data were acquired with a 3.0T Siemens Trio scanner at the Yale Magnetic Resonance Research Center. Diffusion sensitizing gradients were applied along 32 directions using b values 1000 s/mm$^2$ (TR = 7400, TE = 115, matrix = 128 × 128, FOV = 256 × 256 mm$^2$). In addition one image (b0 image) was acquired using b value of 0. Forty contiguous slices parallel to the AC-PC line were acquired, and each slice was 3.0 mm thick (Xu et al. 2010). Two repetitions were acquired for averaging. A high-resolution T1 image was routinely acquired and examined by a neuroradiologist to identify any structural anomalies.

Image Processing

The procedure for DTI processing was described recently (Xu et al., 2010). FMRIB’s Diffusion Toolbox (FDT 2.0) and Tract-Based Spatial Statistics (TBSS 1.2, Smith et al. 2007; Smith 2004; Smith et al. 2006) from FMRIB’s Software Library (FSL 4.1.4, Smith et al. 2004; Woolrich et al. 2009, http://www.fmrib.ox.ac.uk/fsl/) were used for image analyses. A set of mean images was created by aligning and averaging the two image sets from each subject and were used to construct the diffusion tensor using FDT. FDT typically generates maps of fractional anisotropy (FA), parallel eigenvalue ($\lambda_1$), mean diffusivity (MD), $\lambda_2$ ($\lambda_2$), and $\lambda_3$ ($\lambda_3$). The map of perpendicular eigenvalue ($\lambda_T$) was generated by averaging maps of $\lambda_2$ and $\lambda_3$.

TBSS was used to register the FA map of each subject into the Montreal Neurological Institute (MNI) template space. A mean FA map was created by averaging registered FA images from all subjects, and a mean FA skeleton was created by thinning the mean FA image (Smith et al. 2007; Smith 2004; Smith et al. 2006). The highest local FA value was projected to the skeleton after searching the local area in the direction perpendicular to each tract. The transformation matrices created for FA map registration were used to register $\lambda_1$, $\lambda_T$, and MD maps. Skeletons for $\lambda_1$, $\lambda_T$, and MD were generated using the same procedures for creating the FA skeleton.

We used a voxel-wise whole-brain analytic approach to assess the relationships between scores on the BIS/BAS scale and values of FA, $\lambda_1$, $\lambda_T$, and MD using correlation analyses with age, gender, and education as covariates. Among adults, aging is associated with decreased WM integrity as expressed by decreased FA values and increased MD values in the WM (Gunning-Dixon et al. 2009; Madden et al. 2009). Image analyses were executed using the “randomise” program with 5000 permutations. This program uses permutation-based, non-parametric inferences to perform voxel-wise, cross-subject statistics (Nichols & Holmes 2002). Statistical thresholds for all image analyses were voxel-level t > 2.0 and cluster p < .05, FWE-corrected for multiple comparisons in the voxel-wise whole-brain analysis. JHU ICBM-DTI-81 White-Matter Labels and JHU White-Matter Tractography Atlas provided by FSLVIEW 3.1.2 were used to identify the location of significant clusters (Mori et al. 2008; Mori et al. 2009), and the significant clusters were defined as regions of interest (ROI). The function “fslmeants” from FSL was used to extract means of FA, $\lambda_1$, $\lambda_T$, and MD from these ROIs, and correlations between these extracted values were analyzed using SPSS 16.
Results

Correlations between BIS/BAS subscale scores

Table 1 presents correlations between scores on each subscale of the BIS/BAS scale. The scores on BAS-Drive, BAS-Fun, and BAS-Reward correlated positively with each other, and with the total scores of BAS scale. The scores on the BIS scale showed a modest but significant correlation with scores on the BAS-Reward subscale.

Correlations between DTI and BIS/BAS scores

The correlations between values of DTI parameters and scores on BIS/BAS were assessed after controlling for age, gender, and education. The scores on the BAS scale correlated positively with $\lambda_1$ values in one cluster, but not with other DTI parameters (Fig. 1 & Table 2). The significant cluster was at the left CR and SLF. Scores on the BAS-Fun subscale significantly correlated with FA, $\lambda_1$, and MD, but not with $\lambda_T$ (Table 2 & Fig. 2). In both FA and $\lambda_1$ maps, one cluster at the left CR and SLF positively correlated with scores on the BAS-Fun subscale (Fig. 2). Visual inspection and the data on the sizes of significant clusters and MNI coordinates of peak voxel in each cluster indicated that the significant clusters in the FA and $\lambda_1$ maps overlapped with each other in space, and that the cluster in the $\lambda_1$ map was almost identical in location, size, and shape to the cluster showing a significant correlation between $\lambda_1$ and scores on BAS scale. In the MD map, one cluster at the left Inferior fronto-occipital fasciculus (IFOF) and inferior longitudinal fasciculus (ILF) positively correlated with scores on the BAS-Fun subscale (Fig. 2). Scores on the BAS-Drive and BAS-Reward subscales and the BIS scale did not show significant correlations with any DTI parameters.

ROI Analysis

The cluster showing significant correlation between FA and BAS-Fun scores was defined as a ROI. Partial correlation analyses showed that the correlation between BAS-Fun scores and mean FA values from the ROI was still significant after controlling for either $\lambda_1$ ($r = .413, p = .003$) or $\lambda_T$ ($r = .406, p = .003$), but became non-significant ($r = .14, p = .35$) after controlling both $\lambda_1$ and $\lambda_T$. Correlation analyses showed that mean FA values from the ROI significantly correlated with mean values of $\lambda_1$ ($r = .67, p < .001$) and $\lambda_T$ ($r = -.85, p < .001$), but mean values of $\lambda_1$ and $\lambda_T$ did not significantly correlate with each other ($r = -.18, p = .21$). The cluster showing a significant correlation between MD values and BAS-Fun scores was defined as another ROI. Partial correlation analyses showed that the correlation between BAS-Fun scores and mean MD values from the ROI became non-significant after controlling for either $\lambda_1$ ($r = .19, p = .18$) or $\lambda_T$ ($r = .15, p = .30$). Correlation analyses showed that mean MD values significantly correlated with mean values of $\lambda_1$ ($r = .94, p < .001$) and $\lambda_T$ ($r = .97, p < .001$), and that mean values of $\lambda_1$ and $\lambda_T$ significantly correlated with each other ($r = .84, p < .001$).

Discussion

This study aimed to assess the relationships between WM integrity and BIS/BAS function in HPs. The most interesting finding is that better WM integrity (i.e., greater FA values) in the left CR and SLF along with worse WM integrity (i.e., greater MD values) in the left IFOF and ILF correlate with higher scores on the BAS-Fun subscale. These findings suggest that specific regions of WM integrity may underlie BAS sensitivity, especially the motivation for seeking and participating in fun and novel situations. In addition to this interesting finding, scores on the BIS/BAS subscales show positive correlations. Implications are discussed below.
Correlations Between BIS/BAS Measures

The scores on the BIS scale and each subscale of BAS reported by HPs in the present study are similar to those reported by HPs in several previous studies (Caseras et al 2003; Franken et al 2006; Meda et al 2009; Miller et al 2004). The current findings of significant positive correlations between scores on subscales of the BAS and between scores on the BIS scale and BAS-Reward subscale are consistent with previous findings of significant intercorrelations between these measures (Johnson et al 2003; Miller et al 2004; O’Connor et al 2004; Poythress et al 2008; Ross et al 2002). The consistent findings between current and previous studies suggest that the current HPs are representative of general healthy populations.

Correlations Between WM Integrity and BAS Scores

Scores on the BAS scale and BAS-Fun subscale showed significant correlations with $\lambda_1$ at almost identical WM locations (i.e., the left CR and SLF), while scores on the BAS-Drive and BAS-Reward subscales did not show significant correlation with any DTI parameters. Therefore, the significant correlation between scores on BAS scale and $\lambda_1$ appears driven by the significant correlation between BAS-Fun subscale scores and $\lambda_1$ measures. Furthermore, the scores on the BAS-Fun subscale positively correlated with FA values in a cluster overlapping with the significant cluster in the $\lambda_1$ map. These findings suggest that better WM integrity in the CR and SLF is associated with greater scores on BAS-Fun subscale. The SLF connects parietal and frontal cortices, while the CR connects cortical and subcortical structures including the thalamus and midbrain (Schmahmann et al 2008). Therefore, better anatomical connections among PFC, parietal cortex, and subcortical structures including thalamus and midbrain appears associated with a greater motivation for seeking and participating in fun and novel experiences. A previous fMRI study reported significant correlation between BAS scores and task-related activity in the lateral PFC, anterior cingulate, and parietal cortex while performing a cognitive control task (i.e., n-back working memory task) (Gray et al 2005). The current finding of a significant correlation between BAS-Fun scores and FA values in the CR and SLF suggest that WM integrity may contribute to the relationships between BAS sensitivity and task-related activity in brain regions involved in cognitive control.

ROI analyses indicated that the correlation between BAS-Fun scores and mean FA values in the significant cluster remained significant after controlling for either $\lambda_1$ or $\lambda_T$, and only became non-significant after controlling for both $\lambda_1$ and $\lambda_T$. Therefore, both $\lambda_1$ and $\lambda_T$ appear to contribute to the significant correlation between BAS-Fun scores and FA values in the cluster. Furthermore, the mean FA values in the significant cluster correlated positively with mean values of $\lambda_1$ but negatively with mean values of $\lambda_T$, while the mean values of $\lambda_1$ and $\lambda_T$ did not correlate with each other. These data indicate that either increases in $\lambda_1$ values or decreases in $\lambda_T$ values will increase FA values (i.e., improve WM integrity) in the significant cluster, and that individual differences in $\lambda_1$ values are independent of individual differences in $\lambda_T$ values. Because the cellular mechanisms underlying changes in values of $\lambda_1$ and $\lambda_T$ are different (Concha et al 2006; Sidaros et al 2008; Song et al 2002), at least two different cellular mechanisms may be involved with respect to increasing FA values, one via increasing $\lambda_1$ values without affecting $\lambda_T$ values, and the other via decreasing $\lambda_T$ values without affecting $\lambda_1$ values. Therefore, two or more different cellular mechanisms might contribute to individual differences in FA values in the significant cluster observed in the present study.

The positive correlations between scores on the BAS-Fun subscale and MD in the IFOF and ILF indicate that worse WM integrity in these tracts is associated with greater scores on BAS-Fun subscale. The IFOF connects frontal and occipital lobes, while the ILF connects...
occipital and temporal lobe structures including the amygdala, hippocampus, and parahippocampus (Catani et al 2003; Ingegni et al 2003; Mori et al 2005; Schmahmann & Pandya 2007; Schmahmann et al 2008). The current findings suggest that worse anatomical connections among the PFC, occipital cortex, and temporal structures including the amygdala, hippocampus, and parahippocampus are associated with a greater motivation for seeking fun and novel experiences. Prior functional imaging studies reported that BAS scores correlated positively with reactivity in the left hippocampus-parahippocampus area and insula while HPs viewed erotic and disgusting pictures, respectively (Reuter et al 2004). The present cluster showing a positive correlation between BAS scores and MD values was at the left IFL and IFOF and adjacent to the left insula, and might include fibers connecting to the left insula. Therefore, the increased reactivity to emotional stimuli in the insula and hippocampus-parahippocampus area of HPs with high BAS scores may reflect decreased top-down emotional regulation due to decreased WM integrity and decreased anatomical connection among PFC and occipital and temporal lobes. We should note that the JHU White-Matter Tractography Atlas was used to localize the significant cluster in the left IFOF in the current study. However, the existence of IFOF has been challenged by some investigators (Schmahmann & Pandya 2007). Therefore, these findings should be interpreted cautiously and more research should investigate the nature and implications of the current observations.

ROI analyses revealed that the significant correlation between BAS-Fun scores and mean MD values in the significant cluster became non-significant after controlling for either $\lambda_1$ or $\lambda_T$ values. Therefore, both $\lambda_1$ and $\lambda_T$ might contribute to the significant correlation between BAS-Fun scores and MD values. Furthermore, the mean MD values in the significant cluster correlated positively with mean values of both $\lambda_1$ and $\lambda_T$, and that the mean values of $\lambda_1$ and $\lambda_T$ correlated positively with each other. These data suggest that individual differences in values of $\lambda_1$ and $\lambda_T$ in this significant cluster may be due to the same cellular mechanism, which should be different from the cellular mechanisms underlying individual difference in FA values in the cluster showing significant correlation between BAS-Fun scores and FA values.

It was hypothesized that positive emotion and approach behavioral tendencies have been associated with function of the left hemisphere, while negative emotion and withdrawal behavioral tendencies have been associated with function of the right hemisphere (Davidson 1992; Davidson et al 1990). Data from several (but not all) studies using different methods such as fMRI, VBM, and patients with unilateral brain lesion support this hypothesis (Canli et al 2002; Davidson & Irwin 1999; Harmon-Jones 2003; Harmon-Jones et al 2006; Omura et al 2005). The current finding of a significant correlation between BAS-Fun scores and values on DTI parameters in the left hemisphere provide DTI evidence supporting this hypothesis.

Based on previous findings of negative correlations between BAS-related scores and GM volumes in the dorsal striatum and PFC (Barros-Loscertales et al 2006b; Gardini et al 2009), we predicted that poorer integrity of WM interconnecting striatum and PFC would correlate with greater scores on BAS. Though our data showed negative correlations between BAS-Fun scores and WM integrity in the IFOF and ILF, these two fasciculi may not provide direct anatomical connections between PFC and striatum. Furthermore, our data showed positive correlations between BAS-Fun scores and WM integrity in the CR and SLF. Therefore, our data do not support our first prediction, and multiple possibilities exist as to why this might be the case. For example, it is possible that the relationship between GM volumes and integrity of WM is not a linear positive correlation. Future studies should directly test this issue by assessing both GM volumes and WM integrity in the same participants.
Based on previous findings of positive correlations between BIS scores and GM volumes of hippocampus and amygdala (Barros-Loscertales et al 2006a; Cherbuin et al 2008), we predicted that better integrity of WM connecting limbic regions would correlate with higher BIS scores. However, our data did not show significant correlations between BIS scores and any DTI parameters. Furthermore, our data did not show significant correlations between BAS-Reward scores and values of any DTI parameters, even though previous studies reported scores on reward sensitivity negatively correlated with GM values in the striatum and PFC (Barros-Loscertales et al 2006b; Gardini et al 2009). In addition, scores on BAS-Drive did not show significant correlations with values of any DTI parameters. It is currently unclear whether these negative findings reflect truly no relationships between WM integrity and these BIS/BAS measures or are due to methodological issues. The method used in this study analyzed a subset of voxels in the entire WM and employed multiple comparison correction with controlling for family-wise error rate (i.e., FWE-corrected) (Nichols & Holmes 2002). The FWE-corrected method may decrease the sensitivity for detecting statistical significance at each voxel. Therefore, the most parsimonious interpretation of our negative findings is that the employed method did not detect significant correlations between scores on these BIS/BAS parameters and values of DTI parameters in this specific sample of HPs.

Limitations and Strengths

The study has several methodological limitations and strengths. The analytic package used to assess WM (TBSS) searches each voxel adjacent to each tract and assigns the local highest value to the skeleton (Smith et al 2007; Smith 2004; Smith et al 2006). Therefore, TBSS tests only a subset of voxels distributed in the entire WM. Additionally, some of the WM regions identified lie at the border of WM tracts whose function may differ. Therefore, methods with better spatial resolution should be employed in future studies for better localizing significant voxels and implicating specific WM tracts. Study strengths include a large sample size for DTI studies and the use of a whole-brain analytic approach.

Conclusions

By demonstrating significant correlations between DTI parameters in the CR, SLF, ILF, and IFOF and scores on the BAS-Fun subscale, the present study provides evidence indicating that the integrity of WM in these brain regions may contribute to BAS sensitivity in HPs. This finding expands the existing knowledge of the neural correlates of the BAS acquired from previous fMRI and VBM studies, and lays the groundwork for future investigations of how WM integrity may influence risk-taking and sensation-seeking behaviors in community and clinical samples.

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Figure 1.
Correlation between $\lambda_1$ values and scores on BAS scale. Red-yellow color on MNI (Montreal Neurological Institute) T1 template indicates brain regions exhibiting significant correlations between $\lambda_1$ values and scores on the BAS scale. The green color shows the “group mean_FA_skeleton”, the number below the brain image indicates Z coordinates in MNI space, and only clusters surviving correction for multiple comparisons of voxel-wise whole brain analysis are shown on brain images. Scatter-plots demonstrate correlations between mean values of $\lambda_1$ (y-axis) of each participant and scores on the BAS scale. Mean values of $\lambda_1$ were calculated from all voxels in the significant cluster of each participant. Abbreviation: L: left.
Figure 2.
Correlations between values of FA, $\lambda_1$, and MD and scores on Fun Seeking subscale. Red-yellow color on MNI (Montreal Neurological Institute) T1 template indicates brain regions exhibiting significant correlations between values of FA, $\lambda_1$, and MD and scores on the Fun Seeking subscale. The green color shows the “group mean FA skeleton”, the numbers below the brain image indicate Z coordinates in MNI space, and only clusters surviving correction for multiple comparisons of voxel-wise whole brain analysis are shown on brain images. Scatter-plots demonstrate correlations between mean values of FA, $\lambda_1$, and MD (y-axis) of each participant and scores on the Fun-Seeking subscale. Mean values of FA, $\lambda_1$, and MD were calculated from all voxels in the significant cluster of each participant. Abbreviation: L: left.
Table 1

Correlations between subscales of BIS/BAS.

<table>
<thead>
<tr>
<th>Subscale</th>
<th>Mean (SD)</th>
<th>BAS Total</th>
<th>Drive</th>
<th>Fun</th>
<th>Rew</th>
<th>BIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAS Total</td>
<td>38.0 (6.1)</td>
<td>.85**</td>
<td>.87**</td>
<td>.77**</td>
<td>.18</td>
<td></td>
</tr>
<tr>
<td>Drive</td>
<td>10.5 (2.5)</td>
<td>.63**</td>
<td>.48**</td>
<td>-.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fun</td>
<td>11.1 (2.6)</td>
<td>.50**</td>
<td></td>
<td>.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rew</td>
<td>16.4 (2.2)</td>
<td></td>
<td></td>
<td></td>
<td>.39**</td>
<td></td>
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<tr>
<td>BIS</td>
<td>18.2 (3.2)</td>
<td></td>
<td></td>
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</tbody>
</table>

*p < .05  
**p < .01

Abbreviation: BAS: behavioral activation system; BIS: behavioral inhibition system; Rew: reward.
Table 2

Positive Correlations between DTI and BIS/BAS scale scores.

<table>
<thead>
<tr>
<th>Description</th>
<th>Size</th>
<th>t-value</th>
<th>L/R</th>
<th>Voxels</th>
<th>x</th>
<th>y</th>
<th>z</th>
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</thead>
<tbody>
<tr>
<td>BAS Total &amp; λ_1</td>
<td></td>
<td></td>
<td></td>
<td>CR &amp; SLF</td>
<td>L</td>
<td>363</td>
<td>4.1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−25</td>
<td>18</td>
<td>44</td>
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<tr>
<td>BAS-Fun &amp; FA</td>
<td></td>
<td></td>
<td></td>
<td>CR &amp; SLF</td>
<td>L</td>
<td>597</td>
<td>4.26</td>
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<td></td>
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<td>−22</td>
<td>41</td>
</tr>
<tr>
<td>BAS-Fun &amp; λ_1</td>
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<td></td>
<td>CR &amp; SLF</td>
<td>L</td>
<td>438</td>
<td>5.0</td>
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* t value of the peak voxel. Abbreviations: CR: corona radiata; IFOF: Inferior fronto-occipital fasciculus; ILF: inferior longitudinal fasciculus; L: left hemisphere; MNI: Montreal Neurological Institute; SLF: superior longitudinal fasciculus.