**Within-Person Imbalance of Reward Sensitivity
and Executive Functioning: A Longitudinal Examination
of the Dual Systems Model From Childhood to Adulthood**

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Acknowledgments

Dedication

This work is dedicated to Humberto Alonso Lozano. Greatly loved, deeply missed,

forever in our hearts.

Abstract

The dual systems model of adolescent development asserts that the neurobiological systems underlying reward/motivational processes and cognitive control mature at different rates, resulting in an "imbalance" during adolescence whereby adolescents are biased toward rewards but unable to exert sufficient executive control in risk-taking contexts. While an imbalance between these systems is central to the dual systems model, few studies have investigated longitudinal trajectories within and between each system with age. Therefore, this investigation assessed the developmental trajectories of the reward and control systems, and directly quantified within-person differences between these systems using an accelerated longitudinal design including 166 individuals, ages 9-32, assessed biennially up to five times. Results indicate that self-reported reward sensitivity and laboratory-based executive function abilities increase rapidly during early adolescence and plateau by early adulthood. Our findings also demonstrate differences between reward and control systems that change significantly through adolescence and stabilize in early adulthood. This trajectory provides evidence of a functional gap during adolescence whereby reward processes outpace capacities for executive control in early adolescence. However, by mid-adolescence and into early adulthood, the developmental mismatch between these systems favors EF capacity. Collectively, the present report offers a novel and important contribution to our understanding of adolescent development and suggests the ability to exert top-down regulatory control over incentive-reward motivation emerges by middle adolescence. Future directions include investigating how within-person differences between reward and control systems are associated with risk-taking behaviors.

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1. Introduction

Adolescence is a period of marked social, biological, cognitive, and psychological change (Casey et al., 2008; Ernst et al., 2006), including an increased prevalence of risk-taking behaviors, which peak worldwide during late adolescence (Duell et al., 2018). Increased risk-taking may be due to the manner in which adolescents evaluate information and make decisions, particularly in rewarding or affectively salient contexts (Hartley & Somerville, 2015). These processes, in turn, are influenced by the maturation of neural systems that underpin reward processing, the evaluation of cost-benefit structures, and decision-making (Luciana et al., 2012; Luciana & Collins, 2012).

Incentive motivation is the energizing of instrumental behavior by anticipated reward acquisition (Beckmann & Heckhausen, 2018; Depue & Collins, 1999). These processes are mediated by the midbrain tegmental region, the striatum (namely the nucleus accumbens), core limbic regions, such as the extended amygdala, the anterior cingulate, and medial regions of the orbitofrontal cortex, and are associated with reward-reinforcement learning (via encoding of reward prediction errors) and encoding the incentive salience of stimuli (Braams et al., 2015; Depue & Collins, 1999; Luciana et al., 2012; Wahlstrom et al., 2010). Measures that reflect activity in this system include self-report measures of reward sensitivity, such as the BIS/BAS Scale (Carver & White, 1994), and, to some extent, the Sensation Seeking Scale (Zuckerman et al., 1978), as well as behavioral paradigms such as the Monetary Incentive Delay task (Knutson et al., 2000), gambling tasks (Bechara et al., 1994; Rogers et al., 1999; Sinz et al., 2008; Van Leijenhorst et al., 2008), and other fMRI tasks (Silverman et al., 2015). Extant research suggests that the development of the reward system exhibits a quadratic pattern of age-related variation,

with a distinct peak in mid-adolescence (Braams et al., 2015; Harden & Tucker-Drob, 2011; Romer & Hennessy, 2007; Silverman et al., 2015; Steinberg et al., 2008; Urošević et al., 2012).

In contrast, the cognitive control system encompasses executive functions (EFs), which include the suppression of competing goal-irrelevant information (i.e., inhibitory control), active maintenance or updating of goal-relevant information (i.e., working memory), and fast and flexible adaptation to changing circumstances (i.e., behavioral flexibility) (Miyake et al., 2000). Higher-order EFs, such as reasoning, problem-solving, and planning, are built from these core EFs (Diamond, 2013). These processes are mediated by the dorsolateral prefrontal cortex, anterior cingulate cortex, parietal cortex, and dorsal striatum (D'Esposito & Postle, 2015; Geier, 2013; Miller, 2000). Substantial past research suggests a protracted, largely linear maturational pattern of these abilities through adolescence (Luciana et al., 2005; Luna et al., 2004; Shulman et al., 2016; Somerville et al., 2011; Veroude et al., 2013; Weiss & Luciana, 2022).

Taken together, the dual systems model of adolescent development posits that adolescents are biased to respond vigorously to rewarding and novel experiences due to the more rapid maturation of the reward system relative to the cognitive control system (Casey et al., 2008; Ernst et al., 2006; Luciana & Collins, 2012; Steinberg, 2008). In this context, adolescents' cognitive control abilities may not be equipped to regulate motivated decision-making (Luciana & Collins, 2012), which may predispose adolescents toward risky behaviors. However, there is presently a dearth of longitudinal research examining concurrent developmental changes in these two systems, and such studies are necessary to validate the putative developmental imbalances of these systems during adolescence.

Moreover, in their review of analytic methods used in dual systems investigations, Meisel and colleagues (2019) suggest that difference score approaches (i.e., observed difference scores between indexes of each system) provide a straightforward operationalization of the posited imbalance between these systems that can serve as a predictor of risk behavior (as in Vazsonyi & Ksinan, 2017) and may more optimally characterize a potential developmental gap between these systems when compared to the additive or interactive models historically used. If a gap between these systems is observed to vary as a function of age (e.g., during early-, middle-, or late-adolescence), prevention strategies designed to mitigate maladaptive decision-making could be devised. If, on the other hand, reward bias characterizes only some individuals in a trait-like fashion, prevention efforts would be more appropriately directed toward specific individuals and perhaps specific contexts.

Accordingly, the present study investigated the developmental trajectories of the reward and control systems, and within-person differences between these systems in individuals aged nine to 30 years using an accelerated longitudinal design (ALD), including up to five biennial assessments for each participant. To our knowledge, this is the first study to examine longitudinal changes of directly quantified differences between reward and control systems between late childhood and early adulthood. Consistent with the dual systems model, we hypothesized that: 1) the development of the reward system would approximate a quadratic curve, with a peak in mid-adolescence (Harden & Tucker-Drob, 2011; Luciana et al., 2012; Schreuders et al., 2018; Steinberg, 2008; Van Leijenhorst et al., 2010); 2) the control system would exhibit a linear or inverse trajectory (Cowan et al., 2011; Luciana et al., 2005; Luna, 2009; Luna et al., 2004); and 3) the within-person difference between these systems would follow a quadratic function of age, consistent with

peaks in risk-taking behavior observed in adolescence (Duell et al., 2018). We also examined biological sex effects, given that males exhibit greater risk-taking behaviors, including a higher rate of fatal accidents (National Center for Health Statistics, 2023), gambling (Wong et al., 2013), and crime (Smith, 2014). Likewise, males also appear to exhibit higher levels of sensation seeking and impulsivity (e.g., Cross et al., 2011, 2013; Moffitt et al., 2013), and a longitudinal investigation demonstrated sex differences in the growth process of these systems, including a relatively earlier peak and a steeper decline in sensation seeking in females, and a slower rate of impulse control development in males during adolescence (Shulman et al., 2015).

2. Methods

2.1 Sample

This study was approved by the University of Minnesota's institutional review board (IRB: study 0405M59982). Participants provided written consent (if aged 18 or older) or parent permission with child assent (for those younger than age 18) according to local IRB requirements. Participants under the age of 18 years were recruited from a community-based volunteer database managed by the University's Institute of Child Development or via postcards mailed to university non-academic staff members who might be parents. Participants over the age of 18 years were recruited via mailed postcards and posted flyers. Inclusion criteria at baseline included being in the desired age range (9-23 years), native English language, normal to corrected-to-normal vision and hearing, and right-handedness (assessed via the Edinburgh Handedness Inventory; Oldfield, 1971). Baseline exclusion criteria included a history of diagnosed neurological or psychological illness, significant head injury, intellectual disability or learning difficulties, birth

complications, chronic illness, or current MRI contraindications. Inclusion/exclusion criteria were determined through a clinical interview (Kaufman et al., 1997) and an in-lab health questionnaire. Baseline data collection began in late 2004 and ended in 2016. Participants were invited to complete follow-up assessments approximately every two years for up to five assessments. Baseline participant demographics are presented in Table 1.

2.2 Measures

2.2.1 Executive function composite

Participants completed a comprehensive cognitive battery at each assessment. As an index of cognitive control, we generated a composite score of executive ability composed of an individual's performance on several tasks that measure various components of EF (Luciana et al., 2005). These measures include the Stockings of Cambridge and Spatial Working Memory tests from the Cambridge Neuropsychological Test Automated Battery (CANTAB [Cognitive assessment software], Cambridge Cognition, www.cantab.com; Owen et al., 1990), Digit Span from the Wechsler Intelligence Scale for Children, 3rd edition (WISC-III; Wechsler, 1991), and a Spatial Delayed Response Task (DRT; Luciana et al., 1998, 2005; Luciana & Collins, 1997).

The CANTAB Stocking of Cambridge test (Owen et al., 1990) is a modified computerized version of the well-known Tower of London test (Shallice, 1982). Similar to the original test, participants were asked to move an arrangement of colored balls hanging in "pockets" or "socks" to match a goal configuration within a set number of moves. As the task progressed, difficulty was manipulated by varying the number of balls used, the complexity of the final configuration, and the maximum number of moves allotted to

achieve the goal arrangement. From this test, we used the total proportion of items during which participants correctly responded within the allotted number of moves (i.e., the proportion of perfect solutions). A high score indicates superior spatial working memory and planning abilities (Luciana & Nelson, 2002).

The CANTAB Spatial Working Memory test (SWM; Owen et al., 1990) is a computerized self-ordered search task that measures one's spatial working memory, self-monitoring, and behavioral self-organization (Becker et al., 2014; Luciana et al., 2005). Participants were asked to search an array of boxes to obtain hidden tokens. Search complexity varied from searches of three to eight boxes. On each trial, a token was hidden in each of the presented boxes at some point. Participants were instructed to search for tokens and remember the locations where past tokens were found. Within a trial, if participants returned to search a box that previously held a token, an error was recorded. We utilized the total number of these "forgetting errors" (also referred to as "between-search" errors) incurred during the 6- and 8-box trials. A high score represents poor performance. From this assessment, we additionally utilized the average strategy score obtained for 6- and 8-box trials. This score indexes the manner in which one's search strategy is organized. A high score represents decreased strategy use (Becker et al., 2014; Luciana et al., 2005; Owen et al., 1990).

During the Digit Span test, participants were presented with auditory sequences of digits under standardized forward and backward conditions (Wechsler, 1991). In the backward condition, participants were instructed to provide the digits in reverse order after span presentations, yielding a measure of verbal working memory. Each level of this assessment provided two trials during which participants were asked to reverse different

spans of equivalent length. If participants provided a correct response for at least one of the trials at a given level of the assessment, they progressed to the next level. We quantified the length of the last backward span correctly achieved.

Finally, the Spatial DRT (Luciana et al., 1998; Luciana & Collins, 1997) is a spatial working memory task that measures working memory for the locations of spatial targets. During this task, participants were seated with sound-damping headphones and an adjustable chin-forehead rest. During each of 32 trials, participants observed a fixation cross for 3 seconds. A visual cue was then presented for 200 milliseconds (ms) in their peripheral view, followed by a blank screen. After a delay period of 500 or 8000 ms, which were interspersed, participants indicated, using a lightpen input device, the screen location of the presented cue. From this task, we calculated an average efficiency score based on individuals' accuracy (i.e., the distance between the indicated locations and actual cue locations) and speed when providing responses to the most difficult 8000 ms delay trials. Higher efficiency scores represent poorer executive abilities (Luciana et al., 2005). Three DRT efficiency scores were extreme outliers (i.e., one value from the baseline observations and two values from the wave two observations were above Q3+3*IQR) and were removed prior to computing composite scores (see below for more details).

All EF variables were converted to standardized Z-scores. Several methods for scaling were considered, including standardizing repeated measures within individuals, across individuals within assessment waves, and across individuals across all assessment waves. Ultimately, we opted to standardize variables using baseline distributions (i.e., using the baseline mean and standard deviation for each variable as a reference) as the baseline sample provided practice-naïve scores for most ages represented in the full sample

(Sullivan et al., 2022). Practice effects have been shown to significantly affect scores of similar cognitive measures (Sullivan et al., 2017). Variables whose raw values indicate poorer executive abilities (i.e. SWM forgetting errors, SWM strategy, and DRT effectiveness) were reverse-scored to yield Z-scores that all reflect relatively better EF with higher scores. Finally, individual EF composites were computed by averaging all available Z-scores. 97% of composite scores were based on Z-scores of all five measures, 2.5% were based on four measures, and less than 1.5% were based on three or fewer measures.

2.2.2 Reward sensitivity

Participants completed self-reported measures of behavior, including Carver and White's (1994) Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) scale. With this scale, participants indicate the degree to which they agree with 24 simple statements using a Likert scale of 1 (very true for me) to 4 (very false for me). The BAS component of this scale is comprised of three subscales – Reward Responsiveness, Drive, and Fun seeking – and holistically measures the behavioral activation system, which regulates appetitive motives, or behaviors in which one seeks out or moves toward something pleasant (Carver & White, 1994). Combined scores from the Reward Responsiveness and Drive subscales were utilized in these analyses as an index of the reward system, as previous research suggests that these subscales reflect broad reward sensitivity (Smillie et al., 2006) and can be used as reliable indexes of individual differences in reward sensitivity (Carver & White, 1994; Hickey et al., 2010; Scheres & Sanfey, 2006; Schreuders et al., 2018; Urošević et al., 2012). The Reward Responsiveness subscale is composed of five items (e.g., "When I get something I want, I feel excited and energized") and reflects how positively one responds to the occurrence or anticipation of

reward, while the Drive subscale is composed of four items (e.g., "I go out of my way to get things I want") and reflects how persistent one is in pursuing desired rewards (Taubitz et al., 2015). In these analyses, items from both subscales were reverse-scored and summed to create a total reward sensitivity score, capturing one's tendency to both like and want rewards. Similar to EF variables, participants' reward sensitivity scores were converted to Z-scores using its baseline distribution as a reference to bring measures of reward and EF into the same standardized metric.

2.2.3 Difference scores

To aid in visualization, Figure 1 exemplifies the mean developmental gap between the reward and EF systems in adolescence captured by the data. To quantify within-person differences between these systems, difference scores were computed by subtracting each individual's EF composite average Z-score from their reward sensitivity Z-score for each assessment wave. Therefore, positive difference scores represent elevated reward sensitivity relative to one's EF, while negative difference scores represent elevated EF relative to one's reward sensitivity. Difference scores at or close to 0 indicate "balanced" reward sensitivity and executive abilities. Notably, the scaled reward responsiveness and EF composite scores were not significantly correlated across the full range of observations ($r(604)=.03$, $p=.41$).

2.3 Analytic Approach

Hierarchical linear models (nlme package, R version 3.1-162; Pinheiro, Bates, et al., 2023) were used to evaluate the developmental trajectories of reward sensitivity, EF, and the difference between these measures leveraging an ALD (Galbraith et al., 2017). Visual inspection and descriptive analyses confirmed that data from the current

investigation met the assumptions of these models, including assumptions of normality, heteroscedasticity, and independence. In all modeling, we allowed individual variation in the outcomes regarding where they started (i.e., random intercept) and how they changed (i.e., random slope).

At baseline, of the 197 individuals enrolled in the study, 190 individuals (96%) had both reward and EF composite scores available for analysis. A total of 25 individuals participated in only one wave of data collection and were removed from the sample. Due to limited data at extreme ages, six observations over the age of 30 years were excluded to reduce bias in the modeling. This yielded a final longitudinal sample of 166 unique individuals with a total of 606 observations over a 10-year period, ranging in age from 9.2 to 29.6 years. Of the 166 individuals included in these analyses, 42 had data for five observations, 62 for four observations, 24 for three observations, and 38 for two observations. Data missing by design (i.e., in ALD) or due to subject attrition was missing at random conditional on observed information (finalfit, R package version 1.0.6; Harrison et al., 2023). Treating individual age at assessment points as time, maximum likelihood was used as an estimator for all models specified.

For each outcome, continuous age was modeled using four hierarchical linear models including linear, quadratic, cubic, and inverse functions of age, where models including higher-order functions of age (i.e., quadratic and cubic age) additionally included appropriate lower-order functions of age (i.e., linear and quadratic age). Resulting fits were compared using Bayesian Information Criterion (BIC; Schwarz, 1978) to select an unadjusted model (i.e., modeling effects of age without any covariates of interest) with the appropriate functional form. By examining linear and nonlinear models of age, we sought

to determine if the measures of interest change at a constant rate with age (i.e., follow linear trajectories), peak in adolescence and follow a nonlinear adolescent emerging or declining pattern (i.e., follow quadratic or cubic trajectories), or plateau (i.e., follow an asymptotic trajectory such as with an inverse function of age). Table 2 displays the model comparison metrics for all unadjusted model fits.

For all outcomes, modeling was completed assuming residual errors were homoscedastic (equal variance) and uncorrelated (i.e., an independent covariance pattern). Visual inspection and descriptive analyses of residuals suggested that these assumptions were reasonable. Alternative error structures were considered, including one which assumed unequal variances and uncorrelated residuals (i.e., a banded covariance pattern; Fitzmaurice et al., 2011). We additionally considered a continuous first-order auto-regressive structure (Fitzmaurice et al., 2011). Such an error structure has been used when modeling similar outcome variables in the same sample (see Klein et al., 2022) and is more flexible for individuals with missing data (e.g., in the case where someone misses wave 2 but returns for other assessments; Singer & Willett, 2003). However, BIC comparisons and maximized likelihoods for each of the covariance pattern models indicated that using an independent error structure provided the best-fitting parsimonious models for all outcomes (Fitzmaurice et al., 2011).

Finally, to evaluate the effects of natal sex on the developmental trajectories of each outcome, the best-fitting unadjusted models were compared against models with the fixed effects of sex added as a categorical covariate, with and without interactional sex-by-age effects. Sex was dummy coded such that female participants were labeled as 1 and male participants as 0.

3. Results

3.1 Developmental trajectory of executive function

An inverse function of age was the best-fitting model in examining the unadjusted developmental trajectory of EF. Results of this model, included in Table 3, indicate a significant main effect of inverse age on EF composite scores (t=-21.29, p<.001). Tangent lines at ages 9, 14, 19, 24, and 29 along the inverse curve, illustrated in Figure 2, demonstrate that as age increases, the inverse function's slope decreases significantly, becoming less positive and approaching zero by age 29 years. When natal sex as a categorical covariate was added to the best-fitting unadjusted model for EF, there was not a significant fixed effect of sex (t= -0.12, p=.90) or interaction between age effects and sex (t=1.60, p=.11).

3.2 Developmental trajectory of reward sensitivity

Counter to our hypothesis, an inverse function of age was also the best-fitting model in examining the unadjusted developmental trajectory of reward sensitivity. Results of this model, included in Table 4, indicate a significant main effect of inverse age on scaled reward sensitivity scores (t= -2.11, p<.001). Tangent lines at ages 9, 14, 19, 24, and 29 along the inverse curve, illustrated in Figure 3, demonstrate that as age increases, the inverse function's slope decreases significantly, becoming less positive and approaching zero by age 14 years. When natal sex as a categorical covariate was added to the best-fitting unadjusted model for reward sensitivity, there was not a significant main effect of sex (t= 1.92, p=.056) or interaction between age effects and sex (t=-1.79, p=.074).

3.3 Developmental trajectory of reward sensitivity and executive function difference

When examining the unadjusted developmental trajectory of the directly quantified difference between reward sensitivity and EF, an inverse function of age best approximated developmental change. Results of this model, included in Table 5, indicate a significant main effect of inverse age on difference scores (t=5.75, p<.001). Tangent lines at ages 9, 14, 19, 24, and 29 along the inverse curve, illustrated in Figure 4, demonstrate that as age increases, the inverse function's slope increases significantly, becoming less negative and approaching zero around age 29 years. Moreover, at 15.3 years of age, difference scores transition from positive to negative values. When natal sex as a categorical covariate was added to the best-fitting unadjusted model, there was not a significant main effect of sex (*t*=1.86, *p*=.065). When a model including an interaction between inverse age and sex was considered, there was a significant main effect of sex (*t*=2.85, *p*=.005) and a significant interaction effect (*t*=-2.30, *p*=.022). However, comparisons of fit indices indicate that the interaction model may be overfitting to the data. Results of the adjusted models are included in Table 5.

4. Discussion

The present investigation examined the longitudinal development of reward sensitivity and EF from late childhood through early adulthood, and directly quantified and examined longitudinal changes in the difference between these systems. Development of the EF/control system increased rapidly during adolescence and stabilized in young adulthood, consistent with the driven dual systems model and previous reports demonstrating that the development of this system follows an inverse trajectory (Ferguson et al., 2021; Luna et al., 2021; Reilly et al., 2022). However, the development of the reward

system in our sample *also* exhibited an inverse trajectory that increased rapidly during early-adolescence and had largely stabilized by mid-adolescence, which is counter to the U-shaped developmental trajectory with a distinct peak in mid-adolescence asserted by the dual systems model (Casey et al., 2008; Steinberg et al., 2008). Finally, the difference between reward and control systems also exhibited rapid change through adolescence with stabilization by early adulthood. This trajectory provides evidence of a functional gap during adolescence whereby reward processes outpace capacities for executive control in early adolescence. However, by mid-adolescence and into early adulthood, the developmental mismatch between these systems favors EF capacity. Collectively, the present report offers a novel and important contribution to our understanding of adolescent development and suggests the ability to exert top-down regulatory control over incentive-reward motivation emerges by middle adolescence (Luciana & Collins, 2012).

4.1 Developmental trajectories of executive function and reward sensitivity

The development of the EF composite in our sample increased rapidly during adolescence and stabilized by early adulthood (at around age 29 years). These findings align with previous reports documenting increases in EF from childhood to mid-adolescence with stabilization between adolescence and adulthood (Cowan et al., 2011; Luciana et al., 2005, 2009; Luna et al., 2004; Somerville et al., 2011). In contrast, self-reported reward sensitivity increased rapidly during early adolescence, consistent with several past longitudinal investigations (e.g., Collado et al., 2014; Lynne-Landsman et al., 2011; MacPherson et al., 2010). However, the development of this measure appeared to stabilize (i.e., reach near adult levels) by mid-adolescence (at around age 14 years), which is inconsistent with theoretical accounts that the distinct peak in reward sensitivity in mid-

adolescence subsequently declines during late adolescence (Harden & Tucker-Drob, 2011; Romer & Hennessy, 2007; Shulman et al., 2015; Steinberg et al., 2008). Notably, there is a paucity of robust longitudinal investigations of self-reported reward sensitivity or sensation seeking spanning from adolescence to adulthood, and the existing studies have yielded mixed results. Using cross-sectional designs, Steinberg and colleagues (2008) found support for a quadratic pattern of age-related variation in self-reported sensation seeking in individuals aged 10 through 30 years. In contrast, Vazsonyi and Ksinan (2017) found that self-reported sensation seeking was characterized by a cubic trajectory with an adolescent peak that stabilized in young adulthood. Additionally, limited longitudinal investigations with only two observation points per individual suggest mid-adolescent peaks in self-reported sensation seeking (Romer & Hennessy, 2007) and BAS Reward Responsiveness (Urošević et al., 2012), increases in self-reported BAS Drive during early adolescence with stabilization from late adolescence into early adulthood (Urošević et al., 2012), or no developmental change with age in either BAS Reward Responsiveness or Drive through adolescence into early adulthood (Braams et al., 2015). Crucially, the analyses of two or fewer timepoints in these studies limit the ability to make conclusions about the developmental trajectories of the reward system (i.e., age-related change over time) (Farrington, 1991; Parsons & McCormick, 2023).

To our knowledge, only two longitudinal investigations with three or more observation points have been conducted examining self-reported measures of sensation seeking from adolescence into adulthood. Harden and Tucker-Drob (2011) and Shulman and colleagues (2015) both found support for a peak in self-reported sensation seeking in mid-adolescence using the same sample. However, while Harden and Tucker-Drob (2011)

documented age-related decreases in sensation seeking into adulthood, Shulman and colleagues (2015) demonstrated a cubic trajectory with stabilization by early adulthood (age 22-23 years), with females demonstrating a more prominent decline in sensation seeking during late adolescence than males. Moreover, only one robust longitudinal investigation examined the development of self-report reward responsiveness and drive from the BAS scale through adolescence into adulthood. In their investigation, Schreuders and colleagues (2018) documented cubic development trajectories whereby 1) reward responsiveness decreased during early adolescence, increased until early adulthood (around age 24 years), and then declined into adulthood, 2) drive in males decreased until mid-adolescence (around age 15 years), increased until early adulthood (around age 24 years) and then declined, and 3) drive in females increased mostly linearly through adolescence into adulthood.

As such, the empirical evidence supporting the dual systems model is still limited, especially in terms of robust longitudinal studies that have tracked individuals over a prolonged time and can provide strong evidence for the proposed developmental trajectories of the reward system. Moreover, sensation seeking has often been used as an index of the reward system. However, sensation seeking is not the same theoretical construct as reward sensitivity (Luciana et al., 2012). Sensation seeking is a preference for certain types of experiences, regardless of valence, that are physically arousing, intense, or dangerous (Zuckerman, 1994). Reward sensitivity, on the other hand, is a trait that reflects positive emotional valence, and subsumes the degree to which an individual: 1) anticipates a reward (i.e., anticipatory reward processing); 2) is motivated to pursue this reward (i.e., attribution of incentive salience); and 3) the hedonic value of a reward (i.e., consummatory

reward processing). While reward sensitivity is often assumed to subserve and contribute to sensation seeking tendencies (Harden et al., 2018), psychometric analyses suggest that general arousal and positively valenced behavior are orthogonal constructs, mediated by different neural systems and expressed differently in behavior (Depue & Collins, 1999; Watson & Tellegen, 1986). Given the limited robust longitudinal investigations of the developmental trajectories of self-report reward sensitivity, future studies that replicate our findings are warranted.

Importantly, our findings indicate that both laboratory-based EF and self-reported reward sensitivity increase during early adolescence and plateau by early adulthood. The evaluation of slope fluctuations with age, presented in Table 6, suggests that EF undergoes more marked change across the assessed age range and stabilizes later in development than reward sensitivity. For example, at age 9 years, the rate of change of reward sensitivity represents a 2.22% change in development, while the rate of change of EF represents a 10.51% change in development. However, by age 14 years, reward sensitivity underwent <1% change, while EF only began to approach 1% change by age 29 years. Thus, our results suggest that the reward system exhibits earlier maturation than the control system, which partially supports the putative developmental trajectories of these systems posited by the dual systems model.

4.2 Developmental trajectory of the difference between reward and control systems

To more appropriately test for the presence of a developmental gap between reward and control systems in adolescence, we directly quantified differences between these systems and evaluated developmental changes of these differences with age (Meisel et al., 2019). Our findings indicated that in early adolescence, individuals exhibited high

difference scores, indicating heightened levels of reward sensitivity relative to executive abilities until mid-adolescence. By age 15, on average, there appeared to be an approximate balance between these two systems (i.e., individuals' mean difference scores were approximately 0). Progressing from mid-adolescence into late adolescence, difference scores slowly decreased due to increases in executive abilities relative to reward sensitivity, aligning with decreases in latent difference scores of self-reported sensation seeking and premeditation demonstrated by McCabe and colleagues (2021) in a longitudinal sample of individuals between the ages 17 and 20 years. Finally, by early adulthood, difference scores stabilized, and individuals demonstrated elevated levels of executive abilities relative to reward sensitivity. Importantly, these findings suggest that there is heightened reactivity of the reward system during early adolescence, while the control system is still gradually developing. Moreover, because of the increased slope in EF development through the mid-to-late adolescent period, the difference score indicates a prominent shift from a reward system bias to a control system bias in mid-to-late adolescence. As motivational impulses are compelling sources of behavioral influence and contribute to an individual's executive load at any given point in time (Luciana et al., 2012; Luciana & Collins, 2022), our findings suggest that as adolescence progresses, further maturation of these independent systems (Shulman et al., 2016) will proceed and the incentive motivation system should become less reactive as the control system becomes stronger and more efficient (Strang et al., 2013). Taken together, our findings suggest that as the EF system outpaces the motivational system in late adolescence and early adulthood, one's executive load or burden should be reduced, and behavioral control should become easier to achieve. Notably, though, in contrast to hypotheses, we found a balance between these systems (i.e., average difference

scores close to 0) during mid-adolescence (around age 15) when the dual systems model might predict maximal imbalance between these systems. Future investigations exploring how individual differences in this directly quantified developmental gap are associated with decision-making processes and risk-taking behaviors are needed to evaluate the consequence of these patterns and their timing.

4.3 Sex differences in developmental trajectories

Our analyses did not indicate differences due to biological sex in the level or developmental trajectories of EF, reward sensitivity, or within-person differences between these measures from late childhood to early adulthood. These findings align with extant literature which has failed to identify sex differences in EF (Grissom & Reyes, 2019), including spatial working memory (Alarcón et al., 2014; León et al., 2014; Loe et al., 2012; Luciana et al., 2005) and planning abilities (Luciana et al., 2009; Luciana & Nelson, 2002). However, these findings are contrary to past investigations demonstrating higher levels of self-reported BAS Reward Responsiveness in adolescent (Schreuders et al., 2018) and college-aged (Carver & White, 1994) females compared to males, and lower self-reported sensation seeking in females (Cross et al., 2013; Moffitt et al., 2013; Shulman et al., 2015; Vazsonyi & Ksinan, 2017). Moreover, past investigations have suggested more rapid development of self-reported sensation seeking in females relative to males during late adolescence (McCabe et al., 2021; Shulman et al., 2015) and significant sex differences in the developmental trajectory of self-reported BAS Drive during adolescence (Schreuders et al., 2018). Additional research examining sex differences using other indexes of reward sensitivity has also yielded inconsistent results. While some examinations found support for higher reward sensitivity in males during adolescence (Alarcón et al., 2017; Cardoso

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Melo et al., 2023) and adulthood (Dhingra et al., 2021; Eneva et al., 2017), some found higher sensitivity of the neural reward system to prosocial rewards in adult women than in men (Soutschek et al., 2017) and others still found no sex differences in reward sensitivity in adolescents (Colder & O'Connor, 2004) or adults (Scheres & Sanfey, 2006). As such, further investigations are warranted to fully elucidate sex differences in reward sensitivity in day-to-day contexts across this developmental range. Moreover, sex differences in risk-taking tendencies may be driven by sex differences in the assessment of risk, not rewards (Grissom & Reyes, 2019), and future research is necessary to fully explicate potential sex differences in the roles of control, reward, and also avoidance systems in decision-making (Ernst et al., 2006).

5. Limitations

The present work is not without limitations. The sample used in these analyses was predominately White and from middle to upper-middle socio-economic backgrounds. Replications in more sociodemographically diverse samples are needed to establish the generalizability of the present findings. Additionally, we relied on a single questionnaire measure of reward sensitivity in this study, an approach that has also been taken by others (e.g., Harden & Tucker-Drob, 2011; McCabe et al., 2021; Quinn & Harden, 2013; Shulman et al., 2016; Vazsonyi & Ksinan, 2017). Importantly, reward sensitivity is a complex construct, and whether the observed patterns reflect behavior as observed in real-world contexts remains to be determined. Moreover, given the available assessments, the EF composite used in the present investigation does not include a direct measure of inhibitory control. Regardless, the EFs indexed play important roles in decision making processes, and poorer Tower of London of performance has been associated with decreased response

inhibition as measured by the Go-No-Go Task (Luciana et al., 2009). Additionally, our difference score approach used a trait-level measure of reward sensitivity and a more context-dependent measure of EF. Future studies using congruent measurement methods to assess both systems should be considered. Finally, the use of standardized scores to compute difference scores could have impeded our examination of mean level changes from one timepoint to another (Moeller, 2015). However, analyses using raw reward sensitivity and raw and scaled EF measures (data not shown) resulted in the same developmental trajectories, indicating that our scaling procedures preserved distributions and meaningful conclusions regarding changes with age. Moreover, in a cross-sectional investigation of individuals ages 12 to 27 years, Vazsonyi and Ksinan (2017) calculated difference scores by subtracting standardized self-reported sensation seeking and impulse control scores and demonstrated that both sensation seeking and impulse control independently predicted deviant behavior and the gap between these systems (as quantified by their difference score) predicted substantial additional variance in deviance. While Vazsonyi and Ksinan (2017) did not evaluate the developmental trajectory of the discrepancy scores, their investigation demonstrates computational strength in utilizing standardized difference scores and the independent contribution of the gap between these measures to decision-making processes during adolescence.

6. Conclusion

The present investigation represents a novel contribution to the literature and provides useful insights into understanding how reward and control systems develop and interact within individuals through adolescence and into adulthood. By directly quantifying differences between measures of reward sensitivity and EF, we established evidence for

the unique period of developmental imbalance with heightened reward reactivity relative to executive control present in early adolescence, as posited by the dual systems model. Importantly, findings suggest that the ability to exert top-down regulatory control over incentive-reward motivation emerges by middle adolescence and the gap between reward and control capacities varies as a function of age. Further research into how developmental differences between reward and control systems relate to decision-making processes, including risk-taking tendencies, is an important future direction for this research, as well as the development of prevention strategies designed to mitigate maladaptive decision-making for early adolescents and individuals who remain reward biased into late adolescence.

Table 1. **Participant Demographics**

|	
Sample size	N=166
BL Age, m (sd)	15.99 (4)
BL Age Range	9.21-23.44
Female, N (%)	92 (55.42%)
White N (%)	149 (89.76%)
Black N (%)	3 (1.81%)
Hispanic/Latine N (%)	5 (3.01%)
Asian/Pacific Islander N (%)	6 (3.61%)
Multiracial N (%)	3 (1.81%)
Maternal Years of Education, m (sd)	15.67 (2.01)
Number of Observations, m (sd)	3.65 (1.09)

Note. BL=baseline/year 0 of study, m = mean, sd = standard deviation, N = number. Age is presented in years.

Table 2. **Comparisons of Unadjusted Developmental Models**

Variable	Model	df	BIC	bWeight
Scaled Reward Sensitivity	**Age^{-1}**	**6**	**1590.53**	**1.00**
	Age	6	1601.18	0.00
	Age + Age^2	10	1609.57	0.00
	Age + Age^2 + Age^3	11	1615.33	0.00
Executive Function Composite	**Age^{-1}**	**6**	**768.42**	**1.00**
	Age	6	829.01	0.00
	Age + Age^2	10	791.39	0.00
	Age + Age^2 + Age^3	11	796.16	0.00
Difference Score	**Age^{-1}**	**6**	**1758.07**	**0.63**
	Age	6	1759.1	0.37
	Age + Age^2	10	1784.06	0.00
	Age + Age^2 + Age^3	11	1790.47	0.00

Note. df = degrees of freedom; BIC = Bayesian Information Criterion; bWeight = Weight of Evidence for BIC. Bold font indicates best-fitting unadjusted models according to BIC.

Figure 1. **Prototypical plot of reward sensitivity and executive function with age**
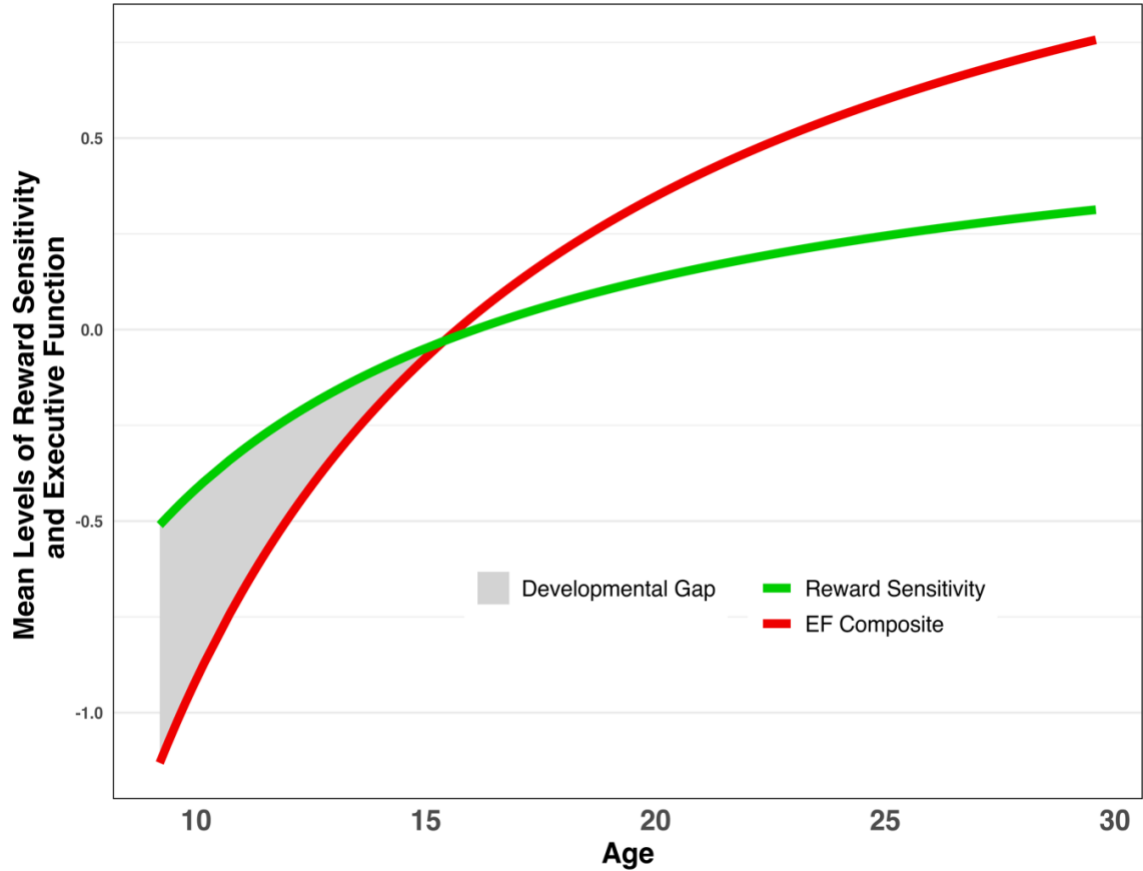
Mean scaled reward sensitivity (green) and EF composite (red) for all participants during the study. The gray-shaded region represents the mean developmental gap between systems present during adolescence.

Figure 2. **Developmental Trajectory of Executive Function**
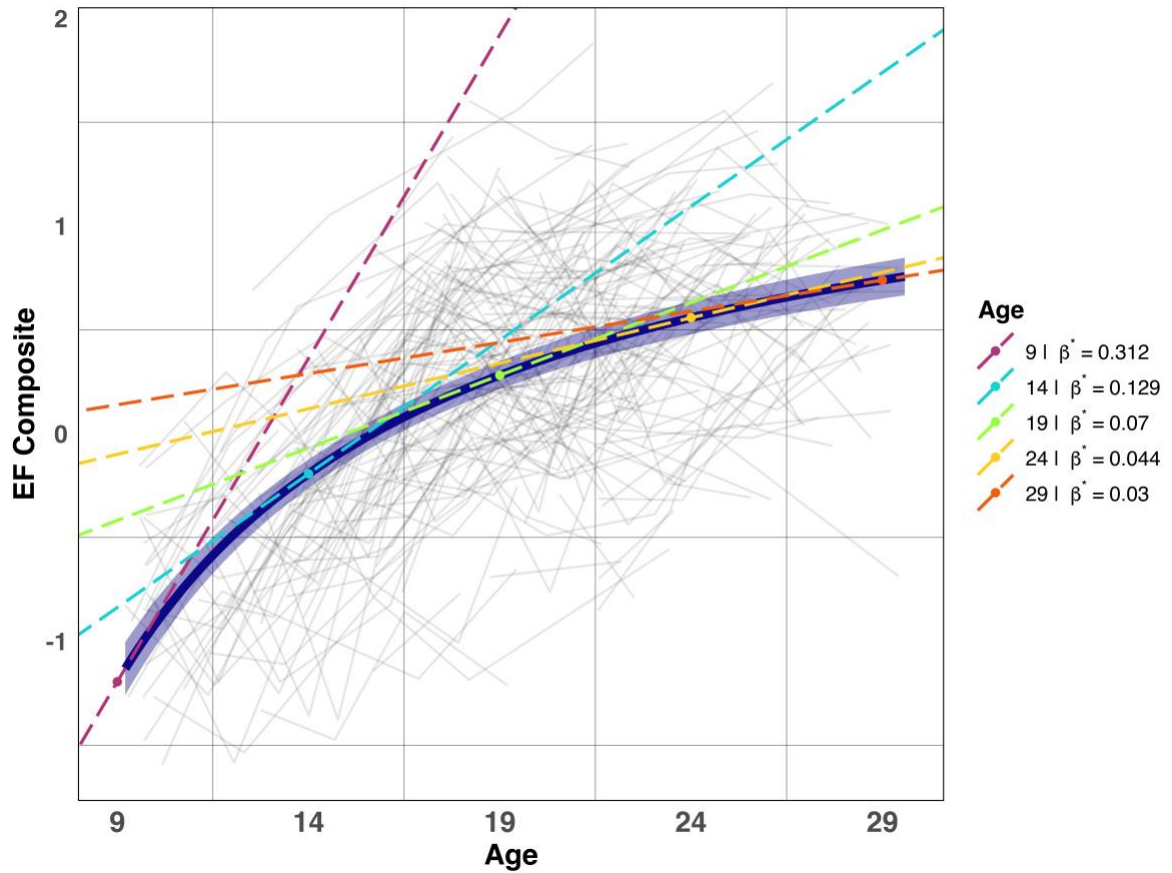
Executive function composite scores for all participants (solid black lines) during the study. The solid purple line represents the predicted values of executive function composite scores from the best-fitting unadjusted model. The purple band around this line indicates the 95% confidence interval around predicted values. The dashed lines represent the tangent lines (i.e., first-order derivative of the model) at each associated age. The legend displays the slope of the tangent line at each corresponding age.

Table 3. **Comparisons of Best-Fitting Unadjusted and Adjusted Models of Executive Function with Age**

Executive Function Composite with Age		
Model Coefficient	Unadjusted Model	Adjusted Model
Intercept (SE)	1.61* [1.45, 1.77] (0.08)	1.61* [1.44, 1.79] (0.09)
Age^{-1} (SE)	-25.24* [-27.57, -22.91] (1.19)	-25.24* [-27.57, -22.92] (1.19)
Female (SE)	-	-0.01 [-0.14, 0.12] (0.07)
Variance Components		
Random Effects	0.33	0.33
Residual	15.34	15.22
Model Fit		
Marginal R^2 (Fixed Effects Only)	0.37	0.37
Conditional R^2 (Fixed and Random Effects)	0.72	0.72
BIC	**768.42**	774.81
Log-likelihood	**-364.99**	-364.98

Note. Model coefficients and corresponding 95% confidence intervals and standard errors (SE) are presented. Bold text indicates superior fit indices when comparing the unadjusted and adjusted models.
* Denotes p<0.05

Figure 3. **Developmental Trajectory of Reward Sensitivity**
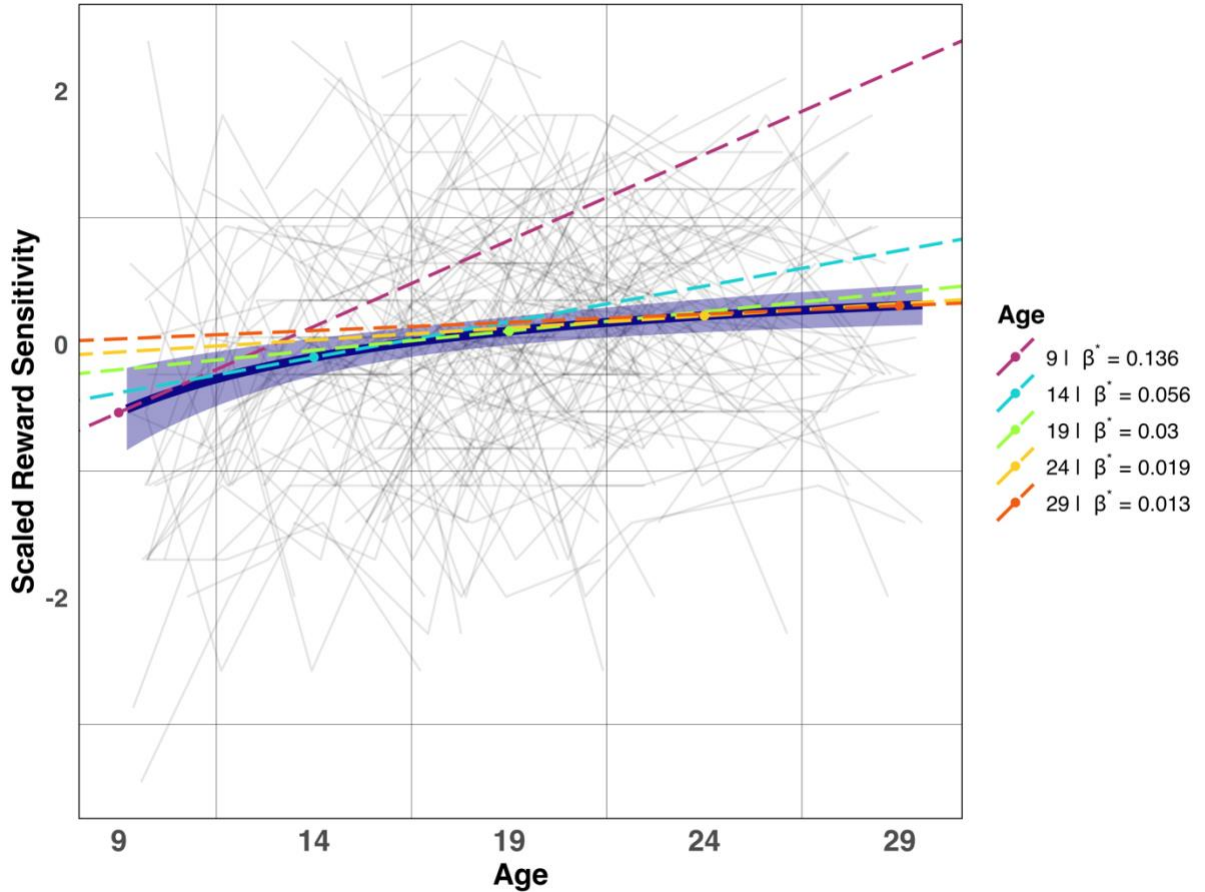
Scaled reward sensitivity scores for all participants (solid black lines) during the study. Self-reported reward sensitivity scores are composed of summed BAS Reward Responsiveness and Drive subscale scores. Values were scaled using the baseline distribution. The solid purple line represents the predicted values of scaled reward sensitivity from the best-fitting unadjusted model. The purple band around this line indicates the 95% confidence interval around predicted values. The dashed lines represent the tangent lines (i.e., first-order derivative of the model) at each associated age. The legend displays the slope of the tangent line at each corresponding age.

Table 4. **Comparisons of Best-Fitting Unadjusted and Adjusted Models of Scaled Reward Sensitivity with Age**

Scaled Reward Sensitivity with Age		
Model Coefficient	Unadjusted Model	Adjusted Model
Intercept (SE)	0.68* [0.36, 1.01] (0.16)	0.55* [0.2, 0.9] (0.18)
Age^{-1} (SE)	-11.0* [-16.62, -5.39] (2.86)	-10.67* [-16.31, -5.03] (2.88)
Female (SE)	-	0.22 [-0.01, 0.44] (0.11)
Variance Components		
Random Effects	1.10	1.00
Residual	239.56	237.02
Model Fit		
Marginal R^2 (Fixed Effects Only)	0.03	0.04
Conditional R^2 (Fixed and Random Effects)	0.47	0.47
BIC	**1590.53**	1593.38
Log-likelihood	**-776.05**	-774.26

Note. Model coefficients and corresponding 95% confidence intervals and standard errors (SE) are presented. Bold text indicates superior fit indices when comparing the adjusted and unadjusted models.
* Denotes $p < 0.05$

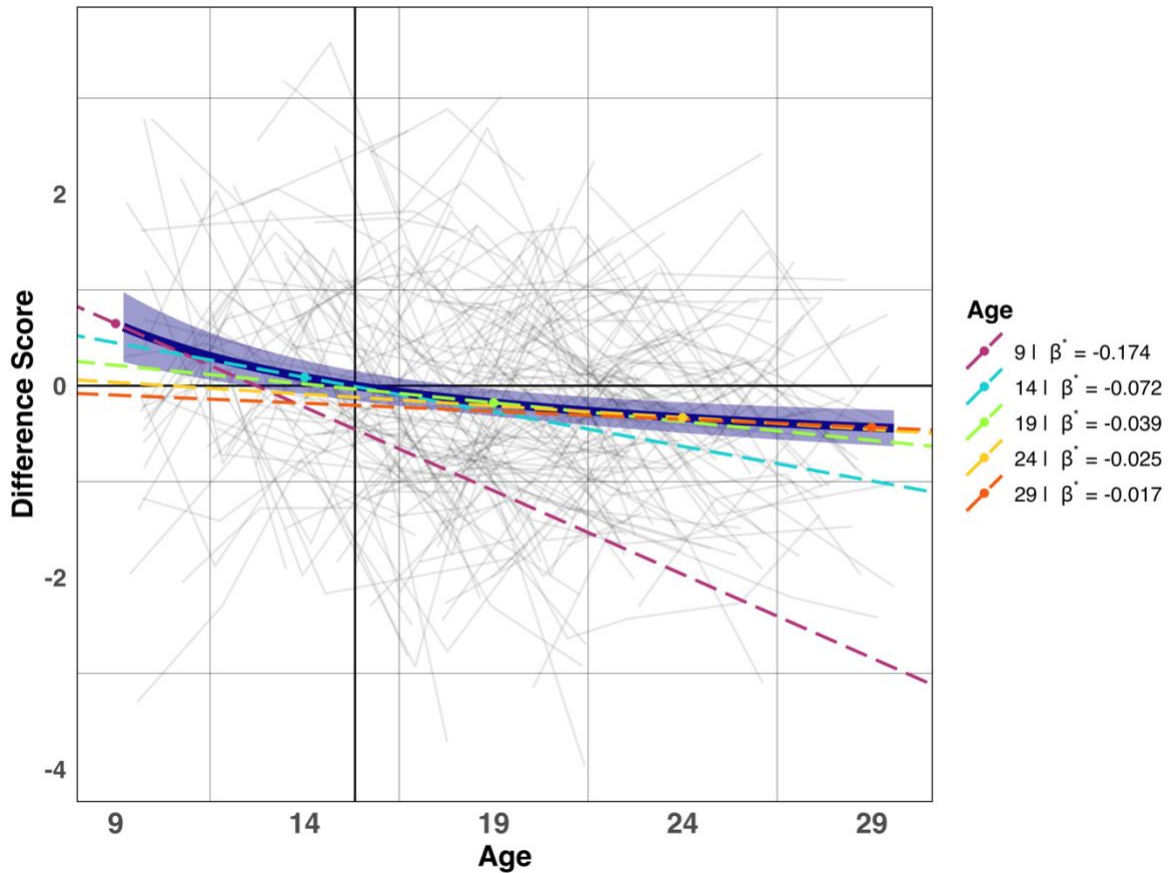*Figure 4.* **Developmental Trajectory of Reward Sensitivity and Executive Function Difference**

Difference scores for all participants (solid black lines) during the study (i.e., reward sensitivity – EF composite). The solid purple line represents the predicted values of difference scores from the best-fitting unadjusted model. The purple band around this line indicates the 95% confidence interval around predicted values. The dashed lines represent the tangent lines (i.e., first-order derivative of the model) at each associated age. The legend displays the slope of the tangent line at each corresponding age.

Table 5. **Comparisons of Best-Fitting Unadjusted and Adjusted Models of Reward Sensitivity and Executive Function Difference with Age**

Difference Score with Age			
Model Coefficient	Unadjusted Model	Adjusted Model: Main Effect	Adjusted Model: Interaction
Intercept (SE)	-0.92* [-1.29, -0.56] (0.19)	-1.09* [-1.48, -0.69] (0.2)	-1.52* [-2.06, -0.98] (0.28)
Age^{-1} (SE)	14.12* [7.92, 20.33] (3.16)	14.47* [8.22, 20.72] (3.19)	22.51* [13.28, 31.74] (4.71)
Female (SE)	-	0.26 [-0.02, 0.54] (0.14)	1.04* [0.32, 1.77] (0.37)
Female X Age^{-1} (SE)	-	-	-14.59* [-27.01, -2.17] (6.34)
Variance Components			
Random Effects	1.35	1.18	1.11
Residual	236.93	231.75	213.15
Model Fit			
Marginal R^2 (Fixed Effects Only)	0.04	0.05	0.05
Conditional R^2 (Fixed and Random Effects)	0.54	0.54	0.54
BIC	**1758.07**	1761.22	1762.34
Log-likelihood	**-859.82**	-858.19	-855.54
Note. Model coefficients and corresponding 95% confidence intervals and standard errors (SE) are presented. Bold text indicates superior fit indices when comparing the unadjusted and adjusted models. * Denotes $p<0.05$			

Table 6. **Percent Change with Age**

Age	Reward	EF	Difference
9	3.35%	10.51%	-16.51%
14	1.38%	4.34%	-6.82%
19	0.75%	2.36%	-3.70%
24	0.47%	1.48%	-2.32%
29	0.32%	1.01%	-1.59%

Values represent age in years or estimated change occurring at each age relative to total change across all ages estimated by best-fitting unadjusted models for each outcome

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