Published in final edited form as:

J Abnorm Psychol. 2020 November ; 129(8): 831–844. doi:10.1037/abn0000627.

Neuroanatomical correlates of impulsive traits in children aged 9 to 10

Max M. Owens¹, Courtland S. Hyatt², Joshua C. Gray³, Joshua D. Miller², Donald R. Lynam⁴, Sage Hahn¹, Nicholas Allgaier¹, Alexandra Potter¹, Hugh Garavan¹

¹University of Vermont, Department of Psychiatry

²University of Georgia, Department of Psychology

³Uniformed Services University, Department of Medical and Clinical Psychology

⁴Purdue University, Department of Psychological Sciences

Abstract

Impulsivity refers to a set of traits that are generally negatively related to critical domains of adaptive functioning and are core features of numerous psychiatric disorders. The current study examined the gray and white matter correlates of five impulsive traits measured using an abbreviated version of the UPPS-P impulsivity scale in children aged 9 to 10 ($N = 11,052$) from the Adolescent Brain and Cognitive Development (ABCD) study. Linear mixed effect models and elastic net regression were used to examine features of regional gray matter and white matter tractography most associated with each UPPS-P scale; intraclass correlations were computed to examine the similarity of the neuroanatomical correlates among the scales. *Positive Urgency* showed the most robust association with neuroanatomy, with similar but less robust associations found for *Negative Urgency*. *Perseverance* showed little association with neuroanatomy. *Premeditation* and *Sensation Seeking* showed intermediate associations with neuroanatomy. Critical regions across measures include the dorsolateral prefrontal cortex, lateral temporal cortex, and orbitofrontal cortex; critical tracts included the superior longitudinal fasciculus and inferior fronto-occipital fasciculus. *Negative Urgency* and *Positive Urgency* showed the greatest neuroanatomical similarity. Some UPPS-P traits share neuroanatomical correlates, while others have distinct correlates or essentially no relation to neuroanatomy. Neuroanatomy tended to account for relatively little variance in UPPS-P traits (i.e., model $R^2 < 1\%$) and effects were spread throughout the brain, highlighting the importance of well powered samples. Keywords: impulsivity, impulsive traits, structural magnetic resonance imaging, diffusion imaging, UPPS-P

General Scientific Summary

Impulsivity refers to a set of traits that are generally negatively related to critical domains of adaptive functioning and are core features of numerous psychiatric disorders. In children aged 9 to

Corresponding Author: Max M. Owens, Department of Psychiatry, University of Vermont, 1 South Prospect St. Burlington, VT 05401; telephone: 843-847-9119; mowens1@uvm.edu.

Author note: The Adolescent Brain and Cognitive Development (ABCD) Study was approved by the institutional review board of the University of California San Diego with study number 160091. The analysis presented in this manuscript was classified as not being “human subjects research” by the University of Vermont. Prior to publication, this manuscript was posted online as a pre-print at <https://psyarxiv.com/crbd4/>.

10 years, impulsive traits related to different features of gray and white matter in a variety of regions and tracts, though these associations had uniformly small effect sizes.

Impulsivity has a long-standing, prominent presence in psychological and psychiatric research, and is pertinent to conceptualizing many forms of psychopathology (e.g., antisocial personality disorder; attention-deficit hyperactivity disorder). In a seminal review, Whiteside and Lynam (Whiteside & Lynam, 2001) concluded that impulsivity is an “artificial umbrella term” (pg. 687) that denotes multiple, distinct psychological processes and personality traits. Consequently, these authors developed the UPPS model of impulsivity, which consists of *Negative Urgency*, (*lack of*) *Premeditation*, (*lack of*) *Perseverance*, and *Sensation-Seeking*. More recently, this model has been expanded to the UPPS-P with the recognition of a fifth domain *Positive Urgency* (Lynam, Smith, Whiteside, & Cyders, 2006b). *Negative Urgency* indexes difficulty controlling behavioral impulses while experiencing strong negative emotions; its counterpart – *Positive Urgency* – references behavioral dysregulation in the presence of strong positive emotions. (*Lack of*) *Premeditation* and (*Lack of*) *Perseverance* reflect tendencies to act without planning or regard for consequences and a difficulty with sustaining attention during times of boredom or tedium, respectively. *Sensation-Seeking* indexes a drive for stimulating, exciting, and potentially dangerous activities.

Since the publication of the UPPS-P, a large body of research has developed that has enriched the nomological networks of these impulsive traits, including their neurobiological correlates. However, the literature on the relation of brain structure to the scales of the UPPS-P is still underdeveloped, with all existing studies having inadequate sample sizes and most using only some of the UPPS-P scales, and a few actually combining scales together—an approach that runs contrary to the UPPS model itself. The largest structural MRI (SMRI) study to date ($N = 328$; age 7 to 21; (Merz, He, & Noble, 2018)) used surface-based morphometry (SBM) to examine cortical surface area (CSA) and cortical thickness (CT), as well as the gray matter volume (GMV) of subcortical structures for their association with total score on UPPS. Although UPPS-P total score was linked to less CT in the ventromedial prefrontal cortex (VMPFC), dorsolateral prefrontal cortex (DLPFC), and ventrolateral prefrontal cortex (VLPFC), a critical limitation of this study was the use of the total UPPS score rather than examining the UPPS-P domains individually. A study of a community sample of adults ($N = 107$) analyzed the association between CT and a three-factor solution for the UPPS-P (i.e., impulsive urgency compromising *Negative Urgency* and *Positive Urgency*; Conscientiousness compromising *Premeditation* and *Perseverance*; and *Sensation Seeking*). This study identified significant negative associations between *Sensation Seeking* and CT of the right pericalcarine cortex, and positive associations of *Urgency* with CT of the left superior parietal cortex and right paracentral lobule (Miglin et al., 2019). In a sample of individuals with schizophrenia or schizoaffective disorder ($N = 33$), negative urgency was inversely associated with cortical thickness in the right frontal pole and right medial orbitofrontal cortex (OFC), whereas positive urgency was inversely associated with thickness of the right frontal pole and left rostral anterior cingulate (Hoptman, Antonius, Mauro, Parker, & Javitt, 2014). There have also been a number of studies examining the relation of negative urgency from UPPS-P with GMV from voxel-based morphometry, which suggest that the structural correlates of negative and positive urgency may be clearer

in clinical samples (Johnson, Elliott, & Carver, 2020), although it should be noted that none of these clinical studies had samples larger than 100 participants. Regions identified in these studies include the frontal pole, medial OFC, anterior insula, ventrolateral prefrontal cortex, ventral striatum, temporal pole, and superior front gyrus (Albein-Urios et al., 2013; Moreno-López et al., 2012; Muhlert & Lawrence, 2015; Ruiz de Lara, Navas, Soriano-Mas, Sescousse, & Perales, 2018; Wang, Wen, Cheng, & Li, 2017). Furthermore, two recent reviews of structural and functional neuroimaging correlates of negative and positive urgency identified several regions of likely relevance, including the OFC, DLPFC, VLPFC, anterior cingulate cortex, amygdala, insula, ventral striatum, and temporal cortex (Johnson et al., 2020; Um, Whitt, Revilla, Hunton, & Cyders, 2019).

To date, only one study has examined the structure of specific white matter tracts in relation to impulsive traits measured by the UPPS-P (Uhlmann et al., 2016)). This study examined associations of the *Negative Urgency*, *Positive Urgency*, and *Perseverance* subscales with mean diffusivity (MD) and fractional anisotropy (FA) in a set of predefined tracts in three groups: individuals with methamphetamine dependence, individuals with a history of methamphetamine associated psychosis, and healthy controls ($Ns = 37, 27, 37$, respectively). This study found positive correlations between *Negative Urgency* and FA in the left uncinate fasciculus in individuals with methamphetamine dependence, a positive association of *Negative Urgency* with MD in the right anterior corona radiata in individuals with a history of methamphetamine associated psychosis, and a positive correlation of *Positive Urgency* with FA of the right uncinate fasciculus and left superior longitudinal fasciculus in healthy controls. Given the small adult sample and the focus on only three UPPS-P subscales and three white matter tracts, analysis of all white matter tracts in relation to all 5 UPPS-P subscales in a larger cohort is needed.

Current Study

The current study advances the literature on neurobiological correlates of impulsivity by examining the gray and white matter correlates of each of the five UPPS-P traits in the largest neuroimaging-based sample of pre-adolescent children ever collected ($N = 11,052$ in gray matter and 10,023 in white matter). For gray matter, SBM was used to examine CT and CSA, which are largely independent cortical features with unique developmental trajectories and genetic, behavioral, and psychiatric correlates (Panizzon et al., 2009; Rimol et al., 2012; Storsve et al., 2014). For white matter, we examined diffusion weighted imaging (DMRI) derived FA and MD, given they are primary measures of white matter microstructure and are related to overall white matter integrity. We used two complementary, exploratory approaches to describing the relations between the UPPS-P traits and neuroanatomical features: traditional univariate analysis (linear mixed effects modeling) of gray or white matter in each region and tract of the brain separately and a multivariate machine learning based approach (elastic net regression) to consider gray matter in all regions and white matter in all tracts.

Methods

Participants

The Adolescent Brain Cognitive Development Study (ABCD) is an ongoing multi-site, longitudinal neuroimaging study following a cohort of youths over ten years (www.ABCDstudy.org; (Casey et al., 2018)). For more details of data collection, see Supplementary Methods. Data collection complied with American Psychological Association's ethical standards; ethical considerations in the ABCD study are discussed extensively in (Clark et al., 2018). In this paper, we used data from the baseline visits at which participants were 9 or 10 years old (starting $N = 11,872$). Participants were excluded if they did not have complete data for the UPPS-P ($n = 26$), family structure or scanner ID ($n = 112$) or did not have at least one structural MRI scan which passed FreeSurfer visual quality control inspection ($n = 682$). Additionally, participants were excluded from the DMRI portion of analyses if they did not have at least one DMRI scan that passed visual and automated quality control assessment ($n = 1,361$; see (Hagler et al., 2019) for details of quality control). This resulted in a total of 11,052 participants included in SMRI analyses and 10,023 participants included in DMRI analyses. Because of missing covariate data, supplementary analyses using age, sex, parental income, parental education, child total cognitive ability, and in-scanner motion had reduced sample sizes of 10,115 for SMRI and 9,177 for DMRI. Demographics based on the maximum number of participants available for each scale are reported in Table 1.

Measures

Abbreviated Youth Version of the UPPS-P Impulsive Behavior Scale—The version of the UPPS-P used (Watts, Smith, Barch, & Sher, 2020) assesses the five facets of impulsivity: *Negative Urgency*, *Positive Urgency*, *Premeditation*, *Perseverance*, and *Sensation Seeking*. The measure has 20 items, four for each facet of impulsivity, rated on a 1 (agree strongly) to 4 (disagree strongly) scale. The scale is generally similar to the adult abbreviated version, but with several items altered to be more appropriate for children. In a study using the same ABCD data, Watts and colleagues (2020) demonstrated that this version of the UPPS-P demonstrates the same five-factor structure as the adult version and shows good convergent and discriminant validity with relevant personality, psychopathology, and neurocognitive measures (Watts et al., 2020); All UPPS-P scales were normally distributed (Table 2A) and reasonably internally consistent (*Negative Urgency*: $\alpha = .62$, $\omega = .59$, mean inter-item $r = .30$; *Premeditation*: $\alpha = .73$, $\omega = .64$, inter-item $r = 0.40$; *Sensation Seeking*: $\alpha = .49$, $\omega = .39$, inter-item $r = .19$; *Positive Urgency*: $\alpha = .77$, $\omega = .74$, inter-item $r = .47$; *Perseverance*: $\alpha = .69$, $\omega = .64$, inter-item $r = .36$), although the Sensation Seeking scale was less internally consistent than the other four domains. The relationships among the UPPS-P subscales ranged from $-.10$ (*Lack of Perseverance* and *Sensation Seeking*) to $.49$ (*Negative Urgency* and *Positive Urgency*; see Table 2B).

MRI Preprocessing—FreeSurfer version 5.3 was used to conduct SBM processing on SMRI data and to derive CT and CSA measures for each of the 34 Desikan atlas (Desikan et al., 2006) regions of interest and GMV for 9 subcortical regions plus the brainstem from the ASEG parcellation in FreeSurfer. We elected to use the Desikan atlas for three reasons: 1) it

is consistent with our prior work on the neuroanatomical correlates of personality (Hyatt et al., 2019b) 2) it is one of the two standard structural MRI atlases available standard in Freesurfer and is one of the two atlases in which ABCD data are offered in the official data release 3) of the two standard Freesurfer and ABCD atlases it is the one with fewer parcels, meaning it would result in fewer tests being conducted which was an important issue to us given the already large number of tests being conducted in examining the entire brain's association with each of the five UPPS-P scales. AtlasTrack, a probabilistic atlas-based method for automated segmentation of white matter fiber tracts, was applied to the DMRI data to derive FA and MD measures for 17 bilateral white matter tracts and 3 tracts that connect the brain's hemispheres (Hagler et al., 2009). We elected to use this atlas because it is the standard DMRI tract atlas used in the ABCD data release. See Supplementary Methods for information about image acquisition protocols and image preprocessing, as well as (Casey et al., 2018; Hagler et al., 2019).

Data Analysis

Pre-Registration Statement—All aspects of our data analysis were pre-registered and posted at <https://osf.io/2z3jy/> and relevant components of our data analysis code can be found at <https://github.com/owensmax/Neuroanatomical-Correlates-of-Impulsivity>. There were some slight deviations from the pre-registration that were made, although, in general, analyses hewed closely to those described in the pre-registration. One deviation was that in addition to the supplementary analysis we originally proposed (i.e., examining mixed effect associations without covariates), we conducted an additional supplemental analysis that examined associations after accounting for the effects of several demographic covariates (i.e., age, sex, parental income, parental education, child total cognitive ability, in-scanner motion). Additionally, we erroneously pre-registered that we would correct for 148 DMRI tests, having accidentally doubled the correct number of tests we were intending (74). Another deviation is that our estimate of the number of participants with full and valid data for the DMRI analyses proved to be slightly optimistic, resulting in an actual total of 10,023 participants in the DMRI analyses instead of the 10,373 participants indicated in the pre-registration. Last, in the pre-registration we erroneously indicated that participants were between the ages of 10–12 during their baseline visit in the ABCD study, whereas they were actually 9- or 10-years-old.

The ABCD data can be accessed with permission at <https://nda.nih.gov/abcd/requestaccess>. Data were downloaded from the ABCD Data Repository on the National Institute of Mental Health Data Archive, using data from ABCD release 2.0.1.

Linear Mixed Effect Analyses—Relationships between impulsive traits and 1) gray matter (measured by SMRI) and 2) white matter (measured by DMRI) were interrogated using linear mixed effects models, conducted in R software version 3.6.1. Separate models were created for each combination of brain region/tract and UPPS-P scale. Mixed effect models were used in order to account for the large numbers of siblings included in the ABCD dataset and for the fact that data were collected at 22 different sites on 29 unique scanners. Specifically, sibling status was modeled as a random effect nested inside of a random effect of scanner. In addition to these random effects, linear mixed effect model

analyses were conducted with estimated intracranial volume included as a fixed effect covariate.

To account for type I error a False Discovery Rate (FDR) correction was used on each family of tests (Benjamini & Hochberg, 1995). Specifically, each of the 5 UPPS-P scales was considered to have two families of tests: 155 tests of SMRI and 74 tests of DMRI. Consequently, we corrected to an FDR-corrected alpha of .05 for 155 tests (SMRI) and 74 (DMRI) tests for each scale.¹

While the primary modeling approach used included only total intracranial volume as a covariate, we completed two supplementary analyses to examine the impact of covariate selection. In the first supplemental analysis, we repeated the primary analysis without covarying for intracranial volume to test for potential suppression effects. In the second supplemental analysis, we repeated the primary analysis covarying for intracranial volume, age, sex, parental income, parental education, child total cognitive ability (from the NIH toolbox), and in-scanner motion to examine how associations in the primary analysis were impacted by these additional demographic covariates. Results of both supplementary analyses are reported in Supplemental Materials. However, these approaches were not interpreted beyond these purposes and were consequently not counted in multiple-comparison correction.

Elastic Net Regression Analyses—Elastic net regression with cross-validation (CV) was used to build predictive models for each of the five UPPS-P traits using SMRI and DMRI in separate models. In this approach, 80% of the data was used in a 5-fold CV with the model from the best performing fold ultimately tested on the remaining 20% of data. The external validation set was used to assure the models 5-fold CV performance was not overly optimistic (see Supplemental Methods for details on the CV framework). Elastic net regression uses complementary regularization strategies to attempt to minimize overfitting and is considered ideal for analyses with a large number of highly intercorrelated predictors (Zou & Hastie, 2005). Additionally, a recent examination of numerous machine learning approaches in the context of neuroimaging found elastic net regression to perform well at a range of effect sizes relative to other approaches (Jollans et al., 2019).

For each scale of the UPPS-P, the UPPS-P scale served as the target of the model (i.e., dependent variable). In SMRI models, predictors (i.e., independent variables) available to the model building algorithm were CSA and CT for each of the 68 Desikan regions and gray matter volume for each of the 9 subcortical ROIs. In DMRI models, predictors available to the model were FA and MD in each of the 37 white matter tracts. Additionally, estimated total intracranial volume was made available as a predictor in both models. A modified coefficient of determination was calculated (R^2) as the measure of prediction accuracy for each model. Elastic net regression analyses were conducted using the glmnet package (http://web.stanford.edu/~hastie/glmnet_matlab/) in Matlab 2018b.

Initially, an external validation sample of participants was selected which was set aside for validation of the final elastic net model; this test set comprised approximately 20% of the total sample. In the approximately 80% of the sample remaining, 5-fold CV was used for the

building and testing of five separate elastic net regression models. In this approach, the training data were split into five equal groupings (i.e., “folds”); then a model was built using four of the five folds (i.e., the training data) and was then tested on the fifth fold (i.e., the test data) to determine its accuracy. After repeating this procedure five times, with each fold serving as the test set exactly once, the best of the five models was used to predict the external validation sample.

Nested within the 5-fold cross validation was a 20-fold regularization hyperparameter tuning CV that was conducted to determine the optimal combination of the elastic net regularization parameters alpha (α) and lambda (λ), with the goal of identifying the most generalizable combination of hyperparameters, as determined by performance on a set aside fold. These hyperparameters represent the ratio of ridge and lasso regularization (α) and the strength of the regularization overall (λ). Twenty values of α (.05 to 1.0 in increments of .05) and 100 values of λ (logarithmically spaced from .01 to an empirically determined maximum [see glmnet documentation for more details]) were tested. In the 20-fold cross validation, the training data were split into 20 folds in each of the five model building phases. Within each of the 20 folds, 2000 combinations of α and λ were tested and the best combination selected. Then the combination which yields the best accuracy from all the folds was used in model building for that k-fold iteration.

Intraclass Correlation Analyses—In order to examine the neuroanatomical distinctiveness of the UPPS-P scales, particularly those assessing *Positive Urgency* and *Negative Urgency*, absolute similarity coefficients (i.e., intraclass correlations) were calculated across the entire set of brain structural measures using the regression coefficients for each regional brain measure from the linear mixed effect analysis results as the elements of this analysis. The double-entry intraclass correlations (McCrae, 2008), which account for absolute similarities in magnitude and direction of the neuroanatomical profiles that characterize each UPPS-P domain, were used to quantify the degree of absolute neuroanatomical similarity among the five UPPS-P traits. These indices were computed across all 155 gray matter structural measures and then again separately across the 74 white matter tracts.

Results

Linear Mixed Effect Analyses

Statistics for significant associations in linear mixed effect analyses of SMRI (after FDR correction) are reported in Table 3 and illustrated in Figure 1. All associations are reported in Supplemental Tables 1-5. *Positive Urgency* was negatively associated with CSA in numerous regions, including the middle temporal gyrus, inferior temporal gyrus, lateral OFC, caudal middle frontal gyrus, precuneus, superior temporal gyrus, superior frontal gyrus, rostral middle frontal gyrus, precentral gyrus, medial orbitofrontal cortex, cuneus, rostral anterior cingulate, pars opercularis, superior parietal lobule, pericalcarine fissure, and fusiform gyrus. Effect sizes for relations between *Positive Urgency* and CSA in these regions, measured as change in R^2 with the addition of each region to the model (R^2), ranged from .33% (middle temporal gyrus) to .07% (pericalcarine fissure, fusiform gyrus).

Positive Urgency was also negatively associated with CT in the left parahippocampal gyrus and positively associated with CT in the left and right rostral middle frontal gyrus, and the right pars triangularis and pars opercularis. The largest effect size between *Positive Urgency* and CT was for the left parahippocampal gyrus ($R^2 = .15\%$). Furthermore, *Positive Urgency* was positively associated with GMV in the left caudate ($R^2 = .08\%$).

In DMRI analyses, *Positive Urgency* was negatively associated with FA of the temporal and parietal sections of the left superior longitudinal fasciculus, the left inferior-fronto-occipital fasciculus, and superior corticostriate tract, as well as the right inferior longitudinal fasciculus. Effect sizes ranged from R^2 of .18% (Parietal Superior Longitudinal Fasciculus) to .09% (Temporal Superior Longitudinal Fasciculus). Significant DMRI results are reported in Table 4 and full results are reported in Supplemental Tables 6-10.

Negative Urgency was negatively associated with CSA in the left lateral OFC and the left middle temporal gyrus, as well as with CT in the left parahippocampal gyrus. It was also significantly negatively associated with FA of the left and right inferior-fronto-occipital fasciculus, the left superior longitudinal fasciculus, as well as both of its subcomponents, namely the parietal and temporal superior longitudinal fasciculus. Effect sizes ranged from .23% (Inferior-Fronto-Occipital Fasciculus) to .12% (Temporal Superior Longitudinal Fasciculus).

Premeditation was positively associated with CSA in the left and right precentral gyrus, the left pars orbitalis and lateral occipital gyrus, and the right inferior temporal gyrus ($R^2 = .17\%$ to $.11\%$). It was also positively associated with FA of the left fornix excluding the fimbria ($R^2 = .13\%$). *Perseverance* was associated with the CT of right isthmus of the cingulate only ($R^2 = .12\%$). *Sensation Seeking* was negatively associated with GMV in the right globus pallidus ($R^2 = .12\%$). It was also negatively associated with FA in the left fornix, excluding the fimbria, and the right anterior thalamic radiations ($R^2 = .13\%$ & $.12\%$).

Among statistically significant regions, no suppression effects were detected (i.e., all associations remained in the same direction) when mixed effects analyses were repeated without covarying for estimated intracranial volume (Supplemental Tables 11-20). Additionally, when mixed effects analyses were repeated using demographic covariates, the majority of SMRI correlates for *Positive Urgency*, *Negative Urgency*, *Premeditation*, and *Perseverance* remained statistically significant; the one region associated with *Sensation Seeking* did not. No DMRI correlates of any UPPS scale remained significant beyond demographic covariates (Supplemental Tables 21-30).

Elastic Net Regression Analyses

For SMRI, the elastic net regression models with the highest out of sample R^2 (i.e., R^2 for predicting the external validation set) were those predicting *Positive Urgency* and *Sensation Seeking* (Table 5). Models for *Premeditation* and *Negative Urgency* had lower model R^2 values. The elastic net algorithm used could not build an effective model to predict *Perseverance* (external validation $R^2 < 0.01\%$; all internal CV $R^2 < 0.2\%$). There was substantial overlap between linear mixed effect model results and the ROIs used in the best

elastic net regression models. Figure 2 depicts the regions included in the best elastic net models for each UPPS-P scale; full descriptions of models are found in Supplemental Tables 31-32. In general, elastic net regression models for DMRI were less effective at predicting the UPPS-P scales out-of-sample. For DMRI, only the models for *Positive Urgency* and *Negative Urgency* were able to predict their scales (i.e., R^2 greater than 0% in the external validation set). Models for *Premeditation*, *Sensation Seeking*, and *Perseverance* all had external validation $R^2 < 0.01\%$ and all internal CV $R^2 < 0.2\%$. All tracts identified as significant beyond the false discovery rate in linear mixed effect models except FA of right Inferior-Fronto-Occipital-Fasciculus for *Negative Urgency* were represented in elastic net regression models.

Intraclass Correlation Analyses

Intraclass correlation analyses indicated the greatest similarity between the gray matter correlates of *Positive Urgency* and *Negative Urgency* ($ICC = .59$; Table 6). Additionally, there was comparable similarity between the gray matter correlates of *Premeditation* and *Perseverance*, *Perseverance* and *Positive Urgency*, and *Sensation Seeking* and *Positive Urgency* (all ICCs $\sim .35$). *Negative Urgency* showed essentially no similarity in its gray matter correlates with any scales other than *Positive Urgency*. In general, the white matter similarity analyses indicated higher similarity among the UPPS-P traits. *Negative Urgency* and *Positive Urgency* had the highest degree of white matter similarity ($ICC = .87$), but *Perseverance* was also highly similar to *Negative Urgency* ($ICC = .72$) and *Positive Urgency* ($ICC = .62$), as well as highly dissimilar to *Sensation Seeking* ($ICC = -.62$).

Discussion

The current study took a comprehensive approach to examining the neuroanatomical correlates of impulsive traits in children using a very large sample and the well-validated UPPS-P model of impulsivity. Results of the univariate SMRI analyses suggest partial congruence with prior literature, in which the largest study to date had also identified the OFC, DLPFC, and VLPFC as being structural correlates of total UPPS-P impulsivity (Merz et al., 2018). The only prior study of impulsivity using the UPPS-P to examine impulsivity associations with DMRI (Uhlmann et al., 2016), found FA in the left superior longitudinal fasciculus to be linked to *Positive Urgency*, consistent with the current study. These results were supported by elastic net regression findings, in which the best models for predicting out of sample contained mostly the same regions as were found in univariate models and were able to predict the majority of scales with modest accuracy. Additionally, ICC findings indicated substantial similarity in the neuroanatomical correlates of *Positive Urgency* and *Negative Urgency* consistent with the idea that these may be particularly closely related traits in which behavioral dysregulation follows emotional (negative and/or positive) dysregulation.

Several broader themes can be identified from these results. The feature of gray matter most linked to impulsive traits was CSA, which had more associations with impulsive traits than CT or subcortical volume. The primacy of CSA's relationship with impulsivity was not specifically predicted; however, results differing between CSA and CT was as expected,

given their distinct genetic bases and developmental trajectories (Giedd & Rapoport, 2010; Panizzon et al., 2009; Tamnes et al., 2017; Vijayakumar et al., 2016). Across almost all instances, impulsive traits were linked with less CSA and more CT. This was consistent with models of cortical development that focus on increasing CSA and decreasing CT through late childhood and adolescence and suggest that these changes reflect neuroanatomical maturation (Tamnes et al., 2017; Vijayakumar et al., 2016). The feature of white matter most linked to impulsive traits was FA, with lower levels of FA linked to greater impulsivity in almost all cases. FA is considered a summary metric of white matter structural integrity and is highly sensitive to microstructural changes in white matter (Alexander et al., 2011); this makes it a logical candidate as the index most related to impulsive traits.

A finding of note is the similarity between the neural correlates of *Positive Urgency* and *Negative Urgency* indicated by their high gray and white matters ICCs, the similarity of significant regions in linear mixed effect models, and the similarity of models that best predicted these scales in elastic net regression analyses. This is consistent with other work on the UPPS-P scales, which also suggest that these traits are conceptually and empirically highly similar (e.g., Berg et al., 2015). For example, using ecological momentary assessment, Sperry et al. (Sperry, Lynam, & Kwapil, 2018) found very little differentiation between Positive and Negative Urgency in terms of their daily relations to cognition, affect, or behavior in daily life; in fact, their “daily life” profiles were virtually identical. We believe the observed similarity between the neuroanatomical correlates of these scales is yet another piece of evidence supporting their similarity, suggesting that these traits may be the same “beneath the skin” (i.e., these traits have overlapping neuroanatomical bases).

An important note regarding the interpretation of elastic net regression results is that a meaningful distinction exists between predictive features in the elastic net regression models and those that were significant in univariate testing. Specifically, the absence of a feature within a predictive model does not necessarily imply a lack of association between that feature and that scale of impulsivity; a feature being absent could alternatively indicate that a different feature better captures some overlapping predictive utility, even if that feature and the target variable are related when considered in isolation. However, if a feature does have predictive utility in addition to a univariate association, it strongly suggests that a real association exists. In the current study, most regions identified in mixed effects analyses also were identified in elastic net regression, but for those that were not it should not be indicative of an absence of association. Additionally, in elastic net analyses it was notable that *Positive Urgency* was better predicted by SMRI than *Negative Urgency* despite these two scales showing substantial similarity in their neuroanatomical correlates in ICC analyses ($r = .59$). Furthermore, it was of interest that despite having very few neuroanatomical correlates in mixed effect modeling, *Sensation Seeking* was predicted better by SMRI than all scales other than *Positive Urgency*. This may reflect a global relationship between *Sensation Seeking* and gray matter that is not reflected in strictly thresholded analyses of individual regions but is seen in elastic net analyses that incorporate all regions simultaneously.

Several regions were identified as structural correlates of multiple scales of impulsivity, specifically the lateral and medial OFC, DLPFC (i.e., caudal middle frontal gyrus, rostral

middle frontal gyrus, superior frontal gyrus), VLPFC (pars orbitalis, pars opercularis, pars triangularis), precentral gyrus, and lateral and medial temporal cortex (i.e., middle temporal gyrus, superior temporal gyrus, inferior temporal gyrus, parahippocampal gyrus). The OFC, DLPFC, and VLPFC, were all identified in the previous largest study of the neuroanatomical correlates of the UPPS-P to date (Merz et al., 2018). Some of our other findings were not consistent with the limited existing literature on the gray matter structural correlates of the UPPS-P (Merz et al., 2018; Miglin et al., 2019; Muhlert & Lawrence, 2015); however, this may be due to the small sample size of these studies and differences in the age of the samples. Morphometry in these regions has also been linked to other measures of impulsivity previously (e.g., delayed reward discounting, impulsivity measured by the Barret Impulsivity Scale), although it should be noted that there is surprisingly weak phenotypic association among different measures of impulsivity (MacKillop et al., 2016). Gray matter in the medial (Mackey et al., 2017) and lateral (Owens et al., 2017) OFC have each been identified in prior large studies of delayed reward discounting. The OFC sits at the intersection between reward processing and cognitive control and has been linked to decision making (Bechara, 2000), experience of pleasure (Kringelbach, 2005), and learning (Wilson, Takahashi, Schoenbaum, & Niv, 2014); the medial OFC is also considered to be a part of the default mode network and its known role in internal mental states (Andrews-Hanna, Smallwood, & Spreng, 2014; Buckner, Andrews-Hanna, & Schacter, 2008). The DLPFC has been linked to general personality across numerous studies, particularly conscientiousness, neuroticism, and openness (DeYoung et al., 2010; Owens et al., 2019; Riccelli, Toschi, Nigro, Terracciano, & Passamonti, 2017) and its central role in the cognitive control network of the brain (Niendam et al., 2012) make it an obvious candidate as a key neural correlate of impulsivity. The VLPFC is known for its role in inhibition of behavior (Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Swick, Ashley, & Turken, 2008).

The precentral gyrus has not been linked previously with impulsivity as defined by the UPPS, though its GMV was negatively linked with impulsive delayed reward discounting by Owens et al. (Owens et al., 2017). However, it is also a known part of the cognitive control network of the brain, with its role in inhibitory control having been specifically noted (Niendam et al., 2012). While the middle temporal gyrus, inferior temporal gyrus, and parahippocampal gyrus have not been linked to impulsivity measured by the UPPS, Owens et al. (Owens et al., 2017) identified GMV in the middle temporal gyrus and entorhinal cortex (which is adjacent to and similar in function to the parahippocampal gyrus) as the most robust correlates of delayed reward discounting in adults. These regions have been identified as key hubs in the default mode network, which are critical to self-reflection, future planning, and decision making (Andrews-Hanna et al., 2014; Buckner et al., 2008). The only prior study of impulsivity using the UPPS-P to examine impulsivity associations with DMRI (Uhlmann et al., 2016) found FA in the left superior longitudinal fasciculus to be linked to *Positive Urgency*, consistent with the current study. The longitudinal fasciculus connects the prefrontal cortex to the rest of the brain (Jellison et al., 2004) and has been linked to various measures of cognitive control in prior work with children (Loe, Adams, & Feldman, 2019). However, given the limitations of the existing literature these regions/tracts should not be considered the only findings of potential importance.

Implications for Cognitive Models and Psychopathology

The current results have implications for models about the cognitive and emotional basis of impulsivity. Many of the regions where structure was linked to negative and positive urgency, particularly the OFC, DLPFC, and VLPFC, are known for their involvement in decision making (Bechara, 2000; Mackey et al., 2017; Owens et al., 2017; Rosenbloom, Schmahmann, & Price, 2012). The cognitive and emotional processes involved in decision making have been proposed as a framework for understanding negative and positive urgency in recent reviews and the OFC, DLPFC, and VLPFC regions have been suggested as supporting the decision making critical to urgency (Johnson et al., 2020; Um et al., 2019). Other cognitive and emotional processes that have been suggested to underlie urgency are emotion generation, emotion regulation, risky decision making, and response inhibition, for which the OFC, DLPFC, and VLPFC are known substrates (Johnson et al., 2020). Thus, the findings that these regions were key correlates of the UPPS-P impulsivity scales provides some support to existing models of cognitive and emotional basis of urgency, though the absence of amygdala volume associations with impulsivity is inconsistent with these models.

Furthermore, understanding the neuroanatomical correlates of different impulsive traits may have important clinical implications (Berg, Latzman, Bliwise, & Lilienfeld, 2015), as the UPPS-P domains show differential relationships to symptoms of substance-use disorders (Coskunpinar, Dir, & Cyders, 2013; VanderVeen et al., 2016), internalizing disorders (Berg et al., 2015), borderline personality disorder (Berg et al., 2015), antisocial behavior (Whiteside & Lynam, 2003), eating disorders (Fischer, Smith, & Cyders, 2008), gambling (MacLaren, Fugelsang, Harrigan, & Dixon, 2011), suicidality/non-suicidal self-injury (Hamza, Willoughby, & Heffer, 2015), and even therapeutic outcomes (Hershberger, Um, & Cyders, 2017). This suggests that neuroanatomical differences in the regions identified are overlap with regions that are relevant to these disorders characterized by impulsivity. For example, attention deficit hyperactivity disorder (ADHD), conduct disorder, and substance use disorders are all characterized by high levels of impulsivity and have similarly implicated brain regions as in our study. Consistent with the inverse associations of cortical surface area of the DLPFC and ACC with *Positive Urgency* found in the current study, a recent large study of adolescents coming from the IMAGEN dataset ($N = 1,093$) found that ADHD symptoms were negatively associated with cortical surface area of the DLPFC and ACC and that conduct disorder was negatively associated with surface area of the ACC (Bayard et al., 2018). Likewise, consistent with findings of an inverse association of caudate volume with *Positive Urgency* in the current study, an ENIGMA ADHD study ($N = 1,713$) found smaller caudate volume in individuals with ADHD, with effects being the largest in children (Hoogman et al., 2017). In adults from the ENIGMA Addiction study ($N = 3,240$) the cortical thickness of the medial OFC, DLPFC, middle temporal gyrus, fusiform gyrus, superior parietal cortex, and precentral gyrus were lower in individuals with substance use disorders (Mackey et al., 2019). These regions were all identified as correlates of impulsivity in the current study, though not necessarily for cortical thickness. Importantly, as in the current study, effect sizes were small in these studies.

The convergence of the neuroanatomical correlates of impulsive traits and disorders characterized by elevated impulsivity is in accord with the Hierarchical Taxonomy of

Psychopathology (HITOP) (Kotov et al., 2017), which suggests that psychological disorders represent extreme degrees of universal traits rather than categorical departures from normal psychology. Likewise, the Research Domain Criteria (RDoC) framework instituted by the National Institute of Mental Health calls for research to understand individual behavioral elements (i.e., constructs) so as to study the components of psychiatric disorders at different levels of analysis (Insel et al., 2010), with impulsivity representing one of these transdiagnostic constructs.

Limitations and Conclusions

There are several additional considerations that should be kept in mind when interpreting the results of this study. One consideration is the version of the abbreviated UPPS-P used. A recent study explored the measurement characteristics of it in the ABCD sample and found it has the same factor structure as the full length UPPS-P, measurement invariance across demographic characteristics, and good convergent and discriminant validity (Watts et al., 2020). Nonetheless, it does still represent a downgrade in measurement precision compared to the full version, particularly the *Sensation Seeking* scale, which was considerably less internally consistent than the other four scales and demonstrated only marginally acceptable internal consistency based on canonical recommendations (Clark & Watson, 1995). This raises the possibility that the small number of significant regions associated with *Sensation Seeking* may be attributable, in part, to the scale's suboptimal psychometric properties. Future work may benefit from use of the full-length scale and from more sophisticated operationalization of this scale in children, such as combining data from child, parent, and teacher reports.

Another consideration is the use of covariates. In our primary analyses, we elected to covary only for estimated total intracranial volume, which we believe represents an important confound to understanding the nature of the relationship between impulsivity and neuroanatomy. Pertinent to our reasoning was that intracranial volume has little theoretical reason to play a causal role in impulsivity and is typically accounted for in SMRI and DMRI literature (Hyatt et al., 2019a). We did not control for sociodemographic factors in the primary analyses as we believe that (a) these variables may represent true sources of variance in impulsivity rather than misleading confounds and (b) because of the difficulty in interpreting the meaning of a variable once covariates have been removed (Lynam, Hoyle, & Newman, 2006a). However, in secondary analyses we did control for key demographic covariates and results were largely consistent for SMRI, indicating that the associations of gray matter with impulsivity are likely not confounded with demographics. In contrast, no associations of impulsivity with DMRI remained significant, suggesting that these associations likely have a more complex relationship with demographics. It may be that lower white matter integrity mediates the established link of impulsivity to demographic factors (e.g., age, sex, socioeconomic status (Assari et al., 2018; Cross et al., 2011; Steinberg et al., 2008)). Alternately white matter integrity may be causally linked to one of these demographic factors and its association with impulsivity is a mirage resulting from this association. Given the cross-sectional nature of the ABCD data currently available, we are not able to distinguish between these two interpretations. However, work clarifying such

distinction should be undertaken with the release of longitudinal data in future ABCD releases.

One further consideration is the use of a sample of pre-adolescent children. Caution is needed in extrapolating the results of the current study to adult populations. There are substantial changes in brain and personality from age 10 to 25 (Caspi, Roberts, & Shiner, 2005; Giedd & Rapoport, 2010; Tackett et al., 2012) and further examination of these relations in adolescent and adult populations is needed. However, while in some ways this represents a limitation, in others it is a strength. Pre-adolescent children may be an ideal group in which to investigate impulsivity, as impulsivity has been argued to peak around age 10 (Steinberg et al., 2008) and in adolescence and adulthood impulsivity often becomes entangled with substance use which is known to substantially alter neuroanatomy (Mackey et al., 2019) and elevate aspects of impulsivity (Quinn, Stappenbeck, & Fromme, 2011). Furthermore, pre-adolescent children are a significantly understudied population in existing personality and neuroimaging research.

Perhaps the most critical consideration is the effect sizes of the results. The maximum R^2 values for a single region in linear mixed effect models was .33% (Pearson's $r_{\text{partial}} = .057$) and the best elastic net regression model tested had an R^2 of 1%. Small effect sizes in large sample studies of the association of neuroanatomy and impulsivity are consistent with prior investigations (e.g., (Mackey et al., 2017; Owens et al., 2017)). Recent work has suggested poor replicability in brain structure-behavior associations with sample sizes in the range of 100–500 even with atypically high quality data (Masouleh, Eickhoff, Hoffstaedter, & Genon, 2019). These problems are exacerbated by “researcher degrees of freedom” such as choice of covariates, which are unstandardized in the structural MRI literature (Hyatt et al., 2019a); for example, the current study examined the effect of adding demographic covariates to its analyses and found substantial alterations to the DMRI results (no associations survived the supplementary covariate analysis), though SMRI analyses were mostly unchanged. We have attempted to adhere to proposed guidelines on improving replicability in behavioral and structural brain imaging association studies (e.g., as found in (Masouleh et al., 2019)) such as use of larger samples, detailed pre-registration of analytic strategy, careful consideration of outliers, use of openly available data, and sharing the code of our analyses. Therefore, we think the current results, particularly the SMRI results, are likely to be replicable, accurate effect sizes in 9–10 year old children. However, the small effects in this study may be indicative that regional structural brain imaging is not the most efficient level of analysis for understanding the neurobiology of impulsivity. This may reflect the fact that the complexity of impulsivity is such that it is better explained by a model of interplay among regions and networks than simply by individual regions.

The most noteworthy strength of the study is its large sample size. Not only does this represent the largest study of the neuroanatomical correlates of impulsivity to date, it does so by an order of magnitude. In addition to its size, the sample used is notably diverse, having been intentionally sampled to reflect the demographics of the United States of America. This provides reason to believe that these results may generalize to youths in this population. Additionally, it is the first study in our knowledge to use a machine learning based approach to predict impulsivity in individuals out-of-sample using their brain structure. This provides

further reason for optimism that the current results are meaningfully generalizable across samples and are not the result of overfitting or type I error. As more longitudinal data from the ABCD study becomes available, we are encouraged by the prospect of continuing to search for neurobiological indicators of impulsivity that may be relevant in predicting important clinical outcomes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This work was funded by NIH/NIDA T32DA043593. Data used in the preparation of this article were obtained from the Adolescent Brain Cognitive Development (ABCD) Study (<https://abcdstudy.org>), held in the NIMH Data Archive (NDA). This is a multisite, longitudinal study designed to recruit more than 10,000 children age 9–10 and follow them over 10 years into early adulthood. The ABCD Study is supported by the National Institutes of Health and additional federal partners under award numbers U01DA041022, U01DA041028, U01DA041048, U01DA041089, U01DA041106, U01DA041117, U01DA041120, U01DA041134, U01DA041148, U01DA041156, U01DA041174, U24DA041123, U24DA041147, U01DA041093, and U01DA041025. A full list of supporters is available at <https://abcdstudy.org/federal-partners.html>. A listing of participating sites and a complete listing of the study investigators can be found at <https://abcdstudy.org/scientists/workgroups/>. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in analysis or writing of this report. The ABCD data repository grows and changes over time. The ABCD data used in this report came from version 2.0.1. This manuscript reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators. The opinions and assertions expressed herein are those of the authors and do not necessarily reflect the official policy or position of the Uniformed Services University or the Department of Defense. This work has been published as a pre-print at <https://osf.io/2z3jy/>. The authors have no conflicts of interest to declare.

References

- Albein-Urios N, Martinez-Gonzalez JM, Lozano Ó, Moreno-López L, Soriano-Mas C, & Verdejo-Garcia A. (2013). Negative urgency, disinhibition and reduced temporal pole gray matter characterize the comorbidity of cocaine dependence and personality disorders. *Drug and Alcohol Dependence*. 10.1016/j.drugalcdep.2013.02.008
- Alexander AL, Hurley SA, Samsonov AA, Adluru N, Hosseinbor AP, Mossahebi P, ... Field AS (2011). Characterization of Cerebral White Matter Properties Using Quantitative Magnetic Resonance Imaging Stains. *Brain Connectivity*. 10.1089/brain.2011.0071
- Andrews-Hanna JR, Smallwood J, & Spreng RN (2014). The default network and self-generated thought: Component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, 1316(1), 29–52. 10.1111/nyas.12360 [PubMed: 24502540]
- Assari S, Caldwell C, & Mincy R. (2018). Family Socioeconomic Status at Birth and Youth Impulsivity at Age 15; Blacks' Diminished Return. *Children*. 10.3390/children5050058
- Bayard F, Nymberg Thunell C, Abé C, Almeida R, Banaschewski T, Barker G, ... Petrovic P. (2018). Distinct brain structure and behavior related to ADHD and conduct disorder traits. *Molecular Psychiatry*. 10.1038/s41380-018-0202-6
- Bechara A. (2000). Emotion, Decision Making and the Orbitofrontal Cortex. *Cerebral Cortex*. 10.1093/cercor/10.3.295
- Benjamini Y, & Hochberg Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*. 10.1111/j.2517-6161.1995.tb02031.x
- Berg JM, Latzman RD, Bliwise NG, & Lilienfeld SO (2015). Parsing the heterogeneity of impulsivity: A meta-analytic review of the behavioral implications of the UPPS for psychopathology. *Psychological Assessment*. 10.1037/pas0000111

- Buckner RL, Andrews-Hanna JR, & Schacter DL (2008). The brain's default network: Anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences*, 1124, 1–38. 10.1196/annals.1440.011 [PubMed: 18400922]
- Casey BJ, Cannonier T, Conley MI, Cohen AO, Barch DM, Heitzeg MM, ... Dale AM (2018). The Adolescent Brain Cognitive Development (ABCD) study: Imaging acquisition across 21 sites. *Developmental Cognitive Neuroscience*. 10.1016/j.dcn.2018.03.001
- Caspi A, Roberts BW, & Shiner RL (2005). Personality Development: Stability and Change. *Annual Review of Psychology*. 10.1146/annurev.psych.55.090902.141913
- Clark DB, Fisher CB, Bookheimer S, Brown SA, Evans JH, Hopfer C, ... Yurgelun-Todd D. (2018). Biomedical ethics and clinical oversight in multisite observational neuroimaging studies with children and adolescents: The ABCD experience. *Developmental Cognitive Neuroscience*. 10.1016/j.dcn.2017.06.005
- Clark LA, & Watson D. (1995). Constructing validity: Basic issues in objective scale development. *Psychological Assessment*. 10.1037//1040-3590.7.3.309
- Coskunpinar A, Dir AL, & Cyders MA (2013). Multidimensionality in impulsivity and alcohol use: A meta-analysis using the UPPS model of impulsivity. *Alcoholism: Clinical and Experimental Research*, 37(9), 1441–1450. 10.1111/acer.12131
- Cross CP, Copping LT, & Campbell A. (2011). Sex Differences in Impulsivity: A Meta-Analysis. *Psychological Bulletin*. 10.1037/a0021591
- Desikan RS, Segonne F, Fischl B, Quinn BT, Dickerson BC, Blacker D, ... Killiany RJ (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *NeuroImage*, 31(3), 968–980. 10.1016/j.neuroimage.2006.01.021 [PubMed: 16530430]
- DeYoung CG, Hirsh JB, Shane MS, Papademetris X, Rajeevan N, & Gray JR (2010). Testing predictions from personality neuroscience. Brain structure and the big five. *Psychological Science: A Journal of the American Psychological Society / APS*, 21(6), 820–828. 10.1177/0956797610370159
- Fischer S, Smith GT, & Cyders MA (2008). Another look at impulsivity: A meta-analytic review comparing specific dispositions to rash action in their relationship to bulimic symptoms. *Clinical Psychology Review*. 10.1016/j.cpr.2008.09.001
- Giedd JN, & Rapoport JL (2010). Structural MRI of Pediatric Brain Development: What Have We Learned and Where Are We Going? *Neuron*. 10.1016/j.neuron.2010.08.040
- Hagler DJ, Ahmadi ME, Kuperman J, Holland D, McDonald CR, Halgren E, & Dale AM (2009). Automated white-matter tractography using a probabilistic diffusion tensor atlas: Application to temporal lobe epilepsy. *Human Brain Mapping*. 10.1002/hbm.20619
- Hagler DJ, Hatton S, Cornejo MD, Makowski C, Fair DA, Dick AS, ... Dale AM (2019). Image processing and analysis methods for the Adolescent Brain Cognitive Development Study. *NeuroImage*. 10.1016/j.neuroimage.2019.116091
- Hampshire A, Chamberlain SR, Monti MM, Duncan J, & Owen AM (2010). The role of the right inferior frontal gyrus: inhibition and attentional control. *NeuroImage*, 50(3), 1313–1319. 10.1016/j.neuroimage.2009.12.109 [PubMed: 20056157]
- Hamza CA, Willoughby T, & Heffer T. (2015). Impulsivity and nonsuicidal self-injury: A review and meta-analysis. *Clinical Psychology Review*. 10.1016/j.cpr.2015.02.010
- Hershberger AR, Um M, & Cyders MA (2017). The relationship between the UPPS-P impulsive personality traits and substance use psychotherapy outcomes: A meta-analysis. *Drug and Alcohol Dependence*. 10.1016/j.drugalcdep.2017.05.032
- Hoogman M, Bralten J, Hibar DP, Mennes M, Zwiers MP, Schweren LSJ, ... Franke B. (2017). Subcortical brain volume differences in participants with attention deficit hyperactivity disorder in children and adults: a cross-sectional mega-analysis. *The Lancet Psychiatry*, 4(4), 310–319. 10.1016/S2215-0366(17)30049-4 [PubMed: 28219628]
- Hoptman MJ, Antonius D, Mauro CJ, Parker EM, & Javitt DC (2014). Cortical thinning, functional connectivity, and mood-related impulsivity in schizophrenia: Relationship to Aggressive attitudes and behavior. *American Journal of Psychiatry*. 10.1176/appi.ajp.2014.13111553

- Hyatt CS, Owens MM, Crowe ML, Carter NT, Lynam DR, & Miller JD (2019a). The quandary of covarying: A brief review and empirical examination of covariate use in structural neuroimaging studies on psychological variables. *NeuroImage*. 10.1016/j.neuroimage.2019.116225
- Hyatt CS, Owens MM, Gray JC, Carter NT, MacKillop J, Sweet LH, & Miller JD (2019b). Personality traits share overlapping neuroanatomical correlates with internalizing and externalizing psychopathology. *Journal of Abnormal Psychology*. 10.1037/abn0000391
- Insel T, Cuthbert B, Garvey M, Heinssen R, Pine DS, Quinn K, ... Wang P. (2010). Research Domain Criteria (RDoC): Toward a new classification framework for research on mental disorders. *American Journal of Psychiatry*. 10.1176/appi.ajp.2010.09091379
- Jellison BJ, Field AS, Medow J, Lazar M, Salamat MS, & Alexander AL (2004). Diffusion Tensor Imaging of Cerebral White Matter: A Pictorial Review of Physics, Fiber Tract Anatomy, and Tumor Imaging Patterns. *American Journal of Neuroradiology*.
- Johnson SL, Elliott MV, & Carver CS (2020). Impulsive Responses to Positive and Negative Emotions: Parallel Neurocognitive Correlates and Their Implications. *Biological Psychiatry*. 10.1016/j.biopsych.2019.08.018
- Jollans L, Boyle R, Artiges E, Banaschewski T, Desrivieres S, Grigis A, ... Whelan R. (2019). Quantifying performance of machine learning methods for neuroimaging data. *NeuroImage*. 10.1016/j.neuroimage.2019.05.082
- Kotov R, Waszczuk MA, Krueger RF, Forbes MK, Watson D, Clark LA, ... Zimmerman M. (2017). The hierarchical taxonomy of psychopathology (HiTOP): A dimensional alternative to traditional nosologies. *Journal of Abnormal Psychology*, 126(4), 454–477. 10.1037/abn0000258 [PubMed: 28333488]
- Kringelbach ML (2005). The human orbitofrontal cortex: linking reward to hedonic experience. *Nature Reviews Neuroscience*, 6(9), 691–702. 10.1038/nrn1747 [PubMed: 16136173]
- Loe IM, Adams JN, & Feldman HM (2019). Executive function in relation to white matter in preterm and full term children. *Frontiers in Pediatrics*, 6, 1–7. 10.3389/fped.2018.00418
- Lynam DR, Hoyle RH, & Newman JP (2006a). The perils of partialling: Cautionary tales from aggression and psychopathy. *Assessment*, 13(3), 328–341. 10.1177/1073191106290562 [PubMed: 16880283]
- Lynam DR, Smith GT, Whiteside SA, & Cyders MA (2006b). The UPPS-P: Assessing five personality pathways to impulsive behavior. *West Lafayette* 10.1016/j.rpsp.2016.05.002
- Mackey S, Allgaier N, Chaarani B, Spechler P, Orr C, Bunn J, ... Garavan H. (2019). Mega-analysis of gray matter volume in substance dependence: General and substancespecific regional effects. *American Journal of Psychiatry*, 176(2), 119–128. 10.1176/appi.ajp.2018.17040415 [PubMed: 30336705]
- Mackey S, Chaarani B, Kan KJ, Spechler PA, Orr C, Banaschewski T, ... Garavan H. (2017). Brain Regions Related to Impulsivity Mediate the Effects of Early Adversity on Antisocial Behavior. *Biological Psychiatry*, 82(4), 275–282. 10.1016/j.biopsych.2015.12.027 [PubMed: 26971049]
- MacKillop J, Weafer J, C. Gray J, Oshri A, Palmer A, & de Wit H. (2016). The latent structure of impulsivity: impulsive choice, impulsive action, and impulsive personality traits. *Psychopharmacology*, 233(18), 3361–3370. 10.1007/s00213-0164372-0 [PubMed: 27449350]
- MacLaren VV, Fugelsang JA, Harrigan KA, & Dixon MJ (2011). The personality of pathological gamblers: A meta-analysis. *Clinical Psychology Review*. 10.1016/j.cpr.2011.02.002
- Masouleh SK, Eickhoff SB, Hoffstaedter F, & Genon S. (2019). Empirical examination of the replicability of associations between brain structure and psychological variables. *ELife*. 10.7554/eLife.43464
- McCrae RR (2008). A note on some measures of profile agreement. *Journal of Personality Assessment*. 10.1080/00223890701845104
- Merz EC, He X, & Noble KG (2018). Anxiety, depression, impulsivity, and brain structure in children and adolescents. *NeuroImage: Clinical*. 10.1016/j.nicl.2018.07.020
- Miglin R, Bounoua N, Goodling S, Sheehan A, Spielberg M, & Sadeh N. (2019). Cortical Thickness Links Impulsive Personality Traits and Risky Behavior. *Brain Sciences*, 9(373), 1–14.

- Moreno-López L, Catena A, Fernández-Serrano MJ, Delgado-Rico E, Stamatakis EA, Pérez-García M, & Verdejo-García A. (2012). Trait impulsivity and prefrontal gray matter reductions in cocaine dependent individuals. *Drug and Alcohol Dependence*. 10.1016/j.drugalcdep.2012.02.012
- Muhler N, & Lawrence AD (2015). Brain structure correlates of emotion-based rash impulsivity. *NeuroImage*. 10.1016/j.neuroimage.2015.04.061
- Niendam TA, Laird AR, Ray KL, Dean YM, Glahn DC, & Carter CS (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cogn Affect Behav Neurosci*, 12(2), 241–268. 10.3758/s13415-011-0083-5 [PubMed: 22282036]
- Owens MM, Gray JC, Amlung MT, Oshri A, Sweet LH, & MacKillop J. (2017). Neuroanatomical foundations of delayed reward discounting decision making. *NeuroImage*, 161, 261–270. 10.1016/j.neuroimage.2017.08.045 [PubMed: 28843539]
- Owens MM, Hyatt CS, Gray JC, Carter NT, Mackillop J, Miller JD, & Sweet LH (2019). Cortical morphometry of the five-factor model of personality: Findings from the Human Connectome Project full sample. *Social Cognitive and Affective Neuroscience*, 14(4), 381–395. 10.1093/scan/nsz017 [PubMed: 30848280]
- Panizzon MS, Fennema-Notestine C, Eyler LT, Jernigan TL, Prom-Wormley E, Neale M, ... Kremen WS (2009). Distinct genetic influences on cortical surface area and cortical thickness. *Cerebral Cortex*, 19(11), 2728–2735. 10.1093/cercor/bhp026 [PubMed: 19299253]
- Quinn PD, Stappenbeck CA, & Fromme K. (2011). Collegiate heavy drinking prospectively predicts change in sensation seeking and impulsivity. *Journal of Abnormal Psychology*. 10.1037/a0023159
- Riccelli R, Toschi N, Nigro S, Terracciano A, & Passamonti L. (2017). Surface-based morphometry reveals the neuroanatomical basis of the five-factor model of personality. *Social Cognitive and Affective Neuroscience*, 12(4), 671–684. 10.1093/scan/nsw175 [PubMed: 28122961]
- Rimol LM, Nesvag R, Hagler DJ, Bergmann O, Fennema-Notestine C, Hartberg CB, ... Dale AM (2012). Cortical volume, surface area, and thickness in schizophrenia and bipolar disorder. *Biological Psychiatry*, 71(6), 552–560. 10.1016/j.biopsych.2011.11.026 [PubMed: 22281121]
- Rosenbloom MH, Schmahmann JD, & Price BH (2012). The functional neuroanatomy of decision-making. *Journal of Neuropsychiatry and Clinical Neurosciences*. 10.1176/appi.neuropsych.11060139
- Ruiz de Lara CM, Navas JF, Soriano-Mas C, Sescousse G, & Perales JC (2018). Regional grey matter volume correlates of gambling disorder, gambling-related cognitive distortions, and emotion-driven impulsivity. *International Gambling Studies*. 10.1080/14459795.2018.1448427
- Sperry SH, Lynam DR, & Kwapił TR (2018). The convergence and divergence of impulsivity facets in daily life. *Journal of Personality*. 10.1111/jopy.12359
- Steinberg L, Albert D, Cauffman E, Banich M, Graham S, & Woolard J. (2008). Age Differences in Sensation Seeking and Impulsivity as Indexed by Behavior and Self-Report: Evidence for a Dual Systems Model. *Developmental Psychology*. 10.1037/a0012955
- Storsve AB, Fjell AM, Tamnes CK, Westlye LT, Overbye K, Aasland HW, & Walhovd KB (2014). Differential Longitudinal Changes in Cortical Thickness, Surface Area and Volume across the Adult Life Span: Regions of Accelerating and Decelerating Change. *Journal of Neuroscience*, 34(25), 8488–8498. 10.1523/JNEUROSCI.0391-14.2014 [PubMed: 24948804]
- Swick D, Ashley V, & Turken AU (2008). Left inferior frontal gyrus is critical for response inhibition. *BMC Neuroscience*. 10.1186/1471-2202-9-102
- Tackett JL, Slobodskaya HR, Mar RA, Deal J, Halverson CF, Baker SR, ... Besevegis E. (2012). The Hierarchical Structure of Childhood Personality in Five Countries: Continuity From Early Childhood to Early Adolescence. *Journal of Personality*. 10.1111/j.1467-6494.2011.00748.x
- Tamnes CK, Herting MM, Goddings AL, Meuwese R, Blakemore SJ, Dahl RE, ... Mills KL (2017). Development of the cerebral cortex across adolescence: A multisample study of inter-related longitudinal changes in cortical volume, surface area, and thickness. *Journal of Neuroscience*. 10.1523/JNEUROSCI.3302-16.2017
- Uhlmann A, Fouche JP, Lederer K, Meintjes EM, Wilson D, & Stein DJ (2016). White matter microstructure and impulsivity in methamphetamine dependence with and without a history of psychosis. *Human Brain Mapping*. 10.1002/hbm.23159

- Um M, Whitt ZT, Revilla R, Hunton T, & Cyders MA (2019). Shared neural correlates underlying addictive disorders and negative urgency. *Brain Sciences*. 10.3390/brainsci9020036
- VanderVeen JD, Plawecki MH, Millward JB, Hays J, Kareken DA, O'Connor S, & Cyders MA (2016). Negative urgency, mood induction, and alcohol seeking behaviors. *Drug and Alcohol Dependence*, 165, 151–158. 10.1016/j.drugalcdep.2016.05.026 [PubMed: 27291583]
- Vijayakumar N, Allen NB, Youssef G, Dennison M, Yücel M, Simmons JG, & Whittle S. (2016). Brain development during adolescence: A mixed-longitudinal investigation of cortical thickness, surface area, and volume. *Human Brain Mapping*, 37(6), 2027–2038. 10.1002/hbm.23154 [PubMed: 26946457]
- Wang H, Wen B, Cheng J, & Li H. (2017). Brain structural differences between normal and obese adults and their links with lack of perseverance, negative urgency, and sensation seeking. *Scientific Reports*. 10.1038/srep40595
- Watts A, Smith G, Barch D, & Sher K. (2020). Factor Structure, Measurement and Structural Invariance, and External Validity of an Abbreviated Youth Version of the UPPS-P Impulsive Behavior Scale. *Psychological Assessment*.
- Whiteside SP, & Lynam DR (2001). The five factor model and impulsivity: Using a structural model of personality to understand impulsivity. *Personality and Individual Differences*. 10.1016/S0191-8869(00)00064-7
- Whiteside SP, & Lynam DR (2003). Understanding the role of impulsivity and externalizing psychopathology in alcohol abuse: Application of the UPPS impulsive behavior scale. *Experimental and Clinical Psychopharmacology*. 10.1037/10641297.11.3.210
- Wilson RC, Takahashi YK, Schoenbaum G, & Niv Y. (2014). Orbitofrontal cortex as a cognitive map of task space. *Neuron*. 10.1016/j.neuron.2013.11.005
- Zou H, & Hastie T. (2005). Regularization and variable selection via the elastic net. *Journal of the Royal Statistical Society, Series B*, 67, 301–320.

Figure 1. Significant associations of UPPS-P scales with CSA and CT in linear mixed effect models. Orange regions represent positive associations and blue regions represent negative associations.

Figure 2.

Regions whose CSA or CT were included in the best model for predicting each UPPS-P scale in elastic net regression. Orange regions represent positive coefficients and blue regions represent negative coefficients.

Table 1.Demographic characteristics of sample ($N= 10115$ with valid demographic data).

Metric	Mean (SD) or Percent
Sex	52.1% Male
Age	119 Months of Age (SD 7 Month)
Race: White	52.8%
Race: Black	14.6%
Race: Hispanic	20.3%
Race: Asian	2.0%
Race: Other	10.3%
Highest Parental Education	16.6 Years (SD 2.8 years)
Combined Parental Income <\$5,000	3.4 %
Combined Parental Income \$5,000–11,999	3.5 %
Combined Parental Income \$12,000–15,999	2.3 %
Combined Parental Income \$16,000–24,999	4.3 %
Combined Parental Income \$25,000–34,999	5.5 %
Combined Parental Income \$35,000–49,999	7.7 %
Combined Parental Income \$50,000–74,999	12.7 %
Combined Parental Income \$75,000–99,999	13.4 %
Combined Parental Income \$100,000–199,999	28.2 %
Combined Parental Income \$200,000+	10.6 %

Table 2.

Descriptives of UPPS-P scales and Pearson's correlations among UPPS-P scales. SD = standard deviation.

A)					
	Mean	SD	Skewness	Kurtosis	
Negative Urgency	8.49	2.63	0.28	−0.43	
Perseverance	7.03	2.24	0.85	0.98	
Premeditation	7.74	2.37	0.72	0.79	
Sensation Seeking	9.79	2.68	0.03	−0.5	
Positive Urgency	7.99	2.96	0.47	−0.41	
B)					
	1.	2.	3.	4.	5.
1. Negative Urgency	-				
2. Perseverance	.13	-			
3. Premeditation	.16	.45	-		
4. Sensation Seeking	.14	−.10	.07	-	
5. Positive Urgency	.49	.17	.21	.19	-

Table 3.

Significant SMRI Correlates of UPPS-P Scales

Negative Urgency							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	Lateral Orbitofrontal Cortex	Surface Area	-0.0005	0.0001	-4.04	5.34E-05	0.0015
Left	Parahippocampal Gyrus	Thickness	-0.3808	0.0989	-3.85	1.19E-04	0.0013
Left	Middle Temporal Gyrus	Surface Area	-0.0003	0.0001	-3.64	2.77E-04	0.0012
Premeditation							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	Precentral Gyrus	Surface Area	0.0002	0.0001	4.33	1.54E-05	0.0017
Right	Inferior Temporal Gyrus	Surface Area	0.0003	0.0001	4.06	4.86E-05	0.0015
Left	Pars Orbitalis	Surface Area	0.0014	0.0003	4.04	5.44E-05	0.0015
Left	Lateral Occipital Gyrus	Surface Area	0.0002	0.0000	4.03	5.61E-05	0.0014
Right	Precentral Gyrus	Surface Area	0.0002	0.0000	3.54	3.96E-04	0.0011
Sensation Seeking							
Hemi	Region	Metric	B	SE	t	p	AR ²
Right	Globus Pallidus	Volume	0.0006	0.0002	3.64	0.0003	0.0012
Positive Urgency							
Hemi	Region	Metric	B	SE	t	p	AR ²
Right	Middle Temporal Gyrus	Surface Area	-0.0005	0.0001	-6.01	1.900E-09	0.0033
Left	Inferior Temporal Gyrus	Surface Area	-0.0004	0.0001	-5.24	1.680E-07	0.0025
Left	Lateral Orbitofrontal Cortex	Surface Area	-0.0007	0.0001	-5.02	5.280E-07	0.0023
Left	Caudal Middle Frontal	Surface Area	-0.0004	0.0001	-4.71	2.500E-06	0.0020
Right	Inferior Temporal Gyrus	Surface Area	-0.0003	0.0001	-4.20	2.670E-05	0.0016
Left	Parahippocampal Gyrus	Thickness	-0.4446	0.1110	-4.01	6.240E-05	0.0015
Left	Precuneus	Surface Area	-0.0003	0.0001	-4.00	6.420E-05	0.0015
Right	Superior Temporal Gyrus	Surface Area	-0.0004	0.0001	-3.98	6.830E-05	0.0014
Left	Superior Frontal Gyrus	Surface Area	-0.0002	0.0000	-3.96	7.470E-05	0.0014
Left	Rostral Middle Frontal	Surface Area	-0.0002	0.0000	-3.93	8.480E-05	0.0014
Left	Middle Temporal Gyrus	Surface Area	-0.0003	0.0001	-3.80	1.430E-04	0.0013
Left	Precentral Gyrus	Surface Area	-0.0002	0.0001	-3.58	3.520E-04	0.0012
Left	Rostral Middle Frontal	Thickness	0.8000	0.2361	3.39	0.001	0.0010
Right	Medial Orbitofrontal Cortex	Surface Area	-0.0006	0.0002	-3.32	0.001	0.0010
Left	Cuneus	Surface Area	-0.0006	0.0002	-3.31	0.001	0.0010
Right	Caudal Anterior Cingulate	Surface Area	-0.0007	0.0002	-3.29	0.001	0.0010
Right	Caudal Middle Frontal	Surface Area	-0.0003	0.0001	-3.28	0.001	0.0010
Left	Rostral Anterior Cingulate	Surface Area	-0.0008	0.0002	-3.28	0.001	0.0010
Right	Pars Opercularis	Surface Area	-0.0004	0.0001	-3.13	0.002	0.0009
Right	Precentral Gyrus	Surface Area	-0.0002	0.0001	-3.11	0.002	0.0009
Right	Rostral Middle Frontal	Thickness	0.7096	0.2331	3.05	0.002	0.0008
Left	Superior Parietal Lobule	Surface Area	-0.0002	0.0001	-3.04	0.002	0.0008
Right	Superior Frontal Gyrus	Surface Area	-0.0001	0.0000	-3.01	0.003	0.0008

Right	Pars Triangularis	Thickness	0.6253	0.2111	2.96	0.003	0.0008
Left	Caudate	Volume	-0.0002	0.0001	-2.93	0.003	0.0008
Right	Pars Opercularis	Thickness	0.6277	0.2186	2.87	0.004	0.0008
Left	Pericalcarine Fissure	Surface Area	-0.0004	0.0001	-2.75	0.006	0.0007
Left	Fusiform Gyrus	Surface Area	-0.0002	0.0001	-2.73	0.006	0.0007
Perseverance							
Hemi	Region	Metric	B	SE	t	p	AR²
Right	Isthmus of the Cingulate	Thickness	0.4709	0.1300	3.62	2.92E-04	0.0012

Table 4.

Significant DMRI Correlates of UPPS-P Scales. TS = temporal superior; PS = parietal superior.

Negative Urgency							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	Inferior-Fronto-Occipital Fasciculus	FA	-5.63	1.16	-4.87	1.12E-06	0.0023
Left	PS Longitudinal Fasciculus	FA	-4.77	1.13	-4.24	2.28E-05	0.0018
Left	Superior Longitudinal Fasciculus	FA	-4.62	1.12	-4.13	3.62E-05	0.0017
Right	Inferior-Fronto-Occipital Fasciculus	FA	-4.62	1.19	-3.88	1.07E-04	0.0015
Left	TS Longitudinal Fasciculus	FA	-4.11	1.08	-3.79	1.49E-04	0.0014
Premeditation							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	Fornix, Excluding Fimbria	FA	3.25	0.91	3.56	3.670E-04	0.0013
Sensation Seeking							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	Fornix, Excluding Fimbria	FA	3.87	1.06	3.65	2.610E-04	0.0013
Right	Anterior Thalamic Radiations	FA	4.03	1.14	3.53	4.120E-04	0.0012
Positive Urgency							
Hemi	Region	Metric	B	SE	t	p	AR ²
Left	PS Longitudinal Fasciculus	FA	-5.44	1.27	-4.30	1.740E-05	0.0018
Left	Superior Longitudinal Fasciculus	FA	-5.38	1.26	-4.28	1.880E-05	0.0018
Left	Inferior-Fronto-Occipital Fasciculus	FA	-5.39	1.30	-4.15	3.290E-05	0.0017
Left	TS Longitudinal Fasciculus	FA	-4.78	1.22	-3.93	8.530E-05	0.0015
Left	Superior Corticostriate	FA	-4.38	1.39	-3.15	0.002	0.0010
Right	Inferior Longitudinal Fasciculus	FA	-3.67	1.19	-3.07	0.002	0.0009

Table 5.

Prediction accuracy (R^2) for elastic net regression models for structural magnetic resonance imaging (SMRI) and diffusion magnetic resonance imaging (DMRI). Models 1–5 indicate the R^2 of the models built in the training phase. “Ex Val” indicates the R^2 of the best model from the training phase being tested on the external validation set. Full elaboration of the models can be found in Supplemental Tables.

	SMRI	DMRI
Negative Urgency		
Model	R^2	R^2
1	0.005	0.000
2	0.004	0.001
3	0.001	−0.001
4	−0.001	0.000
5	0.004	0.008
Ex Val	0.001	0.002
Premeditation		
Model	R^2	R^2
1	0.004	0.001
2	0.001	−0.002
3	0.003	0.000
4	0.004	0.000
5	0.008	0.002
Ex Val	0.005	0.000
Sensation Seeking		
Model	R^2	R^2
1	0.011	−0.001
2	0.011	0.002
3	0.012	−0.001
4	0.013	−0.002
5	0.004	0.000
Ex Val	0.007	0.000
Positive Urgency		
Model	R^2	R^2
1	0.011	0.001
2	0.002	0.004
3	0.004	0.003
4	0.004	0.005
5	0.005	0.012
Ex Val	0.010	0.003
Perseverance		

	SMRI	DMRI
Model	R ²	R ²
1	0.000	0.000
2	0.000	−0.001
3	0.000	0.000
4	−0.001	0.000
5	−0.001	0.000
Ex Val	0.000	0.000

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Table 6.

Neuroanatomical similarity among UPPS-P scales.

	1.	2.	3.	4.	5.
1. Negative Urgency	-	.09	.04	.11	.63
2. Perseverance	.04	-	.36	.27	.39
3. Premeditation	.02	.33	-	.01	.01
4. Sensation Seeking	.00	.22	-.08	-	.40
5. Positive Urgency	.59	.33	.00	.36	-

Note: Values above diagonal represent Pearson's r between the B values for the 155 structural metrics (i.e., 68 indices of regional cortical surface area + 68 indices of regional cortical thickness + 19 indices of subcortical volume) for a given pair of traits; values below the diagonal represent double-entry intraclass correlations (η^2_{CC}) between these same regions.