Goal-Directed Correlates and Neurobiological Underpinnings of Adolescent Identity: A Multi-Method Multi-Sample Longitudinal Approach

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Abstract

This multi-method multi-sample longitudinal study examined how neurological substrates associated with goal-directedness and information-seeking are related to adolescents' identity. Self-reported data on goal-directedness were collected across three bi-annual waves in Study 1. Identity was measured one wave later. Study 1 design and measurements were repeated in Study 2 and extended with structural brain data (nucleus accumbens (NAcc) and prefrontal cortex grey matter volume (PFC), collected across three bi-annual waves. Study 1 included 497 adolescents ($M_{\text{age T1}}$ 13.03 years) and Study 2 included 131 adolescents ($M_{\text{age T1}}$ 14.69 years). Using latent growth curve models, goal-directedness, NAcc, and PFC volume predicted a stronger identity one wave later. These findings provide crucial new insights in the underlying neurobiological architecture of identity.

Keywords: Brain development, Identity formation, MRI

Goal-Directed Correlates and Neurobiological Underpinnings of Adolescent Identity: A Multimethod Multisample Longitudinal Approach

Adolescents face the central task of establishing a clear identity (Erikson, 1968) through searching for self-defined values and commitments within various important life domains. This process of exploring and reconsidering identity alternatives is assumed to result in strong and stable commitments highly important for psychosocial functioning (Erikson, 1968; Klimstra, Hale, Raaijmakers, Branje, & Meeus, 2010; Marcia, 1966). For example, adolescents with weaker identity commitments and more uncertainty about their identity commitments show higher levels of internalizing and externalizing problem behaviors over time (e.g., Becht et al., 2016; Crocetti, Klimstra, Keijsers, Hale, & Meeus, 2009). Thus, development of a strong identity can be considered a crucial task for adolescents' concurrent and future adjustment.

An important question concerns why some adolescents develop a strong identity whereas others do not. One factor that may be particularly important in this regard, but has received little attention in research so far, is the substantial change across adolescence in brain areas involved in behaviors that might facilitate identity formation. Dramatic changes in brain volume are known to occur during adolescence, with protracted development of the prefrontal cortex (PFC; Mills & Tamnes, 2014) relative to the earlier development of limbic regions, such as the nucleus accumbens (NAcc; Mills, Goddings, Clasen, Giedd, & Blakemore, 2014). The aim of this multi-sample longitudinal study was to investigate how identity-relevant behaviors and their neurological substrates relate to subsequent identity in adolescence.

Identity as Goal-Directedness and Information Seeking Behavior

Contemporary models of identity emphasize different dimensions underlying the identity formation process (Crocetti, Rubini, & Meeus, 2008; Luyckx, Goossens, & Soenens, 2006). The

present study used the three dimensional Meeus-Crocetti model to operationalize management of identity commitments (Crocetti et al., 2008; Meeus, Van De Schoot, Keijsers, Schwartz, & Branje, 2010). Within this model, commitment refers to strong choices adolescents have made and the certainty they derive from these choices. Reconsideration of commitment represents adolescents' commitment uncertainty and willingness to abandon current commitments to search for new ones. These dimensions define the identity formation cycle in which adolescents form commitments by considering and reconsidering them. Through in-depth exploration, adolescents maintain their current identity commitments by exploring and gathering new information on their commitments cyclically (Crocetti et al., 2008, Meeus et al., 2010).

Based on the Meeus-Crocetti model (Crocetti et al., 2008), establishing a strong identity requires at least two processes involved in identity commitment: goal-directedness and information seeking. First, motivation and goal-directedness are important capacities needed to pursue valued goals and make commitments (Burrow & Hill, 2011; Crone & Dahl, 2012; Erikson, 1968). Indeed, adolescents with strong commitments who explore their commitments to a greater degree demonstrate stronger goal-directed thinking (Burrow, O'Dell, & Hill, 2010). Moreover, adolescents with stronger feelings of agency report stronger identity commitments (Schwartz, Coté, & Arnett, 2005). For example, adolescents who were actively seeking out identity options and critically evaluating self-relevant information to negotiate identity questions displayed the strongest identity commitments (Berzonsky & Niemeyer, 1994). Second, information seeking plays a role in identity formation. For example, adolescents with an informational identity style report stronger identity commitments and more active exploration of their commitments in order to strengthen these commitments further (Crocetti, Rubini, Berzonsky, & Meeus, 2009).

Brain Development and Identity Formation: Goal-Directedness and Information Seeking

Adolescence is accompanied by structural changes brain regions critically involved in goal-directedness and information seeking behavior (Mills & Tamnes, 2014). Large-scale changes in PFC and NAcc grey matter volume have been reported with substantial individual differences between adolescents (Gogtay et al., 2004; Mills & Tamnes, 2014). Concerning the developmental trajectories of NAcc, inconsistent findings have been reported in differentiating left and right NAcc, with some studies reporting decreasing left NAcc (Urošević et al., 2012), increasing left NAcc, but decreasing right NAcc volume (Denisson et al., 2013) across adolescence and young adulthood. A consistent decrease has been reported for bilateral NAcc (e.g., Mills et al., 2014; Østby et al., 2009). However, for PFC grey matter volume, a consistent decrease in volume has been reported with age (e.g., Raznahan et al., 2011; Mills et al., 2014), which is assumed to reflect decreasing density of synapses and increasing white matter volume to facilitate greater efficiency of information processing (Mills et al., 2014).

Individual differences in level and change observed in subcortical brain regions have also been reported, particularly in the NAcc, which supports reward processing, goal-orientation, and motivated behavior. In one of the few longitudinal brain-behavior studies, adolescents with greater versus smaller increases in NAcc volume over time reported more motivation to pursue valued goals (Urošević, Collins, Muetzel, & Luciana 2012). Additionally, in a cross-sectional study, higher grey matter volume in NAcc positively related to pursuit of long-term goals (Nemmi, Nymberg, Helander, & Klingberg, 2016). Because NAcc volume relates to goal-directedness, NAcc volume might be involved in identity as well.

The PFC has been linked to the development of cognitive control and information seeking behavior (Casey, 2015). The PFC shows a protracted development across adolescence

(Tamnes et al., 2013), which is assumed to reflect neural plasticity that provides adolescents opportunities to learn new skills, but also 'build an identity' (Blakemore & Mills, 2014). Thus, although decreasing grey matter volume reflects normative brain maturation, individual differences in its initial level and change over time defines a certain window of opportunity that differs between adolescents. Based on the window of opportunity principle, adolescents who maintain relatively higher PFC volume during adolescence might also reflect more actively on identity issues. Because information seeking behavior is important for exploring and maintaining identity (Berzonsky & Niemeyer, 1994), we expected that individual differences in the level and changes in PFC structure would predict adolescents' identity as well. To date, most studies have investigated structural development of the NAcc and PFC brain regions separately from behavioral changes (Mills et al., 2014). Yet, individual differences in baseline level of and changes in structure likely relate to behavior (Walhovd, Tamnes, & Fjell, 2014). In the current longitudinal study, we used a novel approach to test whether the changes in brain areas during adolescence (Mills et al., 2014; 2016) that are involved in observed changes in self-reported goal-directedness and information seeking behaviors predict later identity.

The Present Study

The purpose of the present research was to investigate self-reported and neural processes underlying adolescents' identity in two separate studies. In Study 1, we tested the hypothesis that adolescents with higher and increasing goal-directedness would show a stronger later identity (indicated by relatively high commitments, high in-depth exploration and low reconsideration). In Study 2, we drew on questionnaire and neuroimaging data from a second large-scale longitudinal imaging study. First, we aimed to replicate the questionnaire-based findings of Study 1. Second, we examined the general developmental trajectories of NAcc and PFC. Based

on prior studies, we expected a decrease in PFC brain volume across adolescence (Raznahan et al., 2011; Mills et al., 2014). Because prior studies were inconclusive about change in NAcc volume across adolescence, we could not formulate clear expectations regarding the developmental trajectories of left and right NAcc. Next, we combined questionnaire and imaging data to test whether individual differences in initial level and structural changes of NAcc and PFC grey matter volume predicted later identity commitments, in-depth exploration, and reconsideration of commitments. We hypothesized that a more protracted developmental trajectory in both NAcc and PFC grey matter volume would provide for more opportunities for identity exploration and therefore predict a more mature identity (Erikson, 1968).

Method

General Methodological and Statistical Approach

Studies 1 and 2 provided four waves of longitudinal data from two community samples of adolescents. In Study 1, we investigated whether goal-directedness predicted later identity, using self-reports. Similarly, in Study 2 we examined whether self-reported goal-directedness predicted later identity. We also investigated whether structural brain changes predicted identity in Study 2. Specifically, we investigated whether initial level and changes in volume of the NAcc and PFC predicted later identity.

To study whether changes in goal-directedness (measured with self-reports, and with structural brain measures for areas involved in goal-directedness) and information seeking (assessed with structural brain measures) predicted later identity, we conducted a series of Latent Growth Curve Models (LGM; Duncan, Duncan, & Strycker, 2013) on the predictor variables. In both studies, these LGMs were based on three biennial measurement waves (separated by two-year intervals), covering ages 11-21 years across waves (Study 1) and ages 12-22 years across

waves (Study 2). We assessed adolescents' identity at the fourth wave (see Figure 1 for the conceptual models). LGM is a highly flexible method for analyzing longitudinal data by capturing both the level where individuals start out at the first measurement point (referred to as the initial level or intercept) as well as the change over time from the first to third wave (referred to as the slope). LGM provides estimates of the average intercept and slopes parameters (i.e., fixed effects), which represent the estimates for the entire sample. Individual differences around these overall growth parameters are captured by a variance component (or random effect). LGM allows one to include the intercept and slope estimates to predict the outcome variable, in our study identity, within the same model (Duncan et al., 2013). That is, we investigated whether adolescents' starting point at the first wave as well as the change over time from Wave 1 one to Wave 3 predicted identity at the fourth measurement wave.

Because adolescents in both studies varied significantly in age at each measurement wave, we applied a model where individually varying times of observations could be estimated (i.e., TSCORES option in M*plus*, Muthén & Muthén, 1998-2012). Please find an elaborate description of this TSCORES method as online supplementary material S.1. Given the fact that there were only three measurement waves, we restricted our model to estimate linear slopes only. Because of the multilevel structure when modelling individually varying times of observation (using the TSCORES option in M*plus*), standardized coefficients were not available in our prediction models. Therefore, we reported unstandardized coefficients. In all our prediction models, we controlled for gender differences in goal-directedness and structural brain measures (i.e., NAcc and PFC volume) as well as possible age and gender differences in level of identity commitments, exploration-in depth, and reconsideration. If these covariates were, however, non-significant, they were trimmed from the models for reasons of parsimony.

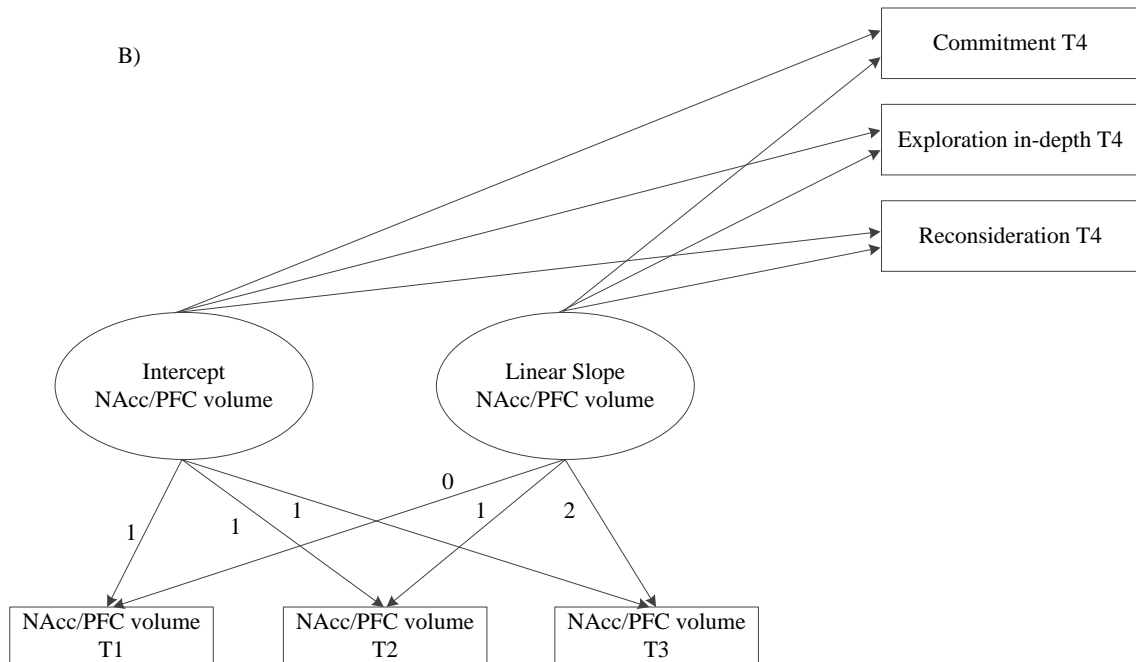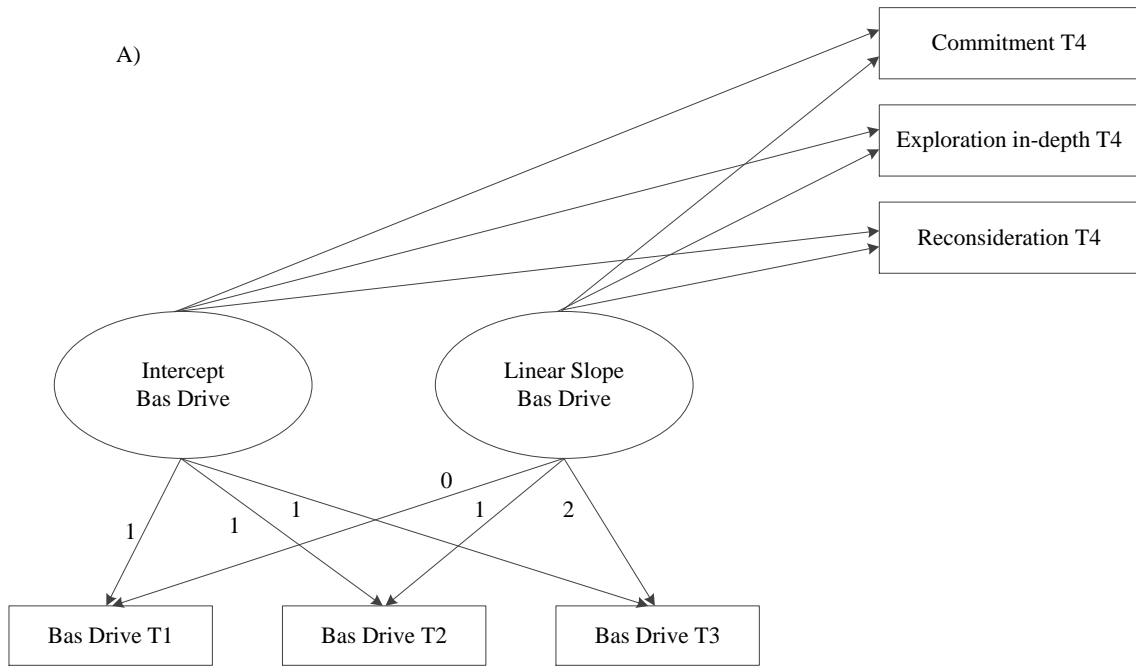*Figure 1.* Conceptual latent growth curve model with intercept and slope of (panel A) BAS Drive predicting identity (Study 1 and Study 2), BAS = Behavioral Activation System, and (panel B) intercept and slope of NAcc and PFC volume predicting identity (Study 2). NAcc = Nucleus Accumbens, PFC = pre-frontal cortex. Note that separate models were conducted for left NAcc, right, NAcc, left PFC and right PFC.

Study 1

Method

     Participants and procedure. Participants were 497 Dutch adolescents (283 boys, M_{age} T1 = 13.03, SD = 0.46) from the ongoing longitudinal project Research on Adolescent Development and Relationships Young Cohort (RADAR-Y). Most adolescents came from medium or high SES families (87.9%). For the present study, we used data from T1, T3, T5 and T6, which will be designated as Waves 1 through 4, respectively. Wave 1, 2, and 3 were separated by a 2-year interval. Wave 3 and 4 were separated by a 1-year interval. We chose these measurement waves to match the longitudinal design of Study 2. Adolescents were aged between 11 and 21 years across waves. At Wave 1, adolescents' age ranged between 11.01 and 15.56 years. Adolescents filled out questionnaires during home visits.

     Missing value analysis indicated 86% of all possible data points were completed by the adolescents across waves. Little's MCAR test revealed a chi-square (χ^2/df) of 1.58, indicating that is unlikely that results were biased as a result of missing values. Hence, missing data were handled in M*plus* 7.4 using Full Information Maximum Likelihood (FIML). Participants received €10 (equivalent to approximately US $11) when they completed the questionnaires. All participants signed an informed consent form. The medical ethical committee of the University Medical Center Utrecht has approved the RADAR-study.

     Measures.

     Identity. Adolescents reported on their identity using the Utrecht-Management of Identity Commitments Scale (U-MICS, Crocetti et al., 2008). This 26-item questionnaire measures identity in three dimensions across educational (13 items) and interpersonal identity domains (13 items). Within the educational and interpersonal domains, the U-MICS measures commitment

with 5 items, exploration in-depth with 5 items and reconsideration with 3 items. Sample items

for educational and interpersonal identity are respectively, "My education/best friend makes me

feel confident about myself" (commitment), "I often think about my education/best friend" (in-

depth exploration), and "In fact, I'm looking for a different education/best friend"

(reconsideration), answered on a 5-point Likert scale (1 = *completely untrue,* 5 = *completely*

true). While the U-MICS allows identity to be measured in different domains, we investigated

global identity by combining the educational and interpersonal identity domains in line with

other studies (e.g., Crocetti et al., 2008; Meeus et al., 2010). The factorial validity of the U-MICS

for the assessment of global identity has been confirmed (Crocetti et al., 2008). Moreover, the U-

MICS shows good reliability and measurement invariance across sex and time (Crocetti et al.,

2008). Cronbach's alpha at Wave 4 was .96, .88, and .91 for commitment, exploration in-depth

and reconsideration, respectively.

     Goal-Directedness. Adolescents reported on their goal-directedness using a Dutch

version of the BAS Drive subscale of the BIS/BAS questionnaire (Carver & White, 1994). BAS

Drive was assessed with four items, for example "I undertake a lot of effort to get things I want"

or "When I want something, I usually go all-out to get it". Items were rated on a 4-point Likert

scale (1 = *strongly disagree,* 4 = *strongly agree*). Factorial validity of the BAS Drive subscale

has been established for both the original version (e.g., Carver & White, 1994) and the translated

Dutch version (Yu, Branje, Keijsers, & Meeus, 2011). Cronbach's alpha was .58, .67, and .76 for

Waves 1 through 3, respectively.

Results

Means, standard deviations, and correlations among study variables of Study 1 can be found as

online supplementary material S.2.

Development of goal-directedness and identity. Parameter estimates of intercept and slope factors of self-reported goal-directedness predicting identity are depicted in Table 1. Results indicated that, on average, BAS Drive was stable across adolescence, intercept = 12.17, p <.001, σ = 23.88, p = .013, linear slope 0.03, p = .436, σ = .12, p = .005. Intercept and slope were negatively correlated, -1.65, p = .009, indicating that when adolescents started with relatively higher initial BAS Drive level, they reported relatively stronger decreasing BAS Drive levels over time. Girls reported lower initial levels of BAS Drive, b = -2.87, p = .002, but a stronger increase in BAS Drive over time, b = .21, p = .001, compared to boys. Consistent with our hypothesis, adolescents with relatively higher initial levels of BAS Drive reported stronger commitments, and less reconsideration of identity commitments one-wave later (Table 1). Higher baseline levels of BAS Drive were not related to exploration in-depth. When adolescents reported a stronger increase in BAS Drive they reported stronger commitments, more exploration in-depth and less reconsideration, one wave later.

Discussion

Findings of Study 1 supported the hypothesis that adolescents who engage in goal-directed efforts (as assessed by BAS Drive) were more likely to show stronger identity commitments, more in-depth exploration and less reconsideration of identity commitments at a later moment in time.

Table 1

Unstandardized Parameter Estimates and Standard Errors Predicting Identity

Predictor	Commitment		Exploration in-depth		Reconsideration	
	Parameter	SE	Parameter	SE	Parameter	SE
Study 1 Questionnaire part						
BAS Drive Int.	0.163*	0.059	0.097	0.050	-0.128*	0.059
BAS Drive Slope	2.222**	0.718	1.790**	0.620	-2.070*	0.742
Study 2 Questionnaire part						
BAS Drive Int.	0.151***	0.009	0.117***	0.006	0.024	0.013
BAS Drive Slope	-0.060	0.108	0.058	0.073	0.001	0.133
Study 2 MRI part						
Left NAcc Int.	0.110***	0.019	0.020	0.019	-0.104**	0.030
Left NAcc Slope	-0.110	0.200	0.386*	0.187	0.156	0.313
Right NAcc Int.	0.171***	0.015	0.025	0.018	-0.016	0.026
Right NAcc Slope	0.022	0.098	0.173	0.161	0.112	0.155
Left PFC Int.	0.071	0.160	0.171	1.266	0.092	0.415
Left PFC Slope	-0.600	0.937	2.133	7.409	1.448	2.499
Right PFC Int	0.069	0.084	0.124*	0.061	0.097	0.149
Right PFC Slope	-0.292	0.549	1.103*	0.388	0.837	0.957

Note. In all our prediction models, we controlled for gender differences in intercept and slope factors as well as possible age and gender differences in identity dimensions. If these covariates were non-significant, they were trimmed from the models for reasons of parsimony. BAS = Behavioral Activation System, Int. = intercept, NAcc = Nucleus Accumbens, PFC = Pre-frontal cortex, *p* <.05. **p<.01. ***p* <.001.

Study 2

To replicate findings of Study 1 and investigate underlying neural mechanisms of identity, we examined a second sample of adolescents.

Method

Participants and procedure. Participants were 138 Dutch adolescents (69 boys, M_{age} T1= 14.70 year, SD = 1.79) who took part in a large longitudinal study named Braintime. The initial sample of Braintime consisted of 299 participants aged between 8-25 years at T1 (for details, see Braams et al., 2015; Peters et al., 2016). For the present study, focussing on identity in adolescence, and the validity of our identity measure (i.e., U-MICS; Crocetti et al., 2008) aimed at assessing identity during adolescence and early adulthood, we included a sample of adolescents only. To this end, we selected data for participants who were aged between 12 and 22 years across the three measurement waves, resulting in a sample of 138 adolescents. At T1, these adolescents' age ranged between, 12.05 and 17.91 years. We used questionnaire data (for replication of Study 1) and structural brain data from Waves 1 through 3 with two-year intervals between assessment waves. Six months later (Wave 4), adolescents' identity was assessed. These measurement points will be further referred to as Waves 1 through 4, respectively. When participants came to the lab for the scan session, they were instructed to lie as still as possible during the whole scan period. They could watch a movie of their choice during the high resolution structural scan, which was administered at the end of the scan session. Adolescents received €30 (equivalent to approximately US $32) for participation at each time point. Written informed consent for the study (i.e., parental consent and participant assent for adolescents) was provided at each time point. The medical ethical committee of the Leiden Medical Centre approved study procedures. All participants were right-handed, and reported no neurological or

psychiatric impairment at Wave 1. Missing value analyses indicated that 83% of possible data points were completed by the adolescents across waves. Little's MCAR test revealed a chi-square (χ^2/df) of 1.08, indicating that it is unlikely that results were biased as a result of missing values. Therefore, missing data were handled using FIML.

Measures.

Identity. Similar to Study 1, adolescents reported on their identity at Wave 4 using the U-MICS (Crocetti et al., 2008). Cronbach's alpha was .88, .76, and .92 for commitment, exploration in-depth, and reconsideration, respectively.

Goal-Directedness. As in Study 1, adolescents reported on their goal-directedness using the Dutch version of the BAS Drive subscale of the BIS/BAS questionnaire (Carver & White, 1994). Cronbach's alpha was .60, .53, and .72 for Waves 1 through 3, respectively.

Neuroimaging. All participants were scanned on the same 3T MRI scanner. The longitudinal pipeline in Freesurfer 5.3 (http://surfer.nmr.mgh.harvard.edu/) was used for cortical surface reconstruction and volumetric segregation. Per hemisphere, 31 cortical structures were labelled. All images were visually inspected after processing (longitudinal pipeline) for accuracy (e.g., Mills & Tamnes, 2014). Poor quality scans were excluded and high quality scans were reprocessed through the longitudinal pipeline. Note that also single time points were processed longitudinally. We repeated this quality-control procedure until only acceptable scans were included in the processing. No manual editing was performed. From the 404 available scans, we excluded 37 scans. In total, 367 scans were of good quality; 109 participants had scans at three waves, 18 had scans at two waves, 4 had a scan at one wave, and 7 had no available scan of good quality; hence, data of 131 participants were used in the analyses of structural brain data.

Scan acquisition parameters and a detailed description of the structural analyses can be found in the supplementary information S.3.

Regions of interest. We derived the measure of grey matter volume for the NAcc by using the volumetric segmentation procedure. Grey matter volume was obtained using the surface-based reconstructed image. PFC was defined by combining the following subdivisions: rostral middle frontal, caudal middle frontal, caudal anterior cingulate and superior frontal (Mills et al., 2014). We conducted separate analyses for both left and right NAcc and PFC.

Results

Means, standard deviations and correlations among Study 2 variables can be found as online supplementary material S.4.

Development of goal-directedness and identity. To replicate Study 1 findings, we investigated whether intercept and linear slope in adolescents' reported BAS Drive across three waves predicted identity six months later. Parameter estimates of intercept and slope predicting identity are reported in Table 1.

As in Study 1, BAS Drive remained stable across adolescence, intercept = 10.93, $p < .001$, $\sigma = 3.05$, $p = .052$, linear slope 0.58, $p = .512$, $\sigma = 15.33$, $p = .368$. Intercept and slope were not significantly related, -4.83, $p = .399$, indicating that the rate of change in BAS Drive was not associated with the initial level of BAS Drive. Boys and girls did not differ on intercept, $b = 0.33$, $p = .597$ and slope, $b = -1.70$, $p = .344$ of BAS Drive. Consistent with our findings from Study 1, adolescents who reported higher initial levels of BAS Drive reported relatively stronger commitments. In contrast to Study 1, higher initial levels of BAS Drive predicted more exploration in-depth as well. Initial level of BAS Drive was not significantly related to

adolescents' reconsideration of identity commitments. Also in contrast to Study 1, the linear slope of BAS Drive was not related to commitment, exploration in-depth and reconsideration.

Structural brain changes and identity. To test whether structural brain changes in volume of the NAcc and PFC related to adolescents' identity one wave later, we conducted four separate growth curve models (i.e., a model for left NAcc, a model for right NAcc, a model for left PFC, and a model for right PFC). Based on the intercept and linear slope factors of these brain volumes we predicted adolescents' identity six months later. Parameter estimates of NAcc and PFC volume intercept and slope predicting identity are reported in Table 1. The observed individual volume trajectories and average trajectories of left and right NAcc and PFC are presented in Figure 2.

NAcc Grey Matter Volume. Due to previous inconsistency in empirical findings concerning the developmental trajectory of the NAcc, we explored the developmental changes of NAcc volume. We found, that, on average, NAcc volume did not significantly change across adolescence, left NAcc intercept 5.81, $p < .001$, $\sigma = 1.28$, $p = .546$, linear slope -0.43, $p = .405$, $\sigma = 0.39$ $p = .994$, right NAcc intercept 6.62, $p < .001$, $\sigma = 0.89$, $p = .019$, linear slope -0.76, $p = .054$, $\sigma = 0.62$, $p = .884$. Intercept and slope were not significantly related for left NAcc volume, $b = -0.24$, $p = .984$, and right NAcc volume, $b = -0.51$, $p = .696$. These findings imply that the relative change in NAcc volume was not associated with the initial level of NAcc volume. Boys and girls did not differ on initial left NAcc volume, $b = .63$, $p = .053$ or change over time, $b = -.18$, $p = .841$. Yet, boys had higher initial right NAcc volume, $b = .97$, $p = < .001$, but a similar rate of change in right NAcc volume, $b = -1.20$, $p = .090$, relative to girls.

Adolescents with higher initial volume of NAcc (both left and right NAcc) reported stronger identity commitments at Wave 4. In addition, higher initial volume of the left (but not

right) NAcc predicted less identity reconsideration six months later. Finally, when adolescents showed a stronger increase in left NAcc volume over time they reported more exploration in-depth six months later but this finding was not found for right NAcc volume.

     PFC Grey Matter Volume. PFC volume decreased during adolescence, left PFC intercept 5.92, $p <.001$, $\sigma = 0.37$, $p = .002$, linear slope -1.01, $p = .001$, $\sigma = 0.12$, $p = .927$, right PFC intercept 6.00, $p <.001$, $\sigma = 0.43$, $p <.001$, linear slope -0.91, $p = .006$, $\sigma = 0.18$, $p = .910$. Intercept and slope were non-significantly related for left PFC volume, $b = -0.08$, $p = .847$ and right PFC volume, $b = -0.11$, $p = .748$. These findings demonstrate that the rate of change in PFC volume was not associated with the initial level of PFC volume. Boys' initial left PFC volume was higher, $b = .57$, $p = .001$, as well as boys' initial right PFC volume, $b = .68$, $p <.001$. However, the rate of change was similar for boys and girls, for left PFC, $b = -.19$, $p = .662$, and right PFC, $b = -.02$, $p = .976$.

     A higher intercept of right (but not left) PFC volume was related to more exploration in-depth. Moreover, when adolescents showed a weaker decreasing right PFC volume (i.e., they kept relatively higher volume levels across a longer period of time compared to other adolescents), they reported relatively more exploration in-depth six months later. However, individual differences in left PFC volume intercept and change were not significantly related to exploration in-depth. Hence, findings were not replicated across left and right PFC. Moreover, left and right PFC volume intercept and slope were not related to commitment and reconsideration of identity commitments.

Discussion

     The purpose of Study 2 was to replicate findings based on self-reported goal-directedness of Study 1 and to investigate the relationship between structural brain changes and subsequent

identity. First, Study 2 partially replicated findings from Study 1, using self-reports, by showing that adolescents' who engaged in goal-directedness developed stronger identity commitments and explored these commitments more in-depth in order to maintain their commitments. Second, we showed that structural changes in NAcc and PFC during adolescence related to later identity. Specifically, higher baseline differences in both left and right NAcc volume positively predicted later identity commitments. Increase in left NAcc volume over time predicted more in depth-exploration but this finding was not found for right NAcc volume. Furthermore, adolescents with higher initial levels of right (but not left) PFC volume as well as less steeply decreasing right (but not left) PFC volume over time showed more in-depth exploration of their identity commitments.

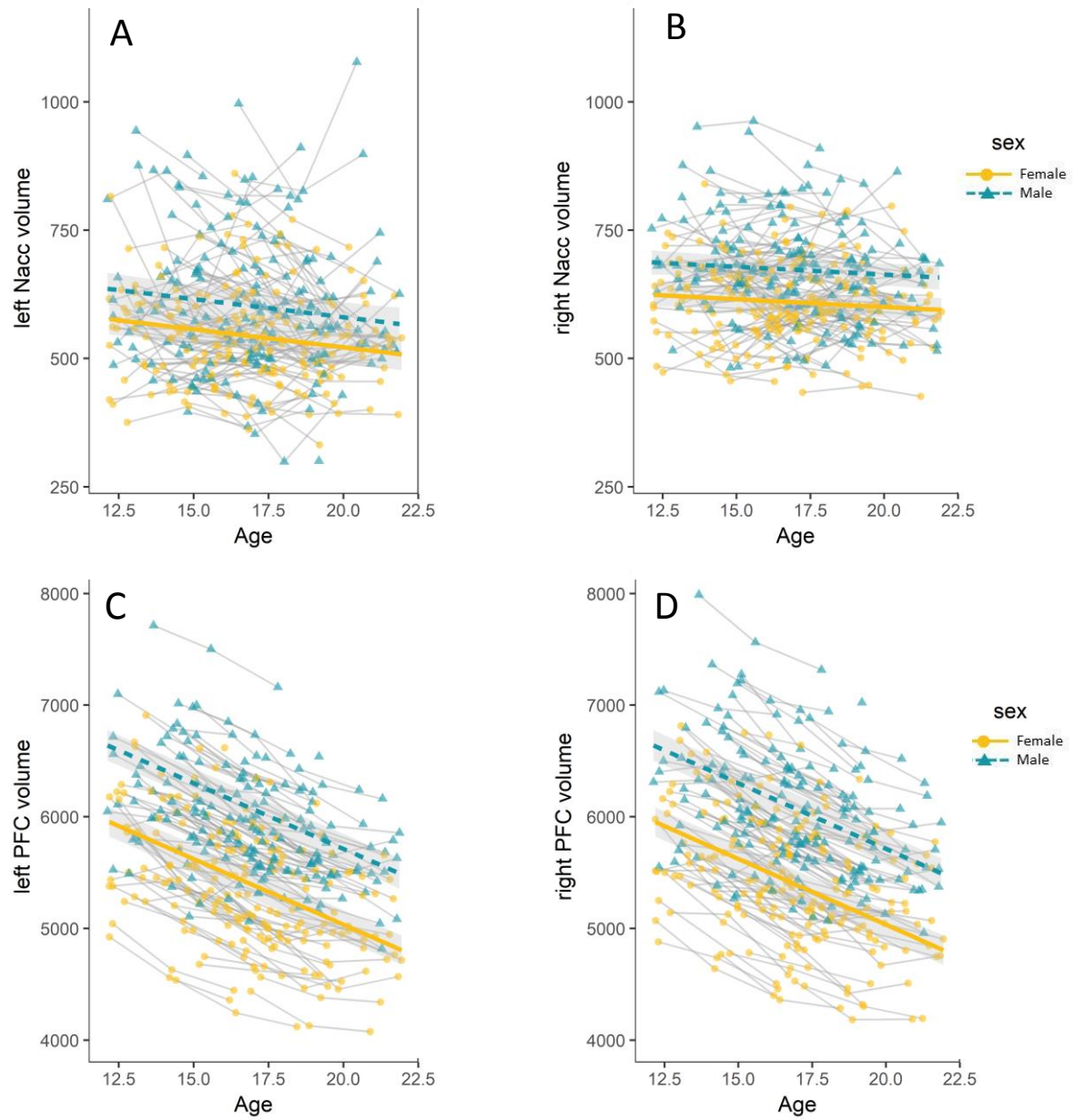*Figure 2*. Observed individual volume (in mm^3) trajectories and average trajectories for (**A**) Left NAcc, (**B**) right NAcc, (**C**) left PFC, and (**D**) right PFC volume. Shaded areas represent 95%CI. Raw mean scores for NAcc and PFC volume are displayed.

General Discussion

This longitudinal multi-sample study investigated how subcortical and cortical regions involved in goal-directedness and information seeking behavior relate to adolescents' identity. Previous studies on adolescents' identity formation suggested the importance of goal-directedness and active information seeking to explore, develop, and maintain strong identity commitments (e.g., Burrow et al., 2010; Marcia, 1966; Schwartz et al., 2005). While adolescents' search for identity is accompanied by, and perhaps also facilitated by changes in brain structure, empirical studies investigating structural brain changes and identity are lacking. In this study, we combined a large-scale questionnaire and a structural brain development study. We applied a two-step approach to investigate the longitudinal associations between brain regions, goal-directedness, and identity. In the first step, we showed that individual differences in developmental trajectories of self-reported goal-directedness predicted later identity. These findings were partially replicated in a second longitudinal adolescent sample. In the second step, we extended these self-reported findings to the neural level by showing how individual differences in initial level and change of NAcc and right PFC grey matter volume predicted adolescents' later identity.

Goal-Directedness and Identity

Our longitudinal self-report findings from Study 1 and Study 2 indicated that adolescents who showed higher initial levels of goal-directedness reported relatively stronger identity commitments, explored these commitments more in-depth and were less uncertain about their commitments. We also found that increasing goal-directedness over time predicted stronger identity commitments, more in-depth exploration and less reconsideration (e.g., Burrow et al., 2010; Schwartz et al., 2005) but these findings were not replicated in Study 2. Goal-directedness

might facilitate the identity exploration process, which is an important predictor for the formation of identity commitments (Luyckx et al., 2006). For example, when adolescents start questioning and evaluating what type of study or work they want to do later in life, adolescents with a strong goal-orientation may be more likely to commit to possible identity choices and to explore them actively to determine what type of study or work suits them. In Study 1 and Study 2 we found that higher initial level in goal-directedness positively predicted later identity commitments.

Findings regarding in-depth exploration and reconsideration were not consistent across studies. That is, few associations replicated across Study 1 and Study 2, especially with respect to the linear slopes that were not significant in Study 2. One possible explanation for this discrepancy in findings might result from the difference in sample size between Study 1 and Study 2. Generally, smaller sample sizes tend to produce larger standard errors, resulting in less power to detect a significant effect. Moreover, the larger age heterogeneity at each measurement wave of Study 2 might also have increased the standard errors of the linear slopes, which makes it less likely to identify a significant linear slope. However, the sign of the slopes (indicating negative or positive change) was not always consistent across Study 1 and Study 2 either. Therefore, future studies are needed to replicate our findings. An important question that remains to be answered is the sequence of identity formation processes, which could not be answered in the current study because identity was measured only at the latest wave. Future work should further investigate the consecutive steps of identity formation, to see whether changes in goal-directedness predict changes in identity exploration, which in turn predict stronger identity commitments. In sum, findings from Study 1 and Study 2 suggested that self-reported goal-

directedness consistently predicted identity commitments. Findings for exploration in-depth and reconsideration were not consistent across Study 1 and Study 2.

Developmental Trajectories of NAcc Volume, and PFC Volume

At the neural level, we tested the relationship between trajectories of change in NAcc and PFC volume, on the one hand, and subsequent identity, on the other. First, we found that NAcc (both left and right) grey matter volume remained stable across three waves, which partially replicates previous findings. For example, similar to our findings, right NAcc grey matter volume has been found to be stable across two waves (Urošević et al., 2012), although decreases have been reported as well (Dennison et al., 2013). Prior studies also reported different findings for left NAcc volume development. For example, one study found a decrease during young adulthood across two waves (Urošević et al., 2012) whereas another study reported increased left NAcc across two waves (Dennison et al., 2013).

These discrepancies in findings might have resulted from differences in the age range of participants between studies. With respect to age, the developmental mismatch model would predict that subcortical regions (such as the NAcc) develop earlier relative to cortical regions (Somerville, Jones, & Casey, 2010). Thus, volume of subcortical regions may show a linear increase early in adolescence, and then stabilize later in adolescence. Consistent with this idea, Urošević et al. (2012) found that left NAcc increased in early adolescence (ages 9-12 years) but stabilized during late adolescence (13-17 years), and decreased in young adulthood. Hence, future studies need to include a broader age range from childhood through young adulthood to further investigate the developmental shape of NAcc. Because the NAcc is a small structure, challenges exist concerning its measurement that might also explain inconsistencies regarding the shape of NAcc volume development (Mills et al., 2014). To further our understanding of

developmental trajectories of the NAcc during adolescence, future research should include at least four or more waves of measurement to increase statistical precision (Muthén & Curran, 1997) and be able to identify the shape of NAcc volume development (i.e., linear, quadratic, and cubic).

Highly consistent findings were observed for PFC over time. In line with prior studies, we found a decrease of PFC grey matter volume across adolescence (e.g., Gogtay et al., 2004; Mills et al., 2014). Changes were highly comparable for left and right PFC volume over time (e.g., Mills, Lalonde, Clasen, Giedd, & Blakemore, 2014).

Developmental Trajectories of NAcc Volume, PFC Volume, and Identity

To augment our understanding of the neurobiological processes underlying adolescents' identity, we conducted latent growth curve models to investigate how individual differences in NAcc and PFC volume predicted identity. Results showed that higher levels of left and right NAcc volume were associated with stronger identity commitments six months later. In addition, higher levels of left NAcc volume were related to less identity reconsideration six months later. These brain structure findings from Study 2 add to the self-reported findings from Study 1 and previous questionnaire studies, by showing that goal-directedness and its presumed underlying neurological substrates are associated with adolescents' identity formation (e.g., Burrow & Hill, 2011). Past studies have also found that adolescents with increasing NAcc grey matter volume reported relatively more goal-directedness and goal pursuit (Urošević et al., 2012).

Our findings might also further stimulate research on lateralization of the human brain. In general, inconsistent findings in differential functions between the left and right human brain have been reported, except for lateralization for language (Willems, Van der Haegen, Fisher, & Francks, 2014). For NAcc specifically, it has been found that increase in left (but not right)

NAcc was related to higher levels of BAS Drive (Urošević et al., 2012). This finding was similar to our finding that left increase in NAcc was related to more in-depth exploration but not right NAcc. Correlations between left and right NAcc ranged between .26 and .41, which suggest that left and right NAcc are correlated but also differ substantially. Future studies should further test the unique associations of left and right NAcc and identity formation processes. Our results add to the growing brain-behavior literature by showing that neurobiological underpinnings of goal-directedness (i.e., the NAcc) are positively related to adolescents' later commitment making and negatively related to reconsideration of identity commitments.

Together, these findings suggest that different brain regions are involved in different processes of identity formation as described by the identity process model (Crocetti et al., 2008). That is, especially individual differences in initial levels of the left and right NAcc volume were most consistently involved in the process of identity *formation*, also referred to as the *identity formation* cycle. In this cycle, adolescents form commitments by considering and reconsidering them (Crocetti et al., 2008; Luyckx et al., 2006). This cycle constitutes two opposing forces of Erikson's (1968) dynamic of identity synthesis (forming commitments) versus identity confusion (questioning identity commitments). The NAcc has been related to goal-orientation and motivated behavior (e.g., Urošević et al., 2012). Therefore, individual differences in NAcc volume may especially facilitate the process of pursuing and making certain identity commitments, which is central to the identity formation cycle.

In contrast, individual differences in PFC volume were related to processes involved in the *maintenance cycle* of identity formation. The PFC has been involved in information seeking and cognitive control (Casey, 2015). Our empirical findings further support this function of the PFC. Specifically, we found that adolescents with greater right PFC volume at baseline were

more involved in in-depth exploration of the commitments they already have by actively reflecting on their identity choices, and searching for information about these commitments. Also, adolescents who showed a less steep decrease in their right PFC volume reported higher levels of exploring their commitments in-depth. These findings seem to further confirm the role of the PFC in several behaviors that involve certain levels of cognitive control (Casey, 2015). For example, more PFC grey matter volume has been related to more long-term goal-orientation, self-reflection (Blakemore, & Choudhury, 2006), and information seeking behaviors (Casey, 2015). In-depth exploration of identity commitments, involving active reflection upon current commitments, is one such task involving these aspects of cognitive control (e.g., Crocetti et al., 2008; Meeus et al., 2010). Consistent with this role of the PFC, those adolescents with less steeply decreasing PFC volume, and thus relatively more volume across adolescence, were more actively thinking and gathering information about their identity commitments. Our findings that continued higher levels of grey matter volume were related to a stronger identity seem to support a popular neuroscience perspective on adolescent development. According to this perspective, brain changes during adolescence might not only explain increased risk taking but also increasing flexibility to change and adaptation (Casey, 2015; Crone & Dahl, 2012). The formation of a stable sense of identity can be considered one such complex but important adaptive task in order to prepare for adult roles (Blakemore & Mills, 2014; Erikson, 1968).

Interestingly, the results showed that developmental changes in grey matter volume occur within relative stability. That is, when adolescents started with higher grey matter volume compared to their peers, most adolescents kept this position across adolescence. As such, these intercept differences might reflect a certain window of opportunity and plasticity for adolescents to develop a strong identity. Specifically, adolescents with higher initial grey matter volume or

less steep decreasing grey matter volume, might have a larger window of opportunity to explore their identity compared to adolescents with lower levels of grey matter volume. It remains to be empirically tested how changes in brain regions and identity processes influence each other over time. Specifically, an important task for future work is to investigate the temporal order of brain-behavior associations over time.

Strengths, Limitations, and Future Directions

This study has several important strengths. First, our multi-sample design allowed us to test our hypotheses in two independent adolescent samples, supporting the replicability of our findings. Second, the longitudinal design of both studies allowed us to investigate how both individual differences at baseline and individual differences in developmental change in goal-directedness and structural brain regions related to identity. Third, both studies had a relatively large sample, which increases the accuracy of our estimates. Fourth, this multi-method study examined both self-reported measures and neuroimaging data, an approach selected for furthering understanding of brain-behavior associations (e.g., Mills et al., 2014).

This current study also had some limitations. First, despite longitudinal assessment of NAcc and PFC volumes across three waves, we assessed identity as an outcome at one later time point, prohibiting us from controlling for stability in identity dimensions in previous waves. Future studies should test concurrently ascertained correlated change and bidirectional associations between structural brain volume and identity to investigate possible developmental order. Second, we assessed goal-directedness at a global rather than a domain specific level, yet levels of goal-directedness can vary substantially across different content domains (Deci & Ryan, 2000). For example, adolescents' drive of doing well in school may be a particularly important predictor of identity commitment making. Third, we only investigated structural

differences in NAcc, PFC and identity, whereas profound changes in functional connectivity of subcortical and cortical regions, such as those involved in reward responses (e.g., van Duijvenvoorde et al., 2016) occur in adolescence. While we found that structural differences in NAcc predicted adolescents' identity commitment making, some adolescents may experience more feelings of reward when making identity commitments. Future work could test this hypothesis by investigating how individual differences in functional connectivity in reward processing regions relate to adolescents' commitment making. Fourth, we averaged across four subdivisions in the PFC: rostral middle frontal, caudal middle frontal, caudal anterior cingulate and superior frontal, allowing direct comparison with Mills et al. (2014). While our results showed highly consistent developmental trajectories with past work, future work should examine differentiation between PFC subregions. We also focused primarily on lateral PFC given its hypothesized relation with goal-directedness, but medial PFC may be more important for internalized deliberation about the self (Crone & Steinbeis, 2017). Finally, both studies used data from adolescents of relatively high SES families living in The Netherlands. Thus, findings based on self-report measures may not generalize to adolescents living in other countries or from lower SES families.

Conclusion

The present study is one of the first to combine longitudinal assessment of brain development and psychosocial data offering a novel perspective on the neurobiological development underlying adolescents' identity formation. We used a comprehensive assessment of processes related to identity development by relating both the trajectory of goal-pursuit as well as NAcc and PFC structural development to adolescents´ subsequent identity. Our findings confirmed the hypothesis that adolescents' views about their identity are predicted by the

developmental trajectories of level and change of self-reported goal-pursuit and structural brain regions. Adolescents with higher goal-pursuit and higher NAcc volume reported stronger identity commitments and less uncertainty about these commitments. Moreover, adolescents with higher PFC volume and more protracted PFC volume development reported more reflection on their identity commitments in order to strengthen and maintain them. The current findings are the first evidence of brain-behavior relations involving adolescents' identity formation, and set the stage for future longitudinal studies of linkages between white brain matter and other indices of neural function (e.g., resting state connectivity) on the one hand and identity on the other.

Online supplementary material S.1

Because adolescents in both studies varied significantly in age at each measurement wave, we applied a model where individually varying times of observations could be estimated (i.e., TSCORES option in M*plus*, Muthén & Muthén, 1998-2012). In conventional LGM, it is assumed that data are collected at an identical set of fixed ages for all individuals (Mehta & West, 2000). In these models, slope factor loadings of a linear slope are fixed across all individuals to be 0, 1, 2, for Waves 1-3, respectively. However, with the TSCORES option the LGM takes into account heterogeneity in age at each measurement wave. That is, rather than defining linear growth with fixed factor loadings, age is now included in the model as a defining variable to scale the factor loadings and estimate the growth curve. Consider the example where we put the intercept at age 12 years. In this example, the starting point of the developmental trajectory is set at age 12 by fixing the factor loading for each observed measure for each individual to reflect deviation in years from age 12. Therefore, because adolescents vary in age at each measurement wave, the factor loadings are unique to each individual. For instance, an adolescent with an actual age of 12 years at the first measurement wave will obtain the linear slope factor loadings of 0, 1, and 2 for age 12, 13, and 14 years, respectively. However, an adolescent aged 15 years at the first measurement wave will obtain linear slope factor loadings of 3, 4, and, 5 for age 15, 16 and 17 years, respectively. Thus, each individual contributes to the estimation of parts of the growth trajectory for ages at which he or she does provide data (please see Mehta & West, 2000 for a detailed discussion of modelling individually varying times of observations).

Table S.2

Means, Standard Deviations, and Correlations of BAS Drive, and Identity (Study 1)

Variable	*M*	*SD*	2.	3.	4.	5.	6.
1. BAS Drive T1	12.54	1.95	.26***	.18***	.04	.06	-.08
2. BAS Drive T2	12.50	1.95		.39***	.09	.06	-.07
3. BAS Drive T3	12.64	2.14			.23***	.21***	-.15**
4. COM. T4	3.57	0.72				.56***	-.41***
5. EXP. T4	3.21	0.65					-.08
6. REC. T4	2.02	0.81					

Note. BAS = Behavioral Activation System, COM = commitment, EXP = exploration in-depth, REC = reconsideration.
*p <.05. **p<.01. ***p <.001.

Online supplementary material S.3

Tesla Philips Achieva MRI system, with a standard whole-head coil (Philips, Best, The Netherlands) at Leiden University Medical Centre. High-resolution T1-weighted anatomical scans were acquired (TR=9.8 ms, TE = 4.6 ms, flip angle = 8°, 140 slices, 0.875 mm x 0.875 mm x 1.2 mm, and FOV = 224 x 177 x 168 mm). Scan time for the anatomical scan was 296 s. A radiologist evaluated all T1 scans and no anomalous findings were reported. With respect to image processing, cortical reconstruction was performed with the longitudinal stream (Reuter et al., 2012) in FreeSurfer 5.3, a program for cortical surface reconstruction and volumetric segmentation (http://surfer.nmr.mgh.harvard.edu/). The procedure and technical details are described elsewhere (Fischl, Sereno, & Dale, 1999a; Fischl, Sereno, Tootell, & Dale, 1999b; Reuter, Schmansky, Rosas, & Fischl, 2012). To extract reliable volume estimates, an unbiased within-subject template space and image (Reuter & Fischl, 2011) is created using robust inverse consistent registration (Reuter et al., 2010). Several processing steps, such as skull stripping, Talairach transformation, atlas registration as well as spherical surface maps and parcellations are then initialized with common information from the within-subject template, significantly increasing reliability and statistical power (Reuter et al., 2012).

Parcellation of the cortex into gyral regions was based on the Desikan-Killiany-Tourville atlas (Klein & Tourville, 2012). This labelling process involved surface inflation (Fischl et al., 1999a) and registration to a spherical atlas based on subject specific cortical folding patterns (Fischl et al., 2004a, b).

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Table S.4

Means, Standard Deviations, and Correlations of BAS Drive, NAcc, PFC, and Identity (Study 2)

	Predictor	M	SD	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
1.	Bas Drive T1	10.79	2.20	.52***	.21*	-.02	-.04	-.05	.02	.03	-.08	-.02	-.00	-.05	-.02	-.07	-.05	.14	.18*	-.12
2.	Bas Drive T2	11.00	1.91		.42***	.04	-.03	-.07	.01	.06	.04	.03	.02	.06	.05	.08	.06	.08	.05	.23*
3.	Bas Drive T3	11.57	2.26			-.12	.05	-.05	.02	-.04	-.04	-.08	-.04	-.09	-.06	-.08	-.06	.48***	.30***	-.08
4.	Left NAcc T1	5.94	1.28				.26**	.79***	.38***	.84**	.34***	.19*	.16	.22*	.19*	.25**	.22*	.17*	-.03	-.26**
5.	Right NAcc T1	6.47	0.98					.25**	.80***	.36***	.80***	.48***	.52***	.50***	.53***	.52***	.54***	.14	-.05	-.03
6.	Left NAcc T2	5.59	1.12						.36***	.81***	.35***	.21*	.21*	.22*	.23*	.25**	.23*	.16	-.03	-.14
7.	Right NAcc T2	6.41	0.90							.40***	.77***	.44***	.48***	.47***	.50***	.51***	.53***	.25**	.03	-.10
8.	Left NAcc T3	5.64	1.20								.41***	.22*	.18*	.24**	.20*	.26**	.21*	.13	-.03	-.14
9.	Right NAcc T3	6.35	0.93									.43***	.44***	.44***	.45***	.49***	.48***	.19*	.01	-.05
10.	Left PFC T1	5.89	0.63										.94***	.97***	.91***	.96***	.89***	.22*	.11	-.09
11.	Right PFC T1	5.98	0.67											.93***	.97***	.93***	.96***	.22*	.07	- .08
12.	Left PFC T2	5.63	0.62												.95***	.97***	.91***	.21*	.10	-.08
13.	Right PFC T2	5.73	0.66													.93***	.97***	.20*	.05	-.10
14.	Left PFC T3	5.43	0.57														.95***	.25**	.07	-.15
15.	Right PFC T3	5.51	0.62															.23*	-.03	-.16
16.	COM. T4	3.75	0.55																.42***	-.54***
17.	EXP. T4	3.31	0.53																	-.18*
18.	REC. T4	1.81	0.80																	

Note. BAS = Behavioral Activation System, NAcc = Nucleus Accumbens, PFC = Pre-frontal cortex, COM = commitment, EXP = exploration in-depth, REC = reconsideration. Raw mean scores for NAcc and PFC volume have been transformed to facilitate reliable estimation of parameter estimates. To obtain the original raw scores again please multiply NAcc by 100 and PFC by 10000.
*p <.05. **p<.01. ***p <.001.