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The matter of motivation: Striatal resting-state connectivity is dissociable between grit and growth mindset

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Abstract

The current study utilized resting-state functional magnetic resonance imaging (fMRI) to examine how two important non-cognitive skills, grit and growth mindset, are associated with cortico-striatal networks important for learning. Whole-brain seed-to-voxel connectivity was examined for dorsal and ventral striatal seeds. While both grit and growth mindset were associated with functional connectivity between ventral striatal and bilateral prefrontal networks thought to be important for cognitive-behavioral control. There were also clear dissociations between the neural correlates of the two constructs. Grit, the long-term perseverance towards a goal or set of goals, was associated with ventral striatal networks including connectivity to regions such as the medial prefrontal and rostral anterior cingulate cortices implicated in perseverance, delay and receipt of reward. Growth mindset, the belief that effort can improve talents, notably intelligence, was associated with both ventral and dorsal striatal connectivity with regions thought to be important for error-monitoring, such as dorsal anterior cingulate cortex. Our findings may help construct neurocognitive models of these non-cognitive skills and have critical implications for character education. Such education is a key component of social and emotional learning, ensuring that children can rise to challenges in the classroom and in life.

Key words: resting-state fMRI; grit; growth mindset; character education; functional connectivity

Introduction

High-stakes testing epitomizes the long-standing attribution of cognitive skills to success. This focus has monopolized students' classroom time and left little resources for development of non-cognitive skills (e.g. perseverance, mindset) critical to social and emotional learning (SEL). However, a growing body of evidence associates non-cognitive skills with academic outcomes (Blackwell *et al.*, 2007; Duckworth *et al.* , 2007), and thus has begun to gain traction in academic policy. Emerging alongside the SEL movement's growing popularity come a number of gaps in the evidence needed to feasibly embark on widespread integration in educational practice. First, studies have shown that a number of non-cognitive skills can be developed (Cunha and Heckman, 2008), but their underlying mechanisms have yet to be explored to elucidate how they interact with cognitive traits. Second, SEL, non-cognitive skills and character education

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have all emerged as catch-all terms that combine many potentially distinct constructs (Heckman and Rubinstein, 2001).

It is important moving forward to understand the uniqueness and similarities of these skills in order to improve measurement and understand their implementation. This may help to unpack non-cognitive skills into manageable parts subject to intervention. Neuroscience research has been an important contributor to supporting and refining models of cognitive skills and abilities central to schooling, such as reading and math, and has played a pivotal role in developing well-informed interventions. Such an integrative research approach incorporating behavioral and neurological query is well suited for developing our understanding of non-cognitive skills.

Here, we examine the neural correlates of two important non-cognitive skills: grit and mindset. Grit is the *long-term perseverance for a goal or set of goals*. Duckworth *et al.* (2007) found that grit scores accounted for an average of four percent of the variance in success outcomes even beyond scores of intelligence and conscientiousness (p. 1087). These authors arrived at this figure by averaging the percent variance in success scores explained by grit across six of their studies with a range of percent variance (1.4–6.3%) and varying aims (such as predicting: grade point average (GPA), educational attainment and spelling bee rankings). More recent studies also demonstrate the unique contribution grit has to success outcome including: completing an Army Special Operations Forces selection course, job retention, graduating from Chicago Public Schools, and remaining married for men (Eskreis-Winkler *et al.*, 2014). Taken together, these findings, while small, consistently underscore the importance of long-term perseverance for difficult goals over and above the contribution of talent to success outcomes (Duckworth *et al.*, 2007; Eskreis-Winkler *et al.*, 2014).

Mindset refers to the views one holds about the malleability of ability and was assessed using a theory of intelligence scale. A growth mindset (an incremental theory of intelligence) is the belief that intelligence is malleable and that one may 'grow' their intelligence and *achieve their goals through hard work and dedication*; a fixed mindset (entity theory of intelligence) is the belief that talents and intelligence cannot be changed (Dweck, 2006). Growth mindset is not only positively correlated with math achievement for seventh graders (Blackwell *et al.*, 2007), but more powerfully, experimental studies demonstrate that shaping or operationalizing growth mindset impacts the motivation and performance for aspiring clinicians in organic chemistry (Grant and Dweck, 2003), and for minority students in the face of stereotypes about their race and perceived intelligence (Aronson *et al.*, 2002).

The constructs of grit and mindset have been brought into focus among educators seeking to shape non-cognitive skills to positively impact measures of success from academic achievement to life outcome. Recent evidence suggests that the two constructs are moderately correlated ($r = 0.18$, $P < 0.001$) (West *et al.*, 2014). In unpublished cross-sectional studies of school-aged children, Duckworth and colleagues found positive associations between grit and growth mindset, leading the authors to speculate that growth mindset may contribute to propensity for goal commitment and sustained effort (Duckworth and Eskreis-Winkler, 2013; Perkins-Gough, 2013). Therefore, shaping a growth mindset may be an intervention pathway to help an individual develop grit.

Though related, presumably by overlapping motivation strategies, how do grit and growth mindset dissociate? Whereas growth mindset is the malleable view that our intelligence can be improved through effort and has been studied extensively in theoretical, correlational and experimental work, grit has entered the motivation literature much more recently (Duckworth *et al.*, 2007; Duckworth and Quinn, 2009; Eskreis-Winkler *et al.*, 2014). As Duckworth *et al.* (2007) has found, someone who is gritty 'approaches achievement as a marathon' (p. 1088). These individuals are not deterred by boredom or setbacks, but rather they remain steadfast toward their goals (Duckworth *et al.*, 2007). Motivation for the gritty individual is long-term, whether that is to be a top-notch researcher or to win an Olympic gold medal. A person with a growth minds*et a*lso believes in the efficacy of hard work and dedication to improve their abilities, but may not necessarily hold a definitive reward in mind as the outcome. Instead, these individuals self-regulate their learning on a regular basis, characterized by goal setting, goal operating and goal monitoring (Burnette *et al.*, 2013), employing strategies such as learning from new knowledge and adjusting when errors are made.

In this study, we sought to further understand the similarities and differences between grit and growth mindset by examining associated brain networks in a sample of children using resting state functional connectivity (RSFC). RSFC, measured by functional magnetic resonance imaging (fMRI), is thought to reflect the brain's functional organization (van den Heuvel and Hulshoff Pol, 2010). Due to our interest in bridging motivation and learning and the known importance of the striatum to reward-related learning (Shohamy, 2011; Liljeholm and O'Doherty, 2012; Pauli *et al.*, 2016), we focused on dorsal and ventral striatal (dStr, vStr) connectivity and adopted whole-brain seed-to-voxel analyses. Since growth mindset is a belief system that favors hard work and performance monitoring and grit is a combination of long-term effort, we hypothesized that the striatal connectivity for growth mindset and grit would overlap in regions of the prefrontal cortex implicated in cognitive-behavioral control and dissociate in regions implicated in error-monitoring (e.g. dorsal anterior cingulate cortex) and in affective response (e.g. rostral anterior cingulate cortex).

Materials and methods

Participants

Twenty healthy children (9 females, average age 11.2) were included from a larger study with a primary focus on examining the neural pathways important for academic achievement in native-English speakers in the US (refer to Supplementary ma terial, Table S1 for demographic information). A comprehensive socio-emotional survey was administered approximately 2 years, on average, following collection of structural and resting-state functional MRI scans (refer to Supplementary material text and Table S1 for further details).

Behavioral measures

The grit scale was developed by Duckworth and Quinn (2009) to capture an individual's passion and persistence towards long-term goals. Participants responded to a collection of eight items (e.g. 'New ideas and projects sometimes distract me from old ones'), each of which was rated on a 5-point Likert scale. Participants' grit scores were then calculated from responses across eight items. Indexed by Cronbach's alpha, the scale had an internal consistency of $\alpha = 0.80$ in our sample.

To assess mindset, the theory of intelligence scale was administered (Dweck, 1999). The measure consists of six items, three entity theory statements (e.g. 'You have a certain amount of intelligence, and you really can't do much to change it.') and three incremental theory statements (e.g. 'You can always greatly change how intelligent you are.'). Participants were asked to rate their agreement with each statement using a 6-point scale. The mean on the six-item scale indicated the participant's mindset, with greater scores (i.e. closer to 6) representing a growth mindset. The internal consistency of this scale was $\alpha = 0.84$ in our sample.

MRI data collection

Imaging data were collected at the Richard M. Lucas Center for Imaging at Stanford University in the summer and fall of 2011 and 2012. Prior to the scanning session, families received a packet of materials, including a CD of scanner noises and a DVD of a child going into a scanner, designed to prepare him/her for the scanner sounds and environment. To further minimize movement, children participated in simulated MRI sessions at the Center for Interdisciplinary Brain Sciences Research (http://cibsr.stanford.edu/participating/Simulator.html).

MRI data were acquired using a GE Healthcare 3.0 T scanner 20.x software revision and an 8-channel phased array head coil (GE Healthcare, Waukesha, WI). Images acquired included an axial-oblique 3D T1-weighted sequence with fast spoiled gradient recalled echo pulse sequence (inversion recovery preparation pulse (TI) = 400 ms; repetition time (TR) = 5.5 ms; echo-time (TE) = 1.7 ms; flip angle = 30°; Receiver bandwidth + 32 kHz; slice thickness = 1.2 mm; 156 slices; NEX= 1; field-of-view (FOV) = 22 cm; Phase FOV = 0.75; acquisition matrix = 256 × 256). All scans were inspected by three experienced imaging researchers, without the knowledge of the purpose of the study, for the presence of excessive motion and excluded when agreed upon by the researchers.

Functional MRI data were acquired using an axial 2D GRE Spiral In/Out (Glover and Law, 2001) pulse sequence (repetition time [TR] = 2000 ms; echo time [TE] = 30 ms; flip angle = 80°; Receiver band-with = 125 kHz; slice thickness = 4.0 mm; number of slices = 31, descending; 3.44 × 3.44 mm in-plane resolution; number of temporal frames= 180; field of view [FOV]= 22 cm). The total duration of the resting state scan was 6 min.

Image preprocessing

The Statistical Parametric Mapping 8 statistical package (SPM8; http://www.fil.ion.ucl.ac.uk/spm) including the voxel based morphometry (VBM8) and Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra (DARTEL) toolboxes (Ashburner, 2007) was used in the preprocessing of the structural images. Images were bias-field corrected and segmented to gray matter, white matter and cerebrospinal fluid (CSF).

Processing of resting state fMRI data was performed with SPM8 in the MATLAB computing environment (The MathWorks, Natick, MA). Data were corrected for acquisition timing and realigned to the third volume of the series. To reduce the effect of head movement on functional connectivity, volumes with a mean intensity >1.5% of the mean global signal or 0.5 mm/TR framewise displacement were detected and repaired via interpolation using the ArtRepair toolbox (Mazaika et al., 2009). After artifact repair, data were spatially normalized to MNI space using normalization parameters obtained from the children's segmented gray matter images transformed to the MNI standard template. Resultant images were re-sampled to 2 × 2 × 2 mm voxels in MNI stereotaxic space. Spatial smoothing was done with a 7-mm isotropic Gaussian kernel. Functional data were analyzed for the presence of motion and excluded if relative motion exceeded 1.0 mm.

Region-of-interest selection

The primary goal of this study was to investigate the behavioral and neurological similarities and differences underlying grit and growth mindset. These traits have been shown to predict success in a variety of domains [e.g. for grit: Duckworth et al. (2007); Duckworth and Quinn (2009); Eskreis-Winkler et al. (2014); e.g. for growth mindset: Aronson et al. (2002); Blackwell et al. (2007); Good et al., (2003)]. As mentioned, grit is perseverance for long-term goals. A growth mindset is marked by a malleable view of intelligence, that is, an individual with a growth mindset will believe that through hard work and dedication intelligence can be improved and goals can be met. By definition, these constructs appear to both highlight the importance of hard work in the pursuit of goals. Thus, we aimed to select our regions-of-interest (ROI) to best characterize the neural overlap and dissociations of these two non-cognitive traits.

Due to the well-known connections with motivation, reward and learning (Shohamy, 2011; Liljeholm and O'Doherty, 2012; Pauli et al., 2016), we selected ROIs of the ventral and dorsal striatum. In order to construct these ROIs, we combined the left and right nucleus accumbens, caudate and putamen from the Harvard–Oxford Subcortical Structural Atlas (Harvard Center for Morphometric Analysis), and divided the ventral and dorsal striatum at MNI coordinate $z = 0$ according to the procedure in Cooper et al. (2012). The resultant two clusters, bilateral ventral striatum ($z < 0$) and bilateral dorsal striatum ($z > 0$) were input as seed ROIs in the functional connectivity analysis run in Conn Toolbox for SPM (Whitfield-Gabrieli and Nieto-Castanon, 2012).

Resting-state functional magnetic resonance imaging connectivity analysis

Resting-state connectivity analyses were performed using the Conn Toolbox (version 13o) for SPM (Whitfield-Gabrieli and Nieto-Castanon, 2012). Within the toolbox, the CompCor method was adopted (Behzadi et al., 2007). Subject-specific white matter and CSF time series were extracted and the first five principal components of each were regressed from the BOLD signal as were the three translation and three rotation movement parameters calculated during realignment in SPM. The residual BOLD signal was band-pass filtered (0.008-0.09 Hz), regressing out the first five principal components derived from subject-specific time series to focus on low-frequency oscillations typically seen in resting-state networks. Primary analysis focused on whole-brain functional connectivity seeded from the bilateral striatum ROIs (defined above). The mean-centered values of grit and growth mindset were input as covariates in models both independently and simultaneously to observe simple and partial correlation effects in the model from the seeded regions.

The statistical significance threshold for whole-brain analyses was determined by Monte Carlo simulation using 3dClustSim in AFNI (Cox, 1996). Analyses were further Bonferroni corrected for the number of ROIs used, such that clusters were significant at $P = 0.025$, which dictated that results were limited to voxel height of $P < 0.02$ and cluster-size of at least 449 contiguous voxels by volume (P = 0.05 Bonferroni corrected for the number of ROIs and for the whole brain). All reported coordinates are in MNI space.

Results

Demographics and behavioral correlations

Descriptive statistics of demographic and behavioral variables are presented in Supplementary material, Table S1. In addition, similarities and differences between grit and intelligence beliefs were observed in a series of correlational analyses. (Supplementary material, Table S2). Grit and growth mindset showed small correlation in line with prior research, but likely due to small sample size, the effect was not significant ($r = 0.34$, $P = 0.14$).

Striatal resting-state connectivity correlations with grit and mindset

Simple correlations between striatal functional connectivity and grit and growth mindset yielded a number of positive resting-state networks ($P < 0.05$ Bonferroni corrected for the number of ROIs and for the whole brain; Figure 1 and Supplementary material, Tables S3 and S4 for details and negative correlations). Dorsal striatal connectivity with a number of regions was positively correlated with greater growth mindset; grit showed no significant positive correlations with dStr connectivity. These included dorsal anterior cingulate cortex (dACC)/anterior midcingulate cortex (aMCC), left dorsolateral prefrontal cortex (DLPFC) and cerebellum (Figure 1a and Supplementary material, Table S3). When regressing growth mindset on grit, the results remained significant and new clusters emerged including connectivity between dStr and a large cluster spanning right middle frontal gyrus, pre-central gyrus and superior frontal gyrus, as well as a cluster proximal to the left pre-central gyrus (Figure 2a and Supplementary material, Table S4).

In contrast, vStr networks were associated with both grit and mindset. First, both greater grit and growth mindset showed positive correlations between vStr connectivity and DLPFC that spatially overlapped (Figure 1b and Supplementary material, Table S3). Only vStr connectivity with right DLPFC remained significantly correlated with greater grit when controlling for growth mindset. Connectivity between vStr and left DLPFC remained correlated with mindset when grit was controlled for. Greater grit was characterized by statistically significant vStr connectivity with rostral ACC (rACC), medial PFC (mPFC), including the right frontal pole, and a cluster in the posterior CC (PCC; in both simple correlation and multiple regression with grit regressing out growth mindset) (Figures 1b and 2b and Supplementary material, Tables S3, S4). A greater growth mindset was positively correlated with connectivity between the vStr and a number of dispersed bilateral regions. These clusters included a region in the cerebellum, a cluster proximal to the

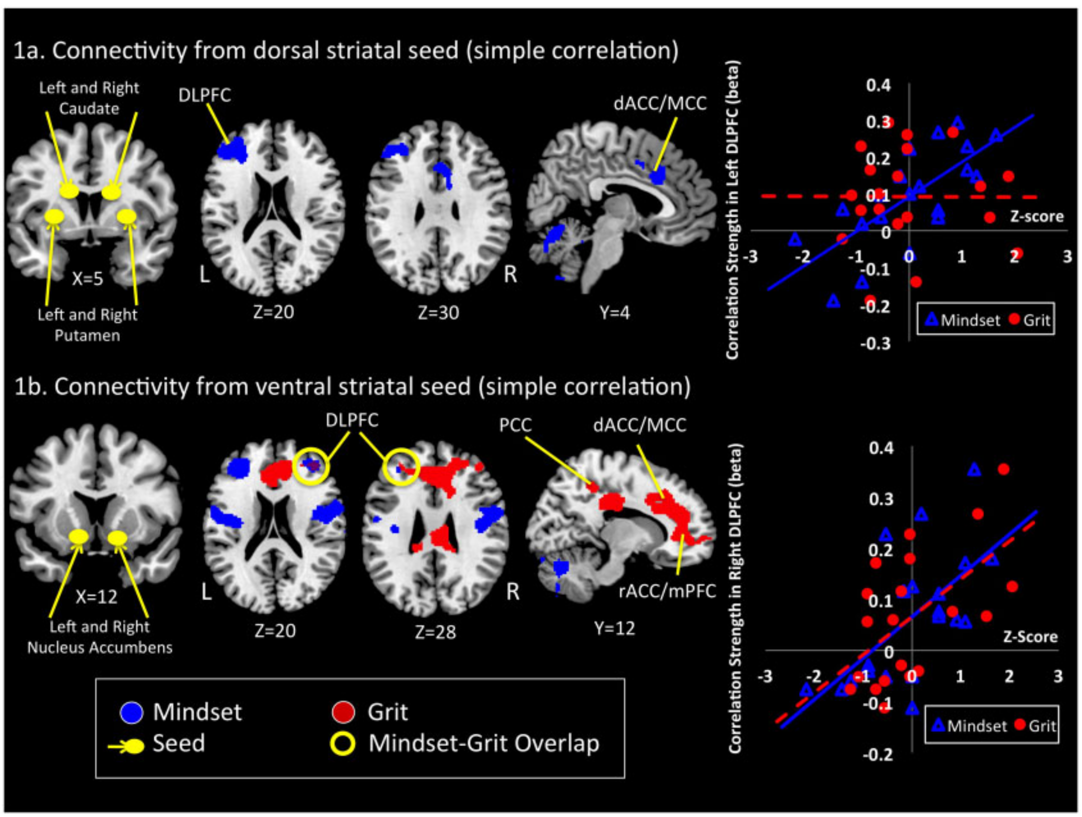

Fig. 1. Striatal networks of grit and mindset (Positive Simple Correlation). Clusters depicted were significant at $P = 0.05$ Bonferroni corrected for the number of ROIs and the whole brain. (A) Resting state functional dorsal striatal connectivity correlation with mindset (blue). No positive dorsal striatum connectivity with grit. Panel on the right is a scatter plot of connectivity strength from dorsal striatal ROI to left dorsolateral prefrontal cortex (DLPFC) plotted against grit (red) and mindset (blue). The left DLPFC cluster is shown on the left panel at $z = 20$. Grit and mindset are in z scores. Linear best-fit lines are shown. (B) Resting state functional ventral striatal connectivity correlation with mindset (blue) and grit (red). Overlapping regions are depicted in purple. Panel on the right is a scatter plot of connectivity strength from ventral striatal ROI to right dorsolateral prefrontal cortex (DLPFC) plotted against grit (red) and mindset (blue). The right DLPFC cluster is shown on the left panel at $z = 28$. Grit and mindset are in z scores. Linear best-fit lines are shown.

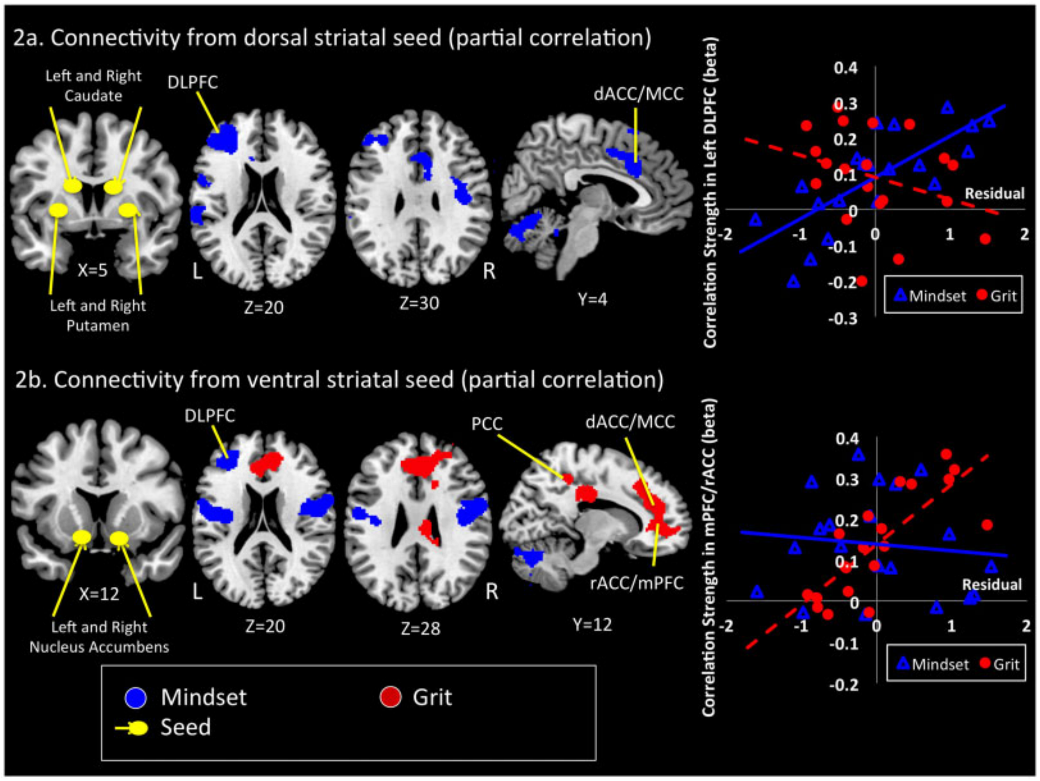

Fig. 2. Striatal networks of grit and mindset (positive partial correlation). Clusters depicted were significant at $P = 0.05$ Bonferroni corrected for the number of ROIs and for the whole brain. (A) Resting state functional dorsal striatal connectivity correlation with mindset while regressing out grit (blue). No positive dorsal striatum connectivity with grit while regressing out mindset. Panel on the right is a scatter plot of connectivity strength from dorsal striatal ROI to left dorsolateral prefrontal cortex (DLPFC) plotted against grit (red) and mindset (blue). The left DLPFC cluster is shown on the left panel at $z = 20$. Grit and mindset are in z scores. (B) Resting state functional ventral striatal connectivity correlation with mindset (blue) and grit (red). Overlapping regions are depicted in purple. Panel on the right is a scatter plot of connectivity strength from ventral striatal ROI to medial prefrontal/rostral anterior cingulate (MPFC/rACC) plotted against grit (red) and mindset (blue). The MPFC/rACC is shown on the left panel at $y = 12$. Grit and mindset are residualized for the opposite and represented in z scores.

right pre-central and post-central gyri, and a left pre-central gyrus/opercular cortex cluster (in both simple correlation and multiple regression with growth mindset regressing out grit) (Figures 1b and 2b and Supplementary material, Tables S3, S4). The imaging correlations with each of the two grit factors, consistency of interest and perseverance of effort, are also described in Supplementary material (see Supplementary, Results 'Imaging Correlations with Two Grit Factors').

Discussion

The striatum is thought to modulate information from regions involved in reward processing and executive functioning including those related to cognitive and behavioral control (Averbeck *et al.*, 2014). Broadly speaking, the dStr is characterized as the 'actor', which holds information about favorable outcomes to ensure that favorable choices are made more frequently and suggested to be involved in cognitive and motor control (O'Doherty *et al.*, 2004). The vStr on the other hand is involved in reward processing, motivation and decision-making. The vStr is hence most often differentiated for its contribution as a 'critic', which 'learns to predict future reward' (O'Doherty *et al.*, 2004). These distinctions, however, are not black and white and work describing a dorsolateral-to-ventromedial gradient in the striatum has been explored. Of relevance, dStr and vStr mediate different dimensions of cognitive flexibility and inhibitory control (Voorn *et al.*, 2004). In our data, grit and growth mindset were both related to cortico-striatal connectivity between vStr and DLPFC, which has been shown to be impaired in those with substance abuse and related to cognitive-behavioral control, more specifically, inhibition, or the ability to ignore irrelevant or harmful stimuli (Motzkin *et al.*, 2014). Both grit and growth mindset are related to staving off distractions, whether it be in pursuit of a goal or learning in general.

Grit was related to positive functional connectivity between vStr and a medial prefrontal network. These medial prefrontal regions include the rACC and portions of the mPFC (Öngür *et al.*, 2003), which project to the ventromedial striatum and are related to prediction of reward. Our findings, based on striatal connectivity, corroborate findings from a previous study of trait persistence in which the authors describe the elimination of the partial reinforcement extinction effect where behavior persists in the absence of reinforcement when lesions to the mPFC and vStr are present (Gusnard *et al.*, 2003). These findings may be particularly relevant to grit, which is characterized by the long-term pursuit of a goal, when intermittent reinforcement may be absent. Further, top-down control of regions related to emotion and motivation, such as the vStr, may be modulated by regions of the PFC (Richard and Berridge, 2013). Of note, vStr connectivity with the right DLPFC remained significantly correlated with grit when regressing out growth mindset. Recent attempts to characterize lateralization of DLPFC activations in the Stroop task noted that the right DLPFC may upregulate cognitive control in the context of conflict, thus reducing interference of irrelevant stimuli (Vanderhasselt *et al.*, 2009), though it is important to note that these findings were not related to *connectivity* between the DLPFC and striatum. Additionally, grit was positively correlated with vStr connectivity to PCC, which may be related to choices involving delayed gratification (Weber and Huettel, 2008). Grit, therefore, may be characterized by a robust network of cognitive and affective control to persevere while maintaining focus on a delayed receipt of reward.

A greater growth mindset compared to grit was uniquely associated with dStr connectivity and cortical projections such as to the dACC and the DLPFC, which are shown to be critical to error-monitoring and concordant behavioral adaptation (Stevens *et al.*, 2009). There is a small body of existing imaging literature, suggesting people with a growth mindset are efficient error monitors and are receptive to corrective feedback (Moser *et al.*, 2011). In an event-related potential study, those with a fixed mindset exhibited a greater anterior prefrontal P3 response, or an emotional response to errors thought to be reflective of concerns about their performance compared to others (Mangels *et al.*, 2006). Mangels *et al.* (2006) go on to suggest that holding a positive view of challenge, as seen in growth mindset, may in some part neutralize affective response to negative feedback. It is important to note that these previous studies examined neural activation while the current study focuses on connectivity and that neural connectivity does not imply the connected regions are more activated. However, the prior work helps to put our findings on functional covariance of spontaneous activity between striatum and cortical regions into perspective. When regressing out grit, growth mindset was more strongly correlated with connectivity between the vStr and left DLPFC. Attempts to differentiate the role of the left DLPFC in cognitive updating using the Stroop task suggest that the left DLPFC is selectively involved in task-switching and regulation of strategies when upcoming incongruent trials are forewarned (Vanderhasselt *et al.*, 2009).

Though this paper is the first of its kind to explore similarities and differences of neural mechanisms of these two non-cognitive constructs, this study has a number of limitations. First, grit and growth mindset are measures that are validated in samples of adolescents, so behavioral measures were collected approximately 2 years after brain measures (in pre-adolescence) were collected. Second, the sample size is small. As more attention is brought to these skills in education, further validation in larger samples will be necessary in order to appropriately accommodate diverse populations before beginning to think about widespread translation to intervention.

We demonstrate that both grit and growth mindset show associations with cognitive-behavioral control networks. Intriguingly, they also demonstrate distinctively divergent networks. Ventral striatal networks involving the mPFC as well as the PCC highly correlated with grit and likely represent strategies for staving off distractions in the face of delayed reinforcement. However, growth mindset correlated networks included those implicated in regulation strategies and error-monitoring, such as seen in correlation with connectivity between dStr and the dACC and left DLPFC. This could be related to the awareness that updating and regulating learning strategies based on new information is critical to learning.

The knowledge gained from studies such as ours may help develop neurobiological models of non-cognitive skills relevant to education and related interventions. The new models can serve as an intermediate step of validating the brain basis of non-cognitive skills in order to better understand targeted interventions and more generally, the development of skills such as grit and growth mindset. The models will also complement similar models of academic skills, such as for reading and math, that have attracted far more attention to date.

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Supplementary data

Supplementary data are available at SCAN online.

Conflict of interest. None declared.

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