THE FEEDBACK-RELATED NEGATIVITY AND EXECUTIVE FUNCTION IN ADOLESCENTS

by

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Abstract

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Adolescents have difficulty countering dysregulating influences and are susceptible to poor decision making in emotionally charged situations. This has important implications for adolescents who are arrested for crimes. Decisions made in legal settings (e.g., waiving rights to counsel; pleading guilty) entail very high stakes and are fraught with emotion.

Effective decision making relies, in part, on the ability to evaluate feedback and adapt behavior accordingly. The neural mechanisms underlying feedback processing involve midbrain dopamine neurons that project to regions of the frontal cortex that are not fully mature in adolescence. This study used an event related potential (ERP) design to investigate the relationship between this feedback processing system and executive function (EF) in adolescent and young adult males. An electrophysiological correlate of external feedback processing, the feedback-related negativity (FRN), was recorded while participants performed a simple gambling task. The FRN was then used as an index of the functional maturity of this system, and examined in relation to both age and performance on three independent measures of EF: the Wisconsin Card Sorting Test (WCST), the Iowa Gambling Task (IGT) and a delay discounting task (DDT).

Despite having larger amplitudes in adolescents, the FRN was found to differentiate less strongly between gains and losses in adolescents compared to adults. For adolescents, but not for adults, poorer performance on the IGT was predicted by longer FRN latency after high loss trials on the ERP gambling task, and slower learning on the WCST was related to smaller FRN amplitudes after losses. These results suggest that the maturity of the “bottom-up” feedback signal might be more directly tied to observed behavior in teenagers than in adults. This study adds to the growing body of evidence that neural maturation in the frontal cortex may impact higher order decision making in adolescents, particularly if decision tasks involve affective components. Results are discussed in the context of their relevance for juvenile justice policy and the clinical evaluation and treatment of at-risk teens.

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Completing a dissertation is not a solo endeavor. Without the support and understanding of my family, friends and adviser this process would have been nearly impossible.

I steal a line from comedienne Tina Fey, as I thank my parents, Cammy and Maria, for instilling in me more confidence than my talents and abilities ever warranted. I am forever grateful to them for their belief in me, for the sacrifices they made that enabled me to reach this point and for instilling in me dreams and values that extend beyond academia. Likewise, any expression of my gratitude to Alicia, Silke and Lisa is inadequate to the love, support and encouragement they have extended to me during this process; I share my success with them. A special thank you also extends to Jen LiMarzi—the Lucy to my Ethel and the George to my Jerry—for her tireless proofreading; but, most of all, for the box of brownies that got me through the end zone.

I wish to dedicate this project to my adviser Jill Grose-Fifer who taught me how to be an academic. It is impossible to express my appreciation for Jill; it goes beyond her painstaking edits, her patience opposite my stubbornness, her immense generosity, her genuine desire for my success, and her enthusiasm for the academic process that she imparted to me. Jill taught me how to think about data and how to enjoy the process of discovery while not losing sight of the goal. This project could never have developed without her guidance. I would also like to acknowledge Patty Zapf, my first mentor, who introduced me to the research process and remained a source of sound advice over the years. I am also grateful to my fellow graduate students, Virginia Barber-Rioja and Gianni Pirelli, who kept me afloat; Tarika Daftary, Erin Williams, and Ginna Fineran, who made the whole ride a lot more fun; and Steve Hoover, my lab partner, who so considerately scheduled his own bouts of panic and anxiety around mine, so that at least one of us always had a clear head.

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Finally, as my faith in Christ has always sustained me, I want to give thanks to God, in whom I believe all strength is found.

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CHAPTER 1: GENERAL INTRODUCTION

Adolescents do not always make good decisions. Despite the development of relatively mature analytical reasoning by midadolescence, this population disproportionately engages in risky behavior (Furby & Beth-Marom, 1992; Steinberg & Cauffman, 1996). Although a transitional period of increased risk taking is developmentally important because it allows adolescents to attain greater independence as they approach adulthood (Kelly, Schochet, & Landry, 2004), not all adolescent risk taking is benign. Adolescents are more likely than children and adults to die in motor vehicle or drowning accidents, or to be killed by firearms (Xu, Kochanek, Murphy, & Tejada-Vera, 2010). Delinquency and crime rates also peak during adolescence (e.g., Farrington, 1986; Moffitt & Harrington, 1996). In 2008, there were 6,318 arrests for every 100,000 adolescents, ages 10 through 17 years, in the United States (OJJDP, 2009).

Adolescents have particular difficulty countering dysregulating influences (e.g., Luna et al., 2004; Monk et al., 2003) and are susceptible to poor decision making in emotionally charged situations or in situations with high cognitive demands (e.g., van Duijvenvoorde, Jansen, Visser & Huizenga, 2010). Consequently, adolescents are more likely to get into trouble when making decisions in the heat of the moment, especially in the presence of peers (Gardner & Steinberg, 2005; Cauffman & Steinberg, 2000; Steinberg & Cauffman, 1996). However, this also has important implications when considering whether adolescents can make competent decisions within the criminal justice system. Decisions made in legal settings often entail very high stakes, such as the possibility of imprisonment, and are fraught with emotion. Adolescents may be particularly vulnerable to poor decision making during the pre-adjudicative process, during which they might be more likely to waive their rights to counsel, to disclose information that is not in their best interest, to confess and to plead guilty (Cauffman & Steinberg, 2000; Grisso, 1980; Grisso et al., 2003; Redlich, Silverman & Steiner, 2003).

Legislative changes in juvenile justice policy during the 1980s and 90s led to a substantial increase in the number of juveniles who are processed and tried as adults in the United States (Grisso, 1997; Grisso & Schwartz, 2000; Loughran et al., 2010). The pool of offenders eligible for transfer to adult court has also become far more heterogeneous as a result of these changes (Schubert et al., 2010*)*. The ramifications of this are far reaching. In the adult justice system, trials are adversarial rather than cooperative and punishment is retributive not rehabilitative (Steinberg and Cauffman, 2001). Not only are adolescents variable with regard to their individual capacities as trial defendants (Grisso, 1997; Grisso et al, 2003), but the long-term outcomes for youth transferred to adult court vary with offense history and offender characteristics (e.g., Loughran et al., 2010; Schubert et al., 2010). Recidivism rates are also higher among juveniles detained in adult facilities compared to those in juvenile detention centers, even after controlling for offense type and offense history (e.g., Bishop, Frazier, Charles & Lanza-Kaduce, 1996; Winner, Lanza-Kaduce & Bishop, 1997).

Although recent legislative changes in many states over the last five years suggest that the retributive/ “just desserts” tide is slowly turning (Arya, 2011), there are still large numbers of juveniles tried as adults in this country each year. According to the latest US Department of Justice, Bureau of Justice (BOJ) Statistics report, as of June 30, 2005, there were 6,759 juveniles housed in adult jails across the nation and an additional 2,266 juveniles held in state prisons[1]; 85% of these offenders were tried and convicted in adult court. The most recent report does not break down the data by age, but according to the BOJ 2000 report, more than 57% of the juveniles housed in adult facilities were between the ages of 14 and 16 years**.** These figures imply that approximately 4,300 fourteen, fifteen and sixteen-year olds face adult adjudication each year, and must make decisions that can have serious lifetime consequences.

Behavioral data already call into question the maturity of adolescent decision making as it pertains both to the culpability of juveniles under the law and the capacities of juveniles as trial defendants (e.g., Cauffman & Steinberg, 2000; Grisso et al., 2003). Longitudinal structural imaging studies of human brain development from childhood through adulthood have revealed substantial maturational changes in the brain during adolescence (e.g., Giedd et al., 1999) that are leading to a better understanding of why, and when, adolescents may not be as competent as adults in their decision making.

Competent decision making largely depends on the integrity of the prefrontal cortex (PFC; Ernst & Paulus, 2005). The PFC has a protracted developmental time course, and some regions, specifically the dorsolateral PFC (DLPFC) and the orbital frontal cortex (OFC), do not reach adult maturity until the third decade of life (e.g., Giedd et al., 1999; Giedd, 2004; Gogtay et al., 2004). In contrast to the PFC, limbic-striatal structures, which mediate appetitive (or approach) behavior, appear to mature earlier (Ernst, Pine & Hardin, 2005; Galvan et al., 2006), with some studies showing evidence of hyper-reactivity of this system in adolescents (e.g., Ernst, Nelson et al., 2005). It has been suggested that this imbalance between approach and control/regulation systems puts

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[1] The Campaign for Youth Justice reported 2,864 juveniles in state prisons in 2009 (Arya, 2011).

adolescents at risk for poor decision making, particularly in situations that are emotionally laden (Casey, Getz & Galvan, 2008; Steinberg, 2008).

Accordingly, cognitive control over emotions, thoughts and actions (i.e., executive function) follows a protracted and non-linear development; some capacities develop early while many develop at a slower and more variable rate well into late adolescence (see Blakemore & Choudhury, 2006, for review). Specifically, performance on measures of executive function (EF) that tap abstract analytical skills applied in relatively decontextualized situations (i.e., cool cognition) tends to mature earlier than performance on EF tasks that include motivationally salient stimuli and outcomes (i.e., hot cognition; e.g., Hooper, Luciana, Conklin & Yarger, 2004; Prencipe et al., 2011)

Not surprisingly, and appropriately, psycho-legal researchers have already begun to introduce neuroscience into discussions on the culpability of juvenile offenders (e.g., Steinberg & Scott, 2003) and on the capacities of adolescents during preadjudicative and adjudicative processes (e.g., Mayzer, Bradley, Rusinko & Ertelt, 2009). However, the complex relationship between functional maturational changes in the human brain and the development of decision-making and executive function has only begun to be elucidated.

Traditionally, developmental changes in executive function have been characterized using cross-sectional studies that compare behavior between different age cohorts. However, many of the capacities measured by these tests develop at different rates across individuals during the decade of adolescence, rendering it difficult to see adult-adolescent differences without very large samples. Indeed, most studies show substantial gains in EF from childhood through adolescence (e.g., Anderson, Anderson, Northam, Jacobs & Catroppa, 2001; Leon-Carrion, Garcia-Orza & Perez-Santamaria, 2004; Levin et al., 1991). Fewer studies exist that compare EF in adolescents and adults, and these are more inconsistent in their results (e.g., Crone and van der Molen (2004); Overman et al., (2004); Somsen, 2007).

Another problem with traditional behavioral investigations is that when age-related differences are found, it is not possible to know the precise nature of the neural processes that contribute to them. Results of studies that show age-related differences in EF are often interpreted in the context of existing lesion or fMRI studies that have shown links between adult performance on the tests and specific brain regions (e.g., Hooper et al., 2004; Overman et al., 2004). While such interpretations are reasonable, it is important to remember that performance on standardized tests of executive function relies on multiple regions of the PFC (as well as other cortical and subcortical regions), and these have different developmental trajectories (Segalowitz & Davies, 2004). Furthermore, the cognitive strategy used on a given task might vary with age, and this could implicate different regions of cortical tissue across development (Segalowitz & Davies, 2004).

Rather than trying to establish how much age contributes to the variance in performance on tests of EF, an alternative approach is to establish how maturational differences in *specific* brain regions or functional networks contribute to the variance in performance on these tests. Adleman et al. (2001) used fMRI to identify and compare the brain regions activated in young adults (18 to 22 years), adolescents (12 to 16 years) and children (7 to 11 years) during a Stroop color-word task (Stroop, 1935), which is considered a standard EF task, but even this more direct method presents problems of interpretation. When measuring brain activity during task performance, it is often difficult to disentangle whether differences in brain activity cause differences in performance, or vice versa (Jonkman, Lansbergen & Stauder, 2003; Murphy & Garvan, 2004). Adleman et al. (2001) reported a positive correlation between age and activity in the left PFC, ACC and parieto-occipital cortices during the Stroop task. But, the authors acknowledged that the assumption of the Stoop task—that word reading is easier than color-naming—may not be true for younger participants; therefore, differences in reading abilities may have confounded their results.

Segalowitz and Davies (2004) have described an approach for verifying the association between a specific neural function and an observable behavior that is more likely to maintain directional interpretation. They have suggested employing real-time measures of brain activity (e.g., EEG), generated by simple tasks or stimuli that activate relatively circumscribed regions of the brain, that can subsequently be used as indices of functional maturity. This activity can then be correlated with performance on *independent* measures of executive or cognitive functioning, and compared across developmental stages (Segalowitz & Davies, 2004).

While neuroimaging techniques, such as fMRI, might seem best suited for indexing functional correlates of anatomical changes in the adolescent brain, these techniques are outside the financial reach of most researchers and can pose difficulties for working with children and teenagers who must remain relatively immobile in a scanner during image acquisition. Furthermore, although fMRI allows for the most reliable identification of functional neuroanatomy, because of its reliance on a relatively slow hemodynamic response it does not provide adequate temporal resolution for studying fast cognitive processes that occur on the order of milliseconds. Therefore, fMRI may lack the sensitivity to detect if the development of a specific brain region leads to a slowing down or speeding up of a neural response (Segalowitz & Davies, 2004).

Electroencephalography (EEG) provides an alternative that avoids these limitations through the use of event related potential (ERP) paradigms. ERPs are non-invasive measures of changes in brain activity associated with specific sensory or cognitive processes. Because ERPs are measures of electrical activity (i.e., changes in voltage), they allow for better temporal resolution of the fast neural transmission that occur during information processing (Luck, 2005).

Electroencephalography (EEG)

Surface EEG, measured with electrodes placed directly against the scalp, is the summation of the synchronous mass response of post-synaptic neurons that have a radial orientation to the scalp. The raw EEG represents the sum of all extracellular current flow across the surface of the brain at a given time (Niedermayer & Da Silva, 2005).

An ERP is the electrophysiological response elicited by an internal or external stimulus or task. Since the background activity is dynamic and random, but the evoked potential occurs at approximately the same time across trials, averaging across many trials allows for the amplification of the ERP against the rest of the noise of the EEG (Luck, 2005). The resultant ERP waveform consists of a series of voltage peaks and troughs, the timing (or latency) of which provides information about the temporal aspects of the underlying neural process. The shape of the waveform and the scalp topography of the ERP vary with stimulus and task (Hillyard & Picton, 1987). The availability of high density electrode arrays (64 or more electrodes) and sophisticated source localization software, also allows relatively accurate inferences to be made about the neural generators of ERPs (Luck, 2005).

Use of ERP Designs to Chart Cortical and Functional Development

Measures of EF are complex and activate multiple neural networks. However, simpler cognitive tasks have been shown to selectively recruit relatively circumscribed brain regions or circuits. If ERPs are recorded during these simpler tasks, it is then possible to correlate the neural activity in a given brain region with performance on separate, more complex, behavioral measures of EF (Segalowitz & Davies, 2004). For this to be successful, the ERP paradigm used must tap a *specific* cognitive processing center in the brain, while not imposing a high level of cognitive demand. If the task used is simple enough, it should be possible to accentuate the contribution of one particular brain region or neural network more than others to the ERP (Segalowitz & Davies, 2004). Subsequently, the ERP can be compared between different age groups to establish whether there are any significant differences in the size and/or timing of the response, or in the location of its neural generators. If there are age-related differences in the ERP, the ERP itself can be used as an index of the maturity of its neural generators. The ERP can then be examined in relation to age and performance on independent measures of EF.

This methodology was used by Lamm, Zelazo and Lewis (2006) to investigate EF in 33 children and adolescents (15 were males) ages 7 through 16 years, (other demographics of the sample were not described). The authors were specifically interested in the development of cognitive control and used a simple Go/NoGo task, which required the participants to respond quickly (i.e., Go), when a centrally presented stimulus appeared on the screen, and to inhibit responding (i.e., NoGo) when a stimulus appeared twice on sequential trials. Their primary measure was a negative ERP component, the N200, which peaks approximately 200 to 400 ms after a response is made and is largest after a correct NoGo response (e.g., Falkenstein, Hoorman & Hohsbein, 1999). In adults, the neural generators of the N200 have been localized to relatively circumscribed regions of the anterior cingulate cortex (ACC) and OFC (Nieuwenhuis, Yeung, van den Wildenberg & Ridderinkhof, 2003). Other studies have shown that age is inversely related to both the amplitude and latency of the NoGo N200 (e.g., Jonkman, Lansbergen & Stauder, 2003; Lewis, Lamm, Segalowitz. Stieben & Zelazo, 2006); therefore, the authors used the N200 as an index of cognitive control and examined its relationship to age and performance on four measures of EF.

The authors selected EF measures that have been shown to activate, predominately, either lateral or ventral medial regions of the PFC. A delay discounting task (DDT) and the Iowa Gambling Task (IGT; Bechara, 1994) were used to measure affective decision-making processes thought to recruit ventral medial frontal structures (Bechara, Tranel, & Damasio,1996; Cardinal, Winstanley, Robbins, Everitt, 2004; Kheramin et al., 2004; Northoff et al., 2006). The Digit Span subtest of the Wechsler Adult Intelligence Scales-III (WAIS-III; Wechsler, 1997) was used to assess working memory and the Stroop color-word test (Stroop, 1935) was used to evaluate selective attention and response inhibition. These non-affective functions are thought to rely more on lateral PFC brain structures (e.g., Kwon, Reiss & Menon, 2002), although, performance on the Stroop has also been associated frequently with ACC and even OFC activity (e.g., Bench et al., 1993).

Consistent with prior studies, Lamm et al. (2006) reported an inverse relationship between age and both N200 amplitude and latency. Age was also shown to be correlated with all measures of EF except for the delayed discounting parameter and Stroop interference scores. Participants with larger N200s had poorer executive function in general, regardless of age. Since N200 amplitude is known to increase with difficulty of the task (e.g., Senkowski & Hermann, 2002), it appears that participants with poor EF found it harder to inhibit their responses on the Go/NoGo task. Of most relevance here, N200 amplitude (but not latency) was associated with performance on the IGT and the Stroop, and the relationship between age and IGT was explained by changes in the N200. Source analysis confirmed that the neural generators of the N200 were predominantly located in the OFC, which is known to be activated during the IGT task, and the ACC, which is active in the Stroop task. Importantly, while the N200 was useful for explaining the effect of age on IGT performance, it also predicted performance on the Stroop, a task for which age alone was not predictive of performance. This study exemplifies how ERP components, in this case the N200, can be used as an index of cortical maturity to identify individual (i.e., within-age) differences in brain function that are correlated with observable behaviors. To my knowledge, no other group has used a similar research design to examine age related differences in EF.

The Present Study

The study reported here uses the same general approach employed by Lamm and colleagues (2006) to investigate the correlation between an ERP component and EF; however, unlike Lamm et al., who studied EF in children and adolescents, this study compared middle-adolescents to adults. Specifically, this study investigated feedback processing in an all-male sample of adolescents (14 to 16 years) and young adults (22 to 25 years) by recording their EEG while they performed a simple gambling task. The latency (timing) and amplitude (size) of the ERP evoked by feedback, generally referred to as the feedback-related negativity (FRN), was then examined in relation to age and performance on independent behavioral measures of executive function.

The ability to evaluate feedback and adapt behavior accordingly is a marker of mature EF (e.g., Lezak, Howieson & Loring, et al., 2004). In humans and primates, feedback processing appears to be mediated by the activity of midbrain dopamine neurons that project to regions of the striatum, ACC and PFC (Shultz, 2002), and maturational changes across these pathways have been linked to increased novelty-seeking and risk-taking behaviors in animal studies (Spear, 2000). The FRN is thought to reflect the arrival of the midbrain dopaminergic signal in the ACC, and possibly the OFC (Nieuwenhuis et al., 2004). Since the FRN has been linked to these relatively circumscribed regions of the brain, it is a particularly suitable ERP component to use as a measure of neural maturity.

The present study had two primary aims. The first aim was to establish normative age-related differences in the FRN in a sample of adolescent and young adult males. The second was to investigate whether links between observable behavior (EF) and brain processes (FRN) can index functional brain maturation more precisely than chronological age. Specifically, the study sought to investigate the relationship between the FRN and the following three measures of executive function: (1) The Wisconsin Card Sorting Test (WCST; Heaton, 1981), which assesses the ability to use feedback from the environment to change previously learned behavior; (2) the IGT (Bechara et al., 1994), which assesses the ability to use feedback from the environment to *adapt* behavior to achieve a future goal; and (3) a DDT, which measures the extent to which one can delay immediate gratification to obtain an objectively superior goal later.

The results of this investigation are discussed in relation to the decision-making capacities of juvenile offenders adjudicated in the adult criminal justice system. Since this is the first study to examine the relationship between the FRN and EF in adolescents, the investigation is exploratory.

Finally, although the same sample was used to establish age related differences in the FRN as well as to investigate the relationship between the FRN and EF, the EF analyses depended upon the findings from the FRN investigation. To enhance readability of the dissertation, these two stages of the investigation are presented in the format of two sequential studies: A general methods section immediately follows this introduction and provides justification for the sample used and describes the standard procedure for all participants, including how participants were recruited and selected. Study 1, entitled:*The feed-back related negativity in adolescents*, follows after the General Methods and is written in standard APA format for a single study, including a separate introduction, methods and results sections and discussion. Study 2, entitled:*The feedback-related negativity and executive function*, immediately follows the Discussion of Study 1, and is written in identical format. The dissertation concludes with aGeneral Discussion.The General Discussion summarizes the results of Studies 1 and 2 and discusses the results in the context of public policy concerning juvenile offenders.

CHAPTER 2: GENERAL METHODS

Participants

The final sample comprised 24 adolescent males (ages 14 – 16 years) and 26 young adult males (ages 22 – 25 years), who were recruited through the on-line classified advertisement website, Craigslist.com and direct advertisement in the community.

This investigation was restricted to male participants because a mixed-gender sample might have impeded the likelihood of detecting significant age-related relationships in neurophysiological processes. Males engage in disproportionately more risky behavior than females (Byrnes, Miller & Schafer, 1999), and there is evidence to suggest that this may be driven by gender-related differential development of the midbrain dopamine system (Andersen, Rutstein, Benzo, Hostetter & Teicher, 1997; Tanida et al., 2009). Also, since pubertal development has been linked with brain maturation (Giedd et al., 1999) and males and females develop at different rates, using an all male sample did not necessitate an assessment of pubertal status.

The age range for the adolescent participants was selected because, as described earlier, youth in this age range have been most affected by the changes in juvenile justice policy during the 80s and 90s. The majority of states that allow for the exclusion of an offender from the juvenile justice system on the basis of offense type alone (i.e., statutory exclusion) have set 14 or 15 years as the minimum age for exclusion (Heilbrun, Leheny, Thomas & Huneycutt, 1997). Consequently, youths between the ages of 14 and 16 who previously might have been evaluated individually before a transfer decision was made, are now automatically tried as adults.

Prospective volunteers were excluded if they met one or more of the following criteria: estimated IQ less than 80; past diagnosis of substance dependence or current diagnosis of substance abuse or dependence; endorsement of symptomatology consistent with a diagnosis of Attention Deficit/Hyperactivity Disorder; history of traumatic brain injury or history of epilepsy. A total of 64 participants were formally enrolled in the study. 14 participants were eliminated from the sample after data collection for reasons as follow: EEG recording issues (*n*=10); failure to complete either the EEG or the EF portion of study (*n*=2); incorrectly following task directions (*n*=1); impaired IQ (*n*=1). Table 1 provides demographic and IQ data for the final sample. Informed consent was obtained from all participants; for adolescents, parental consent and participant assent were obtained. The procedures used in this study met APA ethical guidelines for the treatment of human subjects and were approved by the Institutional Review Board of the John Jay College of Criminal Justice and the Graduate Center, City University of New York.

General Procedure

Participants who met the inclusion criteria were assessed across two separate sessions on the same or different days, in the psychology department of John Jay College of Criminal Justice. During the first session, a brief structured clinical interview and behavioral measures were administered by trained doctoral and masters level students and took approximately 1 to 1.5 hours per participant. The clinical interview comprised several direct questions about current and past drug use, lifetime history of head trauma and neurological illness (e.g., epilepsy) and history of abuse or neglect . As often as possible, for adolescent participants, this information was obtained from the parent or legal guardian. All prospective participants also completed self-report ADHD symptom scales and were administered the matrix reasoning subtest of the Wechsler Abbreviated Scales of Intelligence (WASI; The Psychological Corporation, 1999) as an IQ screen[2]. Demographic information (age, race, education, employment & ESL status) were also obtained at this time. Any participants who met exclusion criteria after this interview were not permitted to continue in the study and their clinical and demographic data was not retained; all others were administered the behavioral tests of EF discussed in Study 2 Methods. During the second session, EEG was recorded while participants performed a simple gambling task involving unpredictable monetary losses and gains of low and high magnitude. The EEG recording took approximately 2 to 2.5 hours. Participants who completed both sessions on the same day were given a break between sessions and offered snacks and refreshments. Parents of adolescent participants were offered a comfortable space in a nearby waiting area and were reminded that they could request that their child stop participating at any time. Participants were paid $15 for the interview and behavioral tasks and $25 dollars for the ERP task. In addition, to create incentive to perform to the best of their ability, participants were entered into various drawings for monetary prizes as described in the detailed procedures section for each investigation.

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[2] A change was made in the IQ assessment protocol part-way through the study, such that 16 adult participants were evaluated using the American North American Adult Reading Test (AMNART; Grober & Sliwinski, 1991). All other participants were evaluated using the Matrix Reasoning Subtest of the Wechsler Adult Scales of Intelligence (WASI; The Psychological Corporation, 1999). No adjustments were made to IQ estimates used in subsequent analyses; Est. IQ of adults administered AMNART was 6 points higher than the Est. IQ of adults administered the WASI.

CHAPTER 3: STUDY 1 – INTRODUCTION

The Feedback-Related Negativity (FRN) in Adolescents

Effective decision making relies, in part, on the ability to evaluate feedback and adapt behavior accordingly. As stated above, feedback processing appears to be mediated by the phasic activity of midbrain dopamine neurons that project to regions of the striatum, PFC and ACC. The midbrain dopamine system responds preferentially to environmental events with rewarding value, and signals the extent to which a rewarding outcome deviates from prediction during learning (see Schultz, 2002 for review). Rewards that are unpredicted or better than expected produce a phasic increase in dopamine response; in comparison, when rewards are omitted or worse than predicted there is a phasic decrease in dopamine. The dopamine response is therefore considered to function as an error prediction signal underlying reinforcement learning (Schultz, 2002).

Two event-related potentials, the feedback- related negativity (FRN) and the error-related negativity (ERN), have been associated with this error detection process (e.g., Falkenstein, Hohnsbein & Hoormann 1995; Gehring & Willoughby, 2002; Hajcak, Holroyd, Moser & Simons 2005; Holroyd, Nieuwenhuis, Yeung & Cohen , 2003; Müller, Möller, Rodriguez-Fornells & Münte, 2005; Nieuwenhuis, Holroyd, Mol, & Coles, 2004; Potts, Martin, Burton & Montague, 2006; Yasuda, Sato, Miyawaki, Kumano & Kuboki, 2004; Yeung & Sanfey, 2004; Yu & Zhou, 2006). In adults, the FRN is elicited by external feedback and peaks approximately 250 ms after feedback onset; whereas the ERN is elicited by internally generated feedback to a mistake, or the realization that one is about to make an error, and peaks within 100 ms after an erroneous response is made. On performance tasks for which right and wrong responses can be learned, external feedback is initially relatively unpredictable, resulting in large FRNs after feedback for an incorrect response. However, as associations are learned between choice and outcome, mistakes become apparent at the time they are made, resulting in larger ERN amplitudes. Since the recognition of a mistake predicts a negative outcome before it occurs, under these circumstances, ERN amplitude varies inversely with the amplitude of the FRN (Holroyd & Coles, 2002; Muller, Moller, Rodriguez-Fornels & Munte, 2005). This reciprocal relationship suggests that the ERN and FRN reflect the activity of a reinforcement learning system (Holroyd & Coles, 2002) and converging evidence suggests that both of these ERPs reflect dopaminergic activity at the ACC (see Nieuwenhuis et al., 2004, for review).

The Feedback-related Negativity (FRN)

Studies of the FRN in adults have consistently shown that the FRN is largest when environmental feedback is unfavorable and unexpected, such as after a monetary loss or being told that one has made an incorrect response. Most of these studies have reported that FRN amplitude has no reliable relationship with the magnitude of the feedback, i.e., the size of the rewards or losses (Hajcak et al., 2006; Gehring & Willoughby 2002; Yeung, Holroyd & Cohen, 2005; Yeung & Sanfey, 2004). Therefore, it has been widely suggested that the FRN reflects a binary evaluation of good versus bad outcomes (Yeung & Sanfey, 2004; Hajcak, Moser, Holroyd, & Simons, 2006). However, it cannot be ruled out that motivational differences in the value of rewards have a differential effect on the FRN. Goyer, Woldorff & Huettel (2008) reported an effect of reward magnitude on FRN amplitude, and although not statistically significant, inspection of the grand average waveforms in a study of the FRN in a blackjack paradigm

(Hajcak et al., 2006) revealed that the FRN was differentially sensitive to positive rewards of varying values.

Several other factors have also been shown to modulate FRN amplitudes to positive and negative feedback. For example, amplitude differences between FRNs elicited by positive and negative feedback are larger for people who score high on the personality trait extraversion (Smillie, Cooper & Pickering, 2010) and for individuals with genotypes associated with extraversion (Marco-Pallarés et al., 2009). Indirect clinical evidence suggests that this may be a result of lower tonic levels of subcortical dopamine in these individuals, which might be associated with increased phasic amplitudes in response to external feedback (Bilder, Volavka, Lachman, & Grace, 2004). In contrast, individuals for whom available extracellular striatal dopamine is presumed to be higher (e.g., individuals with type 1 alcoholism) should have reduced phasic amplitudes (Bilder et al., 2004). A recent study of the FRN in alcoholics provides evidence for this view (Kamarajan et al., 2010). For such individuals, it appears that larger (more salient) differences between feedback conditions might be required to produce a phasic increase in dopamine to rewarding feedback.

FRN and ERN in Children and Adolescents

Although this study investigates age-related changes in FRN, the close relationship of ERN to FRN (i.e., they are both error-prediction signals generated at the ACC) warrants a brief review of what is known about the development of both of these components. Several studies have investigated the ERN in children and adolescents. Very young children (7 to 10 years) do not produce ERNs when they make commission errors (Davies, Segalowitz & Gavin, 2004; Wiersema, van der Meere & Roeyers, 2007). Many studies report that ERN amplitudes increase with age and are still not adult-like by mid-adolescence (Davies et al, 2004; Hogan, Vargha-Khadem, Kirkham & Baldeweg, 2005; Santesso & Segalowitz, 2008; Segalowitz & Davies, 2004). However, others have attributed this apparent lack of maturation to performance confounds (Wiersema et al., 2007). Performance confounds are particularly problematic when studying error-related ERPs; for example, younger children might not produce ERNs (or show reduced ERNs) because they have not learned the rules of the task as well as older children and therefore do not always know when they have made a mistake. While it has been suggested that ERN amplitude is adult-like as early as 10 -12 years of age provided the task is not overly challenging (Eppinger, Mock & Kray, 2009), Santesso and Segalowitz (2008) reported that even though performance on a flanker task is adult-like by 15 to 16 years old, ERN amplitude is still smaller than that of adults.

Like the FRN, the ERN shows considerable inter-individual variation and some children show remarkably mature ERNs for their age (Segalowitz & Davies, 2004). Smaller ERN amplitudes have been associated with low empathy and high risk taking in adolescents and young adults (Santesso & Segalowitz, 2009) and with lower socialization among ten year olds (Santesso, Seglowitz & Schmidt, 2005). It has been suggested that more mature ERNs reflect greater social resilience and social competence (Segalowitz & Davies, 2004); that is, ERN amplitude may be correlated with ability to internalize information (e.g., social norms) conveyed by external feedback (Eppinger et al., 2009).

Fewer studies have examined the FRN in children and adolescents. FRNs have been recorded and compared in children with and without Attention Deficit/Hyperactivity Disorder (ADHD) (Holroyd, Baker, Kerns & Mueller, 2008; van Meel, Oosterlaan, Heslenfeld & Sergeant, 2005) and in adolescents with and without prenatal cocaine exposure (Crowley, Wu, Crutcher, Bailey, Lejuez & Mayes, 2009) and trait surgency (Segalowitz et al., 2011), but none of these studies included adult comparison groups. As of this report, only two studies have compared the FRN in normally developing children and adults (Hammerer, Li, Muller & Lindenberger, 2011; Eppinger et al., 2009) and only one included an adolescent sample (Hammerer et al., 2011).

Hammerer et al. (2011) used a reinforcement-learning task to elicit FRNs in a relatively large sample of 44 children (9 – 11 years), 45 adolescents (13 – 14 years), 46 young adults (20 – 30 years) and 44 older adults (65 – 75 years). Slightly more than half the sample was male; other demographic data were not reported. The ERP task required that participants learn the associations among several symbols and the probability for winning or losing a set amount of money. The authors reported that the amplitude of the FRN was largest in children and decreased with age. The children also had smaller differences between FRN amplitudes in response to losses and gains than did adolescents and young adults. Since adults and adolescents performed better on the task, the authors attributed better learning to the stronger differentiation of the FRN. However, it also possible that that the smaller differentiation of the FRN in children was a *result* of the fact that the children took longer than the adolescents and young adults to learn which symbols were associated with a higher probability of winning, rather than the cause. Since the FRN is modulated by expectancy, its amplitude should change over the time-course of learning (Holroyd & Coles, 2002; Müller et al., 2005). Participants who learned the task faster would be expected to have larger FRNs after unexpected negative feedback (i.e. receiving a monetary loss when choosing a symbol they have learned is associated with a high probability of winning). This possible confound makes it difficult to tease apart the relationship between FRN amplitude and task performance (see Segalowitz & Davies, 2004). Although not statistically significant, Hammerer et al. (2011) also reported weaker FRN discrimination between wins and losses for their adolescent sample compared to the young adults.

The present study investigates the FRN in normally developing adolescent and young adult males, using a simple gambling task without a performance component. Given the aim of this investigation — to establish normative age-related differences in the FRN — the task was intentionally chosen to minimize the performance confound that is inherent in reinforcement learning paradigms. The task, adapted from Yeung and Sanfey, (2004), required participants to choose between two colored cards with unpredictable monetary gains and losses. Participants could never learn to expect wins or losses; therefore, the size of the FRN to losses compared to gains could not be compromised by differences in expectancy that were a direct result of learning.

In contrast, although participants could not learn to associate card color with valence of the outcome (loss or gain), card color was associated with the size of the loss or the gain. In this way, this study also allowed investigation of the effect of reward magnitude on FRN. This phenomenon has not yet been studied in adolescents.

In their sample of college freshman, Yeung and Sanfey (2004) reported that FRN was sensitive only to wins and losses, and was not affected by the magnitude of the outcomes. However, a recent fMRI study suggests that small rewards are not as motivationally salient to adolescents as they are to adults (Galvan et al., 2006); for adolescents, but not adults, receipt of small rewards was associated with reduced activity in the nucleus accumbens, an area of the brain commonly activated by rewarding stimuli. It is possible that reward processing is different in this population. If so, this might underlie some of the developmental differences between adults and adolescents in decision making and executive functions that rely on feedback processing. Based on previous reports in children and adolescents (Eppinger et al., 2009; Hammerer et al., 2011), for the current study, it was hypothesized that FRN amplitudes would be larger in adolescents than in adults. Furthermore, since the ERP task did not include a significant learning component, it was expected that adolescents would show less differentiation in FRN amplitude between gains and losses compared to the adults. The latter hypothesis was based on converging evidence from animal studies, and to a lesser extent human research, suggesting that there is relatively higher availability of striatal dopamine during adolescence relative to adulthood and childhood (see Wahlstrom, White, & Luciana, 2010, for review), which might inhibit the phasic activity of midbrain dopamine neurons (Bilder, Volavka, Lachman, & Grace, 2004) . Finally, although a gambling paradigm can be used to investigate risk taking if some choices are considerably riskier than others, this task was constrained in such a way that the behavior of the participant had minimal effect on outcome. Therefore, the behavioral data (i.e., card choices) for the ERP task itself were of limited interest in this study. Nonetheless, it was hypothesized that adolescents would be more likely than adults to consistently choose high magnitude cards.

CHAPTER 4: STUDY 1 METHOD

Procedure

ERP task. The stimuli for this study, depicted in Figure 1, were adapted from Yeung and Sanfey's study (2004) who recorded the FRN in a sample of young adults. Stimuli were presented using ePrime 2.0 (Psychology Software Tools Inc.,) on a Dell 1908 Flat Panel LCD monitor.

Participants were told to try to win as much money as possible by choosing between two colored cards that were associated with unpredictable monetary gains and losses. Four card colors were used. For every participant, two of the colors were always associated with large magnitude gains or losses; and two were always associated with low magnitude gains or losses. Hence, there were four experimental conditions: High gain, low gain, high loss and low loss. A total of 480 trials were presented, these were divided into 15 equal blocks of 32 trials each. Participants were given the opportunity to rest between blocks. On each trial, participants were presented with a choice between two cards, presented side by side. The participant pressed either the right or left mouse button to indicate which card he had chosen. Participants were free to use whichever hand they wanted to make their response, since the FRN is time-locked to the feedback received but not this behavioral response. The card chosen by the participant was accented with a white border for 500 ms, after which time a positive (win) or negative (loss) number was displayed on the card for 1000 ms indicating how much the participant won or lost on that trial. There was a 500 ms inter-trial delay.

Card presentation was pseudo-randomized. On half of the trials participants had to choose between two high magnitude cards or two low magnitude cards. On the other half of the trials, participants chose between a high magnitude card and a low magnitude card. Each participant experienced an equal number of gains and losses on cards selected; however, the proportion of low to high outcomes depended entirely on the participants' choices. Since valence was unpredictable, the selection of a high magnitude card over a low magnitude card was considered a slightly more risky choice. The low magnitude outcomes ranged between 6 and 11 cents and high magnitude outcomes ranged between 32 and 40 cents; the frequency of outcomes were weighted such that the expected winnings of each participant over the course of the experiment was $4.80. Therefore, in reality no choice was especially risky, since losses were recouped over the course of the study. Participants were not told about these constraints, but were simply told to try to make as much money as possible using whatever strategy they believed would maximize their winnings. Cumulative winnings were shown after each block. To provide motivation, participants were told that they could take home whatever they won on the gambling task.

Recording procedures. EEG was recorded using a Neuroscan SynAmps RT system and Neuroscan acquisition software (version 4.4) with a 64-channel Quikcap, with sintered silver/silver chloride electrodes, referenced to a midline central electrode. All electrode impedances were maintained below 5 kΩ and EEG was continuously recorded with a bandpass of 0.1 – 1000 Hz and digitized at 1000 Hz. All analyses were performed offline using Neuroscan 4.4 Edit software. Data were re-referenced to averaged mastoids. Separate 1200 ms epochs, beginning 200 ms before feedback, were digitally filtered with a band pass of 1-30Hz, using a 200 ms pre-feedback baseline, and averaged for each condition for every participant. Sweeps in which amplitudes exceeded +/- 50 μV were rejected.

Grand average waveforms were visually inspected to verify the presence of the feedback response, which was identified as a slow positive wave (P3) with a superimposed negative deflection (FRN) peaking approximately 250ms following feedback onset at the frontocentral recording sites (Yeung et al., 2005). To allow for individual variations in the timing of the ERP waveforms, the latency of the FRN was determined using individual averages for each condition. Latencies were measured at Fz, where the FRN was maximal. The leading edge of the P3 (hereafter P2, following Hammerer et al., 2011) was identified as the most positive peak in the 150 – 300 ms window following feedback and the FRN was identified as the subsequent negative peak in the 200 – 425 ms window. This latency window is consistent with that used in a recent study of FRN in adolescents (Segalowitz et al., 2011). Following Hammerer et al. (2011) and Hajcak et al. (2006), the FRN amplitude was measured peak-to-peak as the difference between the P2 and the FRN. While the FRN has alternatively been measured as the difference between the most negative peak following feedback and the average amplitude of the preceding and subsequent positive peaks (e.g., Yeung & Sanfey, 2005), the Hammerer et al., 2011 investigation is the only existing study of FRN in normative adolescents; analogous measurement will allow the data from this study to be more directly comparable to theirs.

Analyses

It is well established that the FRN is maximal at frontocentral sites in adults (Nieuwenhuis et al., 2004). However, across studies FRN amplitude has been frequently quantified at the single electrode site where it has been maximal, most often at Fz (e.g., Hajcak et al., 2006) or FCz (e.g., Yeung & Sanfey, 2004) and at least once at Cz (Hirsch & Inzlicht, 2008), or averaged over frontocentral midline electrodes (Pfabigan et al., 2010; Santesso et al., 2009). Therefore, to avoid capitalizing on chance as to where FRN is maximal, FRN amplitude was measured at a cluster of 6 frontocentral electrode sites (Picton et al., 2000), (F1, FZ, F2, FC1, FCZ, FC2), that extend only minimally from the midline. FRN amplitude was entered as the dependent variable in a repeated-measures ANOVA with Electrode (6), Magnitude (high, low), Valence (gain, loss) as within-subjects factors, and Age group (adult, adolescent) as a between-subjects factor.

Based on Hammerer and colleagues' report (2011), FRN amplitude was expected to be larger for adolescents than adults. To examine the relative difference in FRN after gains compared to losses, independent of age-related differences in FRN amplitude, ratio scores (defined as [Loss-Gain]/[Loss]) were calculated for high and low magnitude conditions for each participant and these scores were subjected to similar analyses (see Hammerer et al., 2011 for similar calculation). If there are differences in the efficacy of the signal that generates the FRN, these differences might be due to relative changes from baseline, as opposed to absolute amplitude differences between losses and gains (Holroyd & Coles, 2002). Greenhouse-Geisser corrections were used when assumptions of sphericity were violated.

To test for age-related latency differences, FRN peak latency was entered as the dependant variable in a separate repeated-measures ANOVA with Magnitude (high, low) and Valence (gain, loss) as within-subjects factors and Age group (adult, adolescent) as a between-subjects factor.

Finally, this task was selected to minimize performance confounds associated with learning; therefore, the behavioral data from the ERP task itself is of limited interest. Nonetheless, it was hypothesized that adolescents would choose risky cards more often than the adults. However, post-experiment questioning revealed that a large portion of the participants did not learn to associate card color with reward magnitude; therefore, a test for this hypothesis is not readily interpretable. To ensure there was no statistical differences in card choices between groups that may have been a result of implicit learning, the number of high magnitude (risky) card choices was calculated for trials in which a choice was made between a high and low magnitude card (n=240) for adolescents and adults separately and a t-test was conducted.

CHAPTER 5: STUDY 1 RESULTS

FRN

Visual inspection of the grand average waveforms showed that the FRN was largest at frontocentral electrode sites and was maximal at Fz for both age groups. Figures 2a and 2b show grand average waveforms for adults and adolescents, respectively, in all four conditions at the electrode sites included in the analysis. Table 2 contains the mean FRN amplitudes for adolescents and adults for each condition. As expected, the amplitude of the FRN was larger in adolescents than adults in every condition, $F(1,48) = 22.73$, $p <. 0001$, $\eta_p^2 = .32$, and consistent with other studies (e.g., Gehring & Willoughby, 2002; Potts et al., 2006; Yeung & Sanfey, 2004), FRN amplitude was larger after losses than gains, $F(1,48) = 136.28$, $p < .0001$, $\eta_p^2 = .74$. There was also a Magnitude by Valence interaction, $F(1,48) = 16.76$, $p < .0001$, $\eta_p^2 = . 26$.

Post-hoc comparisons of the interaction, using a Bonferroni adjusted alpha value of .008, revealed no significant difference in FRN amplitude between High Loss and Low Loss conditions ($p = .14$), but a significantly larger FRN was elicited by the Low Gain condition compared to the High Gain condition ($p < .0001$), and both Gain conditions were significantly different from both Loss conditions ($p < .0001$ for all comparisons). This was true for adults, $F(1,25) = 16.49$, $p < .0001$, $\eta_p^2 = .40$, and adolescents, $F(1,24) = 4.74$, $p = <.04$, $\eta_p^2 = .17$.

There was no Electrode by Age group interaction, suggesting that the distribution of the FRN in the cluster of six electrodes used for measurement was similar for both adults and adolescents.

Table 3 contains the mean ratio scores of adults and adolescents for high and low Magnitude conditions. Ratio scores were larger for adults than for adolescents, in both low and high Magnitude conditions, $F(1,48) = 5.91$, $p = .019$, $\eta_p^2 = .11$, suggesting that the neural processes that the FRN reflects discriminate between good and bad events somewhat more strongly in adults than in adolescents. Consistent with the Magnitude by Valence interaction reported above, the ratio scores were greater for high Magnitude conditions than for low Magnitude conditions regardless of Age group, $F(1,48) = 35.13$, $p <. 0001$, $\eta_p^2=.42$. Finally, ratio score differences between adults and adolescents were more pronounced for high Magnitude conditions compared to low, but the Magnitude by Age interaction did not reach significance, $F(1,48) = 1.702$, $p = .198$, $\eta_p^2 = .03$.

Given that adolescents had larger FRN amplitudes than adults in all four conditions, their significantly smaller FRN ratio scores imply that valence had a disproportionate effect on FRN amplitude for either losses or gains. Inspection of the mean FRN amplitudes (Table 2) shows that for losses, adolescent FRNs were about 1.5 times larger than adult FRNs. In comparison, adolescent FRNs were about 2.4 times larger than adult FRNs in the high gain condition, and 1.6 times larger in the low gain condition. Therefore, the significantly smaller FRN ratios for adolescents compared to adults appears to be primarily driven by disproportionally more negative FRNs after gains (specifically high gains) in adolescents. This is also reflected in the grand average waveforms, which show an easily identifiable FRN in the high gain condition for adolescents (Figure 2b) but not for adults (Figure 2a).

Table 4 contains the mean latencies of the FRN for each condition for adolescents and adults. There were main effects of both Magnitude, $F(1,48) = 13.27$, $p = .001$, $\eta_p^2 =$

.22, and Valence, *F(*1,48) = 19.45, $p < .0001$, $\eta_p^2 = .29$, on latency, qualified by a Magnitude by Valence interaction, *F(*1,48) = 15.64, $p < .0001$, $\eta_p^2 = .25$. Post-hoc comparisons, using a Bonferroni alpha correction of .017[3], revealed that the FRN in the High Loss condition was significantly later than the FRN in all other conditions; latency in the low loss and low gain conditions did not differ significantly. This is reflected in the grand average waveforms (Figures 2a and 2b). There was neither a main effect of Age, nor an Age by condition interaction effect, on latency. However, qualitatively, the FRN to high losses had a broader waveform in adolescents than it did in adults. This broader waveform is visible in the individual averages and therefore its morphology in the grand average is representative of the individual data and is not due to increased variability in the adolescent peak latencies compared to the adults. The standard deviations of the latency data for adults (38.6) and adolescents (45.9) in the high loss condition were not significantly different, *F(*1,34) = 1.66, $p = .30$.

Figure 3 shows the topographical distribution of FRN difference waves at the scalp for each group, made by subtracting the grand average gain waveform from the loss waveform, for the high Magnitude conditions. The topographical distribution had a more diffuse and posterior distribution for adolescents compared to adults.

Behavioral Results

There were approximately equal numbers of high and low magnitude trials in the grand average waveforms for adolescents and adults. The number of high magnitude cards chosen by adolescents (M = 133) and adults (M = 126) did not differ significantly ($p = .30$).

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[3] Since both High and Low Gain conditions were measured at the same latency, only three post-hoc comparisons for latency were made: (HL-LL; HL-HG; LL-HG)

CHAPTER 6: STUDY 1 DISCUSSION

Consistent with Hammerer et al., 2011, our data show that adolescents have larger FRNs than adults. However, several other immaturities were also observed. As predicted, despite overall larger FRN amplitude in adolescents, FRN loss/gain ratio scores were significantly smaller for the adolescent participants than for the adults. Hammerer and colleagues (2011) also reported a non-significant effect in this direction in their mixed gender sample. This suggests that the dopaminergic feedback signal in adolescents is not as effective in differentiating between good and bad outcomes as it is in adults. The ratio score difference in this sample appears to be due to proportionally larger FRNs in the gain conditions for adolescents (especially high gains) compared to the adults. This difference might be related to increased availability of dopamine in adolescents relative to adults. Data from animal and, to a lesser extent, human research suggest that striatal dopamine levels are higher in adolescence than they are in childhood or adulthood (Wahlstrom et al., 2010). Excess synaptic dopamine might inhibit the phasic response to external stimuli, requiring greater stimulation for a phasic change to occur (Bilder et al., 2004). Perhaps the “good” was not “good enough” to elicit as large a phasic increase in dopamine in the adolescents compared to the adults in this sample. This interpretation is also in line with an fMRI study that showed that adolescent approach behavior is driven by large but not small rewards (Galvan et al., 2006). Accordingly, individuals with type 1 alcoholism, for whom available extracellular striatal dopamine is presumed to be relatively high, also show reduced FRN ratios to positive and negative feedback (Kamarajan et al., 2010). Whereas extraverts (Smillie, Cooper & Pickering, 2010) and individuals with genotypes associated with extraversion (Marco-Pallarés et al., 2009) have lower tonic levels of dopamine (Bilder et al., 2004) and show an enhanced differentiation in FRN amplitude to positive and negative feedback.

These results also suggest that the FRN elicited by gains (especially high gains) is disproportionately immature compared to the FRN elicited by losses. If this is so, it is possible that that the neural mechanisms that respond to positive and negative feedback might develop at different rates. This interpretation is consistent with that of others who have posited that feedback to gains and losses are mediated by separate brain processes (Kamarajan et al., 2009; Nieuwenhuis, Slagter, von Geusau, Heslenfeld, & Holroyd, 2005), and with intracellular recordings in primates show evidence of differential coding by dopamine neurons for rewarding and aversive stimuli (Matsumoto & Hikosaka, 2009).

A recent paper by Holroyd, Pakzad-Vaezi and Krigolson (2008) has shed light on how losses and gains might modulate the FRN. The authors proposed that unexpected task-relevant feedback essentially acts like an oddball stimulus (i.e., a stimulus that occurs infrequently and randomly during a series of repeated expected stimuli) and generates an N200. The N200, described earlier in the context inhibition of a prepotent response, is a negative deflection that occurs approximately 200 ms after the unpredicted oddball stimulus is presented. Hence, the authors suggested that the FRN and the N200 can be considered to be the same physiological phenomenon; they are both negative waves generated in the ACC and elicited by unexpected task-relevant stimuli (see also Pfabigan et al., 2010; Hajcak et al., 2007). This would imply that, if feedback in a paradigm is always unexpected, then the modulation of FRN amplitude is driven primarily by neural activity elicited by positive, correct or rewarding feedback. According to Holroyd et al., (2009), this secondary process (presumably a phasic increase in dopamine) either inhibits the process that produces the N200 or generates a superimposed positivity. Effectively, when the unexpected outcome is good, the FRN is washed out, or greatly reduced by the superimposed positivity. In the present study, the valence of the outcome was not predictable; hence, according to this hypothesis, all feedback should have elicited an FRN, but rewarding outcomes should have resulted in a substantial reduction of the FRN amplitude. The reduction in FRN amplitude after gains was more pronounced for the adults in our sample than for the adolescents, and this difference was most evident in the high gain condition (see Table 3).

Interestingly, as seen in the grand average waveforms (Figs. 2a and 2b) and in Table 2, neither the adults nor the adolescents showed a pronounced reduction in the amplitude of the FRN to Small Gains, however they did to High Gains; this was supported quantitatively by an overall significant Magnitude by Valence interaction for FRN amplitude. Therefore, while high and low losses resulted in similarly large FRNs, the low gain condition elicited smaller FRN amplitudes than loss conditions but larger FRN amplitudes compared to the high gain condition. This result was not predicted (at least not for adults), given that Yeung and Sanfey (2004), who used a similar research paradigm to elicit the FRN in college undergraduates, found that the magnitude of a loss or a gain did not affect the FRN.

There are at least two possible explanations that might account for this result, both of which could be contributory factors. First, although responses were not formally aggregated, after the study was completed many of the participants (> 50%) reported that they did not associate a card color with a specific magnitude (high/low). Therefore, it is unclear if the participants did, in fact, expect large gains/losses when choosing high magnitude cards or small gains/losses when choosing low magnitude cards. Since the FRN has been shown to reflect errors in prediction of positive *or* aversive outcomes (e.g., Hajcak et al., 2007; Oliveira, McDonald & Goodman, 2007; Pfabigan et al., 2010), violations of expectancy may account, in part, for the Magnitude by Valence interaction obtained. In a gambling task where outcomes are unpredictable, it is assumed that participants always hope for a big win. Therefore, any outcome that violates this expectation is considered less desirable. Consequently, if card color did not alert the participant to expect a low magnitude outcome, small gains could have been be perceived as unfavorable. However, it is notable that this pattern is seen in almost all the subjects at the individual level. Given that many of the participants did correctly state the rule (that color was associated with magnitude), expectancy cannot fully explain the interaction between Valence and Magnitude.

The discrepancy between these results and those of Yeung and Sanfey might also be due to gender differences between the samples. Yeung and Sanfey used a small (n=15) mixed-gender sample, whereas all the participants in the present study were male. Using a similar task with male and female adults, Grose-Fifer, Saul, Yuksel-Sokmen, Zottoli, Hoover and Navarro (2011) have shown a Valence by Magnitude interaction for males, but not for females, such that more males than females had large FRNs to small gains. Kamarajan et al. (2009) also reported an effect of reward magnitude on FRN amplitude for males but not females, such that on average small rewards resulted in more negative FRNs than large rewards in males, but not in females. It is possible that low magnitude rewards are processed as negative outcomes relative to large magnitude rewards by males, regardless of expectancy, but this hypothesis requires further investigation.

At the very least these data suggest that the FRN does not reflect a simple binary evaluation of good versus bad outcomes, but that it appears to co-vary with the subjective relative value of rewarding options. This is not the only study demonstrating a significant effect of reward size on FRN amplitude (Goyer, Woldorff & Huettel, 2008), and it is not inconsistent with the reinforcement learning theory put forward by Holroyd and Coles, who initially hypothesized that the FRN would vary as a function of the subjective value of rewards (Holroyd & Coles, 2002; Nieuwnehuis et al., 2004).

Finally, longer latencies in loss conditions compared to gains are also reported; and although no age related latency differences were found, qualitatively, adolescents had broader waveforms to high losses compared to the adults, suggesting the processes that mediate the evaluation of negative external feedback might be less efficient in adolescents.

Although these results suggest that the FRN is immature in mid-adolescence, and that there are age-related differences in the relative sensitivity to losses and gains, these data do not allow for speculation as to how exactly FRN amplitude is related to the modulation of future behavior. The FRN likely reflects a fast and non-specific dopamine response; how this signal is used by the brain and how it influences behavior depend on its effect on post-synaptic structures (Schultz, 2002). Since the task used to elicit the FRN was explicitly chosen to eliminate performance confounds, data from the ERP task itself is also of limited value in establishing how differences in the FRN are related to differences in behavior.

To date most studies examining the FRN have not used independent behavioral measures to assess the relationship between the FRN and other cognitive functions and decision-making behaviors (but see Crowley et al., 2008; Kamarajan et al., 2009) and no study has looked specifically at FRN and EF. Thus, it is presently unknown if, or to what extent, the neural processes that generate the FRN contribute to executive function and decision-making. The age-related differences obtained in the present study support the use of the FRN as an index of cortical (or functional) maturity, which can be examined as a correlate of performance on independent tasks of EF. Given that FRN amplitude probably reflects phasic activity of mid-brain dopamine neurons received at the ACC, its measurement should be correlated with tests that also require feedback processing for effective performance, especially if those tests recruit ACC or areas of the cortex that the ACC projects to (e.g., OFC).

In addition, there are data to suggest that the phasic activity of midbrain dopamine neurons is attenuated (or enhanced) in individuals with genotypes that are associated with too low (or to high) COMT activity. COMT is an enzyme that metabolizes extracellular dopamine, and individuals with low COMT activity show clinically significant levels of cognitive rigidity, difficulty updating knowledge stores and switching attention. In contrast, higher levels of COMT are correlated with increased distractibility and inability to maintain cognitive sets (see Bilder et al., 2004 for review).

Low COMT activity results in higher than normal tonic dopamine levels (Bilder et al., 2004). It is thought that excess dopamine in the synapse might attenuate the phasic response to external stimuli because greater stimulation is required to reach the required threshold for a change in state (Bilder et. al., 2004). In support of this, at least two studies have shown that the FRN is modulated by genotypical differences in individuals with polymorphisms associated with COMT over or under-activity (Marco-Pallarés et al., 2009; Smillie et al., 2010). These data suggest that attenuated or enhanced differentiation of the FRN might be related to reduced cognitive flexibility or stability; if so, then FRN amplitude might also be associated with performance on tasks that require flexibility in thinking, such as the WCST.

CHAPTER 7: STUDY 1 – INTRODUCTION

The Feedback-Related Negativity and Executive Function

Executive function (EF) is an umbrella term used to describe a set of global functions that include volition, planning, purposeful behavior and effective performance (Anderson, Northam, Hendy & Wrennal, 2001; Lezak, Howieson & Loring, 2004). The executive functions allow us to exert cognitive control over emotions and behavior, resulting in adaptive decision-making (e.g., Lezak. 2004). An important goal of this study was to establish the contribution of neural maturity (as indexed by the FRN) to age-related changes in executive function.

Specifically, this investigation focused on the relationship of the FRN to performance on the Wisconsin Card Sorting Test (WCST; Heaton, 1981), the Iowa Gambling Task (IGT; Bechara et al.,1994) and a Delayed Discounting Task (DDT) – measures of executive function that assess adaptive use of external feedback and/or reward processing.

The WCST task was developed to assess capacity for abstraction and the ability to shift cognitive strategies to match changing external rules (Strauss, Sherman & Spreen, 2006). Successful performance on the WCST requires cognitive flexibility, or the ability to use feedback from the environment to change previously learned behavior. The task requires that the participant learn a sorting rule via the process of trial and error; and, once learned, be able to recognize when the rule changes and then learn and apply the new rule. There are no long-term wins or losses associated with the participant’s choices; the strategy the participant must employ is related only to the discovery of each new rule. Thus, the task requires cognitive flexibility and analytical reasoning, but includes no affective component. The WCST has been long been touted as a test sensitive to prefrontal dysfunction, and the vast majority of imaging studies have shown increased activation in frontal regions (most often DLPFC) during task performance (see Nyhus & Barceló, 2009 for review). Nonetheless, this is a complex task, and successful performance recruits widely distributed networks of brain regions, each of which are associated with different aspects of the task (e.g., parietal cortex and basal ganglia). Consequently, performance deficits on the task are *not* specific to lesions of the PFC (Nyhus & Barceló, 2009).

By the age of 9 or 10 years, performance on the WCST appears to be adult-like with regard to the number of sorting categories completed and the number of perseverative errors made (Chelune & Baer, 1986; Chelune & Thompsen, 1987, as cited by Strauss, Sherman & Spreen, 2004; Kizilbas & Donders, 1999;). The task was designed to assess deficits in abstraction and cognitive flexibility (Berg, 1948); because of this, ceiling effects render it of limited use in studying whether or not there are small changes in flexibility and abstraction abilities between adolescence and adulthood (e.g., Arffa, Lovell, Podell & Goldberg, 1998). However, as discussed earlier in this paper, it is not yet known how the dopamine signal, reflected by the FRN, is used by the brain to modulate future behavior. Based on studies of patients with genotypes that are associated with higher or lower levels of sub-cortical dopamine who appear to show, respectively, more behavioral rigidity or instability than others, Bilder et al. (2004) have suggested that disproportionately large or small phasic shifts in midbrain dopamine neurons might be associated with measures of cognitive flexibility. If FRN ratio scores are related to cognitive flexibility, it is possible that performance on the WCST might be explained in part by FRN ratio scores. On the other hand, performance on the WCST does not appear to be associated with OFC, ACC and limbic regions; therefore, a dissociation of FRN and WCST is also reasonable, and would add empirical weight to the hypothesis that the FRN reflects the arrival of midbrain dopamine signals at the ACC.

In contrast to the WCST, the IGT includes an affective decision-making component (Bechara et al., 1994). The IGT assesses the ability to use feedback to adapt behavior in the service of a future goal in an emotionally charged context of reward, punishment and uncertainty of outcome (Bechara et al., 1994). Negative outcomes on the task have been associated with changes in physiological arousal (e.g., Jenkinson, Baker, Edelstyn & Ellis, 2008). The IGT requires that the participant identify, via trial and error, which two of four decks will provide him or her with the most opportunity for monetary gain over the course of the task. Over time, the participant must learn which decks are advantageous, and then must choose more cards from those decks, than the others, to realize the largest possible award.

Specifically, two of the decks (A and B) result in long-term loss, while the other two (C and D) result in long term gain; however, the decks are also related by the predictability and frequency of rewards and punishment. Although Deck A is disadvantageous and Deck C is advantageous, both are associated with high frequency rewards and losses. In contrast, Deck B is disadvantageous and Deck D is advantageous, but both pay out frequent rewards interspersed with infrequent and unpredictable losses. In addition, both disadvantageous decks (A and B) pay out larger magnitude rewards and losses than both advantageous decks (C and D), and of the two advantageous decks, Deck D pays out higher magnitude rewards and losses than Deck C. Likewise, Deck B is associated with higher magnitude losses and wins than Deck A. Table 5 summarizes the relationships among the decks and reward magnitude and frequency.

The best performance on the task is only possible if a participant can withstand some short-term loss for the possibility of long-term gain (Bechara et al., 1994). The IGT, therefore, requires the ability to utilize feedback from the environment to learn reward and punishment contingencies and to adapt behavior accordingly, as well as the ability to withstand short-term negative consequences to obtain an objectively more desirable future goal (Bechara et al., 1994).

The IGT is purported to reflect real-world decision making and has been shown to be very sensitive to damage to the OFC (Bechara et al., 1994; Bechara, Tranel, & Damasio, 2000). Healthy adults are generally able to learn which decks are advantageous, with a tendency to prefer D over C, even though both are advantageous. This is probably related to the fact that Deck D pays out comparatively larger wins, and results in less frequent losses. Preference for Deck A is usually found only among patients with bilateral VMPFC lesions who tend to opt for cards that pay out high immediate gains regardless of the long-term consequences (Becahara, Tranel & Damasio, 2000). Imaging and lesion studies have consistently implicated OFC involvement in IGT task performance (Bechara, Tranel & Damasio, 1996; Northoff et al., 2006), but recruitment of the DLPFC (Manes et al., 2002; Clark et al., 2003; Christakou, Brammer, Giampietro, & Rubia, 2009), insula, ACC, presupplementary motor area (pre-SMA), and amygdala (Ernst et al., 2002; Bolla et al., 2003, 2005) have also been reported. Using a variant of the task that temporally separated decision making from evaluation of outcome, Christakou and colleagues (2009) have shown that, for adaptive responding, both

VMPFC and DLPFC activity mediates the shift away from disadvantageous decks to advantageous decks. In participants who perform successfully, confirmatory feedback that a deck is disadvantageous gradually accumulates until it results in a shift away from the disadvantageous deck. In this study, expected negative outcomes were associated with increased activity in the VMPFC and the DLPFC (Christakou et al., 2009).

Age has consistently been shown to affect performance on the IGT, with most studies reporting that adults outperform children and adolescents in net advantageous picks (Crone & van der Molen, 2007; Crone & van der Molen, 2004; Crone, Vendel & van der Molen, 2003; Hooper, Luciana, Conklin & Yarger, 2004). It has been suggested that improvement between childhood and adolescence reflects increasing sensitivity to future consequences, rather than reward sensitivity or punishment avoidance (Crone, Vendel & van der Molen, 2003). However, a recent reanalysis of the Crone & van der Molen (2004) data by Huizenga, Crone and Jansen, (2007) has led to revision of their conclusion. The authors suggested that age-related differences do not support a simple “myopia for the future” hypothesis, but are better explained by developmental change in the application of a rule that considers only the frequency of losses encountered to the application of rules that consider both the relative magnitude of wins and losses and the frequency of losses (Huizenga et al., 2007). This result appears to reflect improvements in analytic reasoning, and thus it is not surprising that children perform more poorly than adolescents and adults on the IGT. However, given that the weight of the existing literature suggests that analytical reasoning reaches adult levels by middle adolescence (Steinberg, 2007), a rule-based account cannot as easily explain adult-adolescent differences on the task.

Recently Cauffman et al., (2010) looked at IGT performance in a large and diverse sample of 901 children, adolescents and adults (ages ranging from 10 to 30 years). Using a sophisticated version of the IGT that allowed independent analysis of approach (changes in percentage of plays from advantageous decks) and avoidance (changes in percentage of plays from disadvantageous decks) behavior, the authors reported that by age 14, adolescents and adults did *not* differ on net advantageous picks over the course of the game. However, there were clear differences that emerged in the strategies employed, such that adolescents learned more quickly to approach advantageous decks than adults, whereas adults learned more quickly to avoid disadvantageous decks than adolescents (Cauffman et al., 2010). The authors interpreted these results in the context of the recently espoused hypothesis, discussed earlier, that in adolescence the limbic-striatal-driven “appetitive system” matures prior to the orbitofrontal “control system” (Galvan et al., 2006).

Finally, DDTs measure the rate at which an individual discounts a delayed (future) reward to its present-day value; in other words, DDTs measure the break point at which an immediate reward will be preferred to a delayed reward of higher magnitude. For an example, compared to an immediate reward of $10, the discounting parameter estimates how much larger a value is required by an individual before he or she will prefer to wait a specified period of time to receive the larger reward. This parameter quantifies the degree to which one is willing to delay immediate gratification to obtain an objectively superior reward at a later point in time, and has been associated with “future orientation,” or a tendency to make decisions in the service of one’s long term best interest (Steinberg et al., 2009). Accordingly, individual differences in discounting rates have been linked to risky behaviors such as smoking, drug use and pathological gambling (see Reynolds, 2006 for review).

While performance on DDTs does not depend on feedback from the environment, it does involve option evaluation and reward processing, and is a direct measure of value-laden decision-making behavior. Performance on discounting tasks has been shown to activate ventral and dorsal frontal systems, including VMPPC, DPLPC and cingulate cortex, as well as the amygdala and ventral striatum (Cardinal, Winstanley, Robbins & Everitt, 2004; Kheramin et al., 2004; Kobayashi & Schultz, 2008; see Christakou, Brammer & Rubia, 2011 for additional references) and is correlated with performance on the IGT (e.g., Olson, Cooper, Collins & Luciana, 2007).

Age has been correlated with discounting behavior. Discounting has been shown to decrease with age up through the early twenties; children discount more steeply than adolescents (Olson et al., 2007; Scheres et al., 2006; Steinberg, 2009) and college-aged adults (Steinberg, 2009), who in turn discount more steeply than older adults (65+ years; Green, Fry, & Myerson, 1994). In normal, healthy adults, the decline in discounting appears to plateau by age 30 (Green, Myerson, Lichtman, Rosen, & Fry, 1996). Importantly, age related changes in discounting have been linked to post-pubertal increases in the connectivity of limbic frontostriatal circuitry (i.e., OFC, ACC, and ventral striatum; Christakou, Brammer & Rubia, 2011) and to age-related changes in white matter organization (i.e., myelinization) of the frontal and temporal lobes (Olson, Collins, Hooper, Muetzel, Lim & Luciana, 2009).

Based on the results reported by Cauffman and colleagues (2010), it was expected that age-group differences on the IGT would be more apparent at the level of deck preference than on overall advantageous picks. Clear between age-group differences were also expected for DDT discounting rate. Since most studies report that WCST performance reaches adult levels at ages younger than those studied here, between age-group differences on the WCST were not predicted.

Because this is the first study to examine the relationship of the FRN to performance on independent measures of executive function, relatively few hypotheses were specified. Both the IGT and the WCST require the adaptive use of feedback for successful performance, but only the IGT entails an evaluation of the motivational significance of outcomes. Similarly, while the DDT does not rely on the utilization of feedback, both DDT and IGT tasks involve the processing of rewards. Both DDT and IGT also assess the degree to which one can accept short-term loss in the service of long-term goals, whereas this is not true for WCST. Also, the IGT and DDT, but not the WCST, have been associated with activity of the ACC and OFC. For these reasons, it was expected that a stronger relationship would be obtained between FRN amplitude and latency and performance on the IGT and DDT than performance on the WCST. However, given the suggestion that individual differences in phasic amplitude shifts might be related to individual differences in cognitive flexibility (Bilder et al., 2004) it was considered possible that FRN ratio scores would be related to performance on the WCST, particularly with regard to perseveration on previously learned rules.

With regard to relationships between the FRN, and age group and behavior, it was expected that any between age-group differences on the IGT and DDT would be explained, at least in part, by age-related differences in the FRN. Finally, an important objective of this study was to explore whether or not FRN would account for some of the within age group variability on the measures of executive function employed. As previously described, one of the benefits of this methodology is that it allows for better understanding of individual differences that otherwise might obscure between –age differences in behavior. In summary, age group differences were expected between adults and adolescents on the IGT and the DDT, but not the WCST and the FRN was expected to mediate age related differences on the IGT and DDT. FRN ratio scores were also expected to be correlated with performance on the WCST. In addition, the relationship among the FRN (amplitude, ratio scores and latency) and performance on IGT, DDT and WCST were explored for adults and adolescents to establish whether or not individual differences on the tasks, independent of age group, were related to the FRN.

CHAPTER 8: STUDY 2 METHOD

Participants

All participants in the FRN study reported above (adults: *n*=26; adolescents: *n*=24) completed the entire EF protocol, with the exception of one adult who did not complete a delay-discounting task.

Measures of Executive Function

Wisconsin Card Sorting Task (WCST; Heaton, 1981; Kongs, Thompson, Iverson & Heaton, 2000). A computerized version of the WCST (64 card version) was administered (Psychological Assessment Resources, Inc.). Participants were presented with 64 cards, one at a time, and were told to sort the cards into categories indicated by four target cards at the top of the screen. WCST cards can be sorted by one of three criteria: color, form or number. The participant was not told the sorting criteria, but had to ascertain the criteria by utilizing feedback for correct and incorrect responses provided by the computer. After ten correct responses in a row, the sorting criterion changed unbeknownst to the participant, who had to infer this change from the feedback received and change strategy accordingly. Sorting criteria continued to change after every ten correct responses, until all the cards have been sorted. The measures of interest for the WCST were: the number of categories completed (i.e., how many times the participant ascertained the sorting criteria and made ten correct sorts in a row); the number of trials that it took to figure out the first sorting rule (trials to first category); the number of failures to maintain set (i.e., failing to continue using the sorting category once it had been established over 5 consecutive responses) and the number of perseverative errors (i.e., continuing to sort by a previously learned rule that is no longer correct).

Reliability of the WCST: Test-retest generalizability coefficients[4] for the WCST range between .39 and .72 (Kongs, Thompson, Iverson & Heaton, 2000*)*; these can be considered good given that intact performance on the task indicates that the participant has figured out that the task involves rule switching. Test-retest coefficients are necessarily suppressed by practice effects, especially among healthy participants. Similar problems affect alternate-form methods of reliability testing.

Iowa Gambling Task (IGT; Bechara et al.,, 1994; Bechara, 2007). A computerized version of the standard IGT (Psychological Assessment Resources, INC.) was administered. Participants were required to select cards from four decks. Each deck was associated with monetary gains and losses of varying magnitude and predictability, with two decks resulting in long-term losses (Decks A and B) and two resulting in long term gains (Decks C and D). The goal was for the participant to determine which decks were advantageous and to ultimately make more selections from those decks. Participants made 100 choices, which were broken down into 5 consecutive blocks of 20 choices each for analysis. To create incentive, participants were told (truthfully) they would receive one raffle ticket for each $500 won by the end of the task. The raffle ticket was placed in a drawing to win a $100 gift card. The measures of interest from the IGT included the net advantageous picks (total picks from advantageous Decks C and D minus total picks from disadvantageous Decks A and B), the rate of change in advantageous versus disadvantageous plays over the course of the 5 blocks, and deck preference.

Reliability of the IGT. To date, no studies have examined the reliability of the IGT. Similar problems to those discussed in relation to the WCST (i.e., temporal stability) make the assessment of reliability using test-retest and alternate forms difficult (Buelow & Suhr, 2009).

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[4] Generalizabilty coefficients account for multiple sources of error that contribute to variability not accounted for by true scores. Generalizability coefficients can be interpreted in the same way Classic Test Theory reliability coefficients are interpreted.

Delay discounting task A delay discounting task adapted from Kirby & Marakovic (1996) was used. Participants were asked to respond to a pen and paper questionnaire containing 20 successive choices of the following form: "Which would you rather have? \$x tomorrow[5] or \$y, z days from now?" The lesser sum, \$x, ranged from \$15 to \$83; the greater sum, \$y, ranged from \$30 to \$85; and the delay, z, ranged from 7 to 80 days. The twenty choice pairs were randomized once and presented to all participants in the same order. Participants were told that they had a chance to win one of their choices (randomly selected) at the end of the testing session, so they should make each choice as though they would actually receive the pay-off option selected. After completing the testing session, participants were invited to roll two standard dice in an attempt to win one of their chosen pay-out options. Any participant who rolled double ones (a 1-in-36 chance) would receive the monetary option he selected on one randomly drawn trial. There were no winners over the course of the study.

Decisions between the choice pairs were used to compute the exponential discounting parameter (k) for each participant, following the method of Kirby and Marakovic (1996). Choice pairs were ordered such that choice of immediate reward was associated with increasingly higher discounting rates. The discounting parameter associated with the immediate option for each pair was calculated according to the following formula, $V=Ae^{-kD}$, where V is the present value of the delayed reward, D is the delay in days, and k is the discounting parameter. Each participant was assigned a discounting parameter that corresponded to the geometric mean of the discounting parameters immediately preceding and immediately following the point at which he

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[5] Tomorrow was used, rather than today, for the immediate choice option so as not to confound choice with the possible negative consequence of returning on a different day to the testing location (Margo & Daly, 2006).

began to choose the delayed option consistently. Because the distribution of *k* is skewed, the natural log transform of k was used for statistical analyses.

Data Analyses

Standard ANOVA models were used to examine performance differences between adults and adolescents on the indices of interest, with IQ examined as a covariate. FRN amplitude, ratio scores and latencies were then evaluated as mediator variables explaining any relationships found between age and performance on the EF indices using standard linear regression models. Finally, the relationship between FRN and within-age differences on these measures was also explored.

Yuen's test for the difference between means were employed for two comparisons, as noted in the results section, because of violations of normality (Wilcox, 2003). Yuen's test utilizes Winzorized means and variances and adjusts the degrees of freedom accordingly. Winzorized means and variances are akin to trimmed means and variances, except that data in the tails are replaced with the most extreme remaining values rather than eliminated (Wilcox, 2003). 20% winzorized means were used in this study.

For all analyses involving the FRN and EF, FRN amplitude was averaged across the 6 electrodes used in the analysis above for each of the four conditions: high gain (HG FRN), low gain (LG FRN), high loss (HL FRN) and low loss (LL FRN) and for the high and low Magnitude ratio scores and these values were used as indices of the FRN. Average FRN latency in each condition was also examined in relation to EF.

Importantly, these ERP indices are highly intercorrelated and therefore it was not expected that any more than one index would enter into any regression model as a predictor. Since this is the first study to examine FRN and executive function, no *a priori* hypotheses were generated as to which indices would best predict performance on a given EF test.

For the mediation analyses and the individual differences analyses, exploratory bivariate correlations and/or stepwise regressions were conducted first to establish which index of the FRN was most strongly correlated with the EF measure of interest. However, an index was only included as a predictor if the pattern of relationships among the other FRN indices and the EF measure was theoretically consistent; a single significant correlation between an FRN index and a measure of EF was considered spurious and not included in subsequent analyses.

Mediation analyses were planned using the method described by Baron & Kenny (1986), wherein a variable, Y, is said to mediate the relationship between variable X and variable Z, if the mediating variable, Y, predicts variable Z (step 1), is predicted by variable X (step 2), and, when its effect is partialed out, substantially reduces the effect of variable X on variable Z (step 3). Full mediation is said to occur when the effect of variable X on variable Z falls to zero when the mediator's effect is partialed out[6]. However, as discussed in the results section, conditions for mediation analyses were not met for this study.

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[6] Significance of mediation can be tested using a variety of methods, using theoretical (e.g., Kenny, Kashy and Bolger, 1998) or empirically derived (e.g., Preacher & Hayes, 2004) sampling distributions.

CHAPTER 9: STUDY 2 RESULTS

Age Group and Executive Function

Table 6 contains the mean scores of adults and adolescents on all EF indices of interest.

WCST. The majority of participants, regardless of age, achieved between two and four categories on the WCST, although three adolescents and one adult failed to achieve any categories at all. As expected, there were no significant age group differences on any of the WCST indices (*p*s > .4) and as can be seen in Table 6, the means were very similar between the two groups. However, adults were more variable in their performance on the WCST than the adolescents, with more adults than adolescents scoring below two and above four categories.

IGT. Figure 4 shows the number of net advantageous picks plotted as function of Block for adults and adolescents. There was a significant main effect for Block on net advantageous picks, $F(3.2, 156.2) = 13.20$, $p < .0001$, $\eta_p^2 = .21$. Effects of Age and the Age by Block interaction were not significant (*p*s > .3). However, as is seen in Figure 4, the pattern of net advantageous picks across blocks was very different between adults and adolescents. The effect of Block for adult was linear; adults showed a gradual increase in the number of advantageous picks over time. In comparison, the data for adolescents had an inverted U-shaped pattern, with advantageous picks peaking at Block three and decreasing thereafter. Consequently, performance on block five was better for adults compared to adolescents (but this was only marginally significant ($p = .09$). This difference in patterns justifies comparing the effect of block within age groups, even though the Age by Block interaction was not significant. The null result for Age and the

Age by Block interaction in the ANOVA is likely a result of the substantial variability in the data and the skew in the adolescent data that distorted the central tendency for that group. In support of this, the difference in the Winsorized means (Wilcox, 2003) for net advantageous picks between adults and adolescents was quite substantial (21 cards). Yuen's method for testing mean differences between independent samples, which is robust to small sample sizes and violations of normality (Yuen, 1974 as described by Wilcox, 2003), revealed this difference to be statistically significant, $t(29.5) = 2.34$; $p = .02$.

Adults made significantly less advantageous picks in Block one compared to all other Blocks, $F(1,25) = 7.55$, $p = .01$, $\eta_p^2=.23$, and there were no significant differences across the remaining blocks. Adolescents made significantly more advantageous picks in Block two compared to Block one, but also made significantly more disadvantageous picks in Blocks four, $F(1,23) = 4.67$; $p = .04$; $\eta_p^2 = .17$, and five, $F(1,23) = 4.43$, $p <.05$, $\eta_p^2 = .162$, compared to their average performance across the earlier blocks (one-three). This pattern is interesting, because a significant change in performance for both groups occurred between Blocks one and two (ps < .03), suggesting both groups learned which decks were advantageous before Block three. Furthermore, the slopes of the lines for Block two regressed onto Block one were not significantly different for the two age groups ($z = -1.71$; $p =.09$), suggesting that the rate at which the groups learned was not different.

There was an expected main effect of Deck on card selection, $F(2.3,111.2) = 16.1$; $p < .0001$; $\eta_p^2 = .25$. Consistent with expectations, both adolescents and adults chose from disadvantageous Deck A significantly less often than from any other Deck (adults: ps <

.002; adolescents: *p*s < .04). However, the pattern of means shown in Table 6, suggests that adults and adolescents differed somewhat in their preferences for the remaining decks. Although there was no significant interaction of Deck with Age Group, comparisons of Age Group differences were conducted to test the *a priori* hypothesis that there would be age-related differences in card preference.

Table 6 shows that Deck D was the preferred Deck for all participants. However, adolescents preferred disadvantageous Deck B to both disadvantageous Deck A and advantageous Deck C (*p*s < . 05), and did not differ in their preferences for Decks B and D (*p* =.276). In contrast, adults preferred Deck B to Deck A (*p* < .0001), but did not prefer Deck B to either of the advantageous Decks C or D (*p*s > .05). Finally, adolescents chose fewer cards from Deck C, on average, than adults; by Yuen’s test, this effect was significant; mean difference: 6 cards, *t(*25.8) = 2.02; *p* = .03. In general, then, it appears that adults and adolescents were both inclined toward the pay-out schedules of Deck D and B, but adults were more likely to recognize the consequences of choosing from Deck B, and did not choose from it as frequently as adolescents, who preferred Deck B even over the advantageous Deck C.

This is an interesting pattern of results, since, as described above, Deck C (advantageous) and Deck B (disadvantageous) have different win-loss ratios. Deck B is similar to Deck D in that frequent high wins are punctuated by random infrequent losses; hence both can be considered riskier or less predictable options. Deck C is similar to Deck A in that both wins and losses are frequent. Thus, it appears that in this sample, adolescents preferred Decks (whether advantageous or disadvantageous) that paid out frequent wins with infrequent unpredictable losses (Decks B and D).

DDT. One adult participant did not complete the DDT. These, and all subsequent analyses with the DDT, exclude this participant. Unexpectedly, adults and adolescents did not differ significantly in their performance on the DDT. As shown in Table 6, mean discounting parameters were virtually identical for the two groups, mean difference =.0004; $t(47) = .03$, $p = .98$. The DDT discounting parameter is a measure of the rate at which one discounts a future reward to its present-day value. As an example, the rate of .004, which is the approximate average rate for the two groups, implies that participants would prefer $65 tomorrow over anything less than $79.50 several days later.

FRN and Executive Function

Between group differences. There were no age-related differences between adolescents and adults on the DDT or WCST. FRN amplitude and FRN ratio scores were not correlated with any of the indices of the IGT, including those for which age-group differences were found. Therefore, it is reasonable to conclude that FRN amplitude does *not* account for age-related differences on the IGT.

Individual Differences.

WCST. For adolescents, but not for adults, FRN amplitudes in the loss conditions were correlated with the number of trials to first category, which is a measure of how long it took to learn the first sorting principle and successfully complete the first category on the WCST, rs > .4, ps = .04. Specifically, adolescents who took longer to learn the first sorting category had smaller (less negative) FRN amplitudes to losses than those who learned more quickly. When IQ was entered as a covariate, this effect remained only marginally significant ($p > .05$). FRN amplitude was not significantly correlated with IQ in any condition (ps > .07).

IGT. For adolescents, but not for adults, latency in the high loss condition significantly predicted preference for Deck A, *r* = .48, *p*=.017, and performance in Block 5, *r* = -.42, *p* = .042, such that longer latencies in the high loss condition were associated with increased selections from the disadvantageous Deck A and fewer advantageous picks during Block 5. Importantly, neither age (14 to 16 years) nor IQ better accounted for this within-age effect.

FRN latency in the High Loss condition was also negatively correlated with a preference for advantageous Deck D, *r* = -.48, *p* = <.0001, for all participants, regardless of age, but this effect was more pronounced for adolescents, *r* = -.55, *p* = .005, than for adults, *r* = -.43, *p*=.03. Again, this effect was not better accounted for by age or IQ.

Finally, no significant relationships were obtained between FRN amplitude in any condition and deck Preference.

DDT. No significant relationships were found among indices of the FRN and the DDT.

CHAPTER 10: STUDY 2 DISCUSSION

Age Group Differences in Executive Function

This study revealed modest age-group differences on the IGT that are consistent with other developmental studies that have shown changes in deck preference as a function of age (e.g., Cauffman et al., 2010; Principe et al., 2011; Huizenga et al, 2007). Specifically, adolescents showed a preference for decks with infrequent punishment (Decks D and B) regardless of the long-term advantage, and were less likely than adults to choose from Deck C, an advantageous Deck with predictable high frequency losses. Cauffman et al. (2010) using a modified version of the IGT, reported that adolescents learned more quickly to choose from advantageous decks than adults, who learned more quickly to eschew disadvantageous decks. Their results also suggest that the adolescents chose more indiscriminately. The authors posited that adolescents might attend more to the potential rewards of a risky decision, whereas adults attend to both rewards and costs, and possibly even weigh costs more than rewards (Cauffman et al., 2010). The results of the current study are consistent with this interpretation; adolescents preferred Decks with infrequent losses, regardless of the long term consequences. It is also possible, and not inconsistent with this interpretation, that adolescents preferred Decks D and B because they paid out bigger rewards and were unpredictable with regard to the losses. The appeal of these decks is that, in comparison to Deck C, and also Deck A, they include a greater element of risk. This might make selection from these decks more exciting for adolescents.

It is difficult to interpret the curvilinear relationship of Block on net advantageous picks for the adolescents. This has not been reported elsewhere in the developmental literature; a linear effect of block on advantageous picks has been reported fairly consistently in adolescents and adults (e.g., Cauffman et al., 2010; Hooper et al., 2004). In the adult literature, a pattern similar to that seen in the adolescents in this study was reported for non-college educated adults who were being compared to college educated adults in a South African sample (Fry, Greenop, Turnbull & Bowman, 2009). In that study, non-college educated adults appeared to show a change of preference for advantageous decks at Block 5, similar to the adolescents in this study, but the authors did not provide an interpretative explanation for the interaction. At least two other studies suggest that performance on the first and the second half of the IGT task reflect decision making under different circumstances. The first half reflects decision making under conditions of uncertainty, while the second half reflects decisions made after contingencies have been learned, under conditions of risk (Brand, Recknor, Grabenhorst & Bechara, 2007; Monterosso, Ehrman, Napier, O'Brien & Childress, 2001). In other words, participants inclined to taking risks will only show evidence of this tendency on trials that come after they have learned which decks are associated with risk. For example, in cocaine addicted participants, performance on the latter half of the task has been shown to be correlated with DDT discounting parameters, but performance on the first half has not (Monterosso, Ehrman, Napier, O'Brien & Childress, 2001). Similarly, the phenomenon of "betting on the houses money", that is, picking high risk cards late in the game after contingencies have been learned, has been reported anecdotally in clinical research settings with unimpaired control participants (J. Kielp, personal communication, 2007).

These results indicate that adolescents in the present study might have been more inclined to take risks toward the end of the task than the adults. The fact that this has not been reported by other investigators might be related to the unusual monetary incentive used in this study to provide motivation for the task; participants were told (truthfully) that they would receive a raffle ticket for every $500 won on the IGT task and that the raffle tickets would be entered into a drawing for a $100 cash prize after data collection was complete. It is possible that towards the end of the game, the adolescents, but not the adults, were willing to take bigger risks with disadvantageous decks with the hope of winning more raffles. This is not inconsistent with the earlier suggestion that adolescents weigh the potential advantages of a situation more heavily than the potential risks (Cauffman et al., 2010). In this particular situation, it appears that adolescents were able to tolerate greater risk than the adults for the same potential reward.

In contrast, and opposite to expectations, no differences were found for adolescents and adults on the DDT. This was a surprising result, as many have reported differences in discounting rates between adolescents and young adults of ages similar to those who participated in this study (Olson et al., 2007; Steinberg, 2009; Whelen & McHugh, 2009). However, Lamm, Zelazo and Lewis (2006) did not find a relationship between age and discounting factor in their sample of children and adolescents, and Prencipe et al., (2011) reported differences in discounting between only the youngest participants 8-9 years, and all other age groups studied (10-11, 12-13 and 14-15 years). In addition to developmental stage, discounting has been shown to be related to a number of individual state and trait variables, such as personality and current mood (e.g. Hirsh, Guindon, Morisano & Peterson, 2010; Mishra & Lalumiere, 2010). Given the relatively small sample size, it is possible that individual differences between the adults and adolescents in this study might have obscured developmental differences in discounting rates. In general, though, the discounting rate for both groups in this study is lower than that reported in other studies for adults (e.g., Kirby and Markovec, 1996), suggesting that both adults and adolescents in this sample were relatively conservative with regard to their discounting behavior.

Finally, consistent with existing research (Chelune & Baer, 1986; Chelune & Thompsen, 1987), there were no age related differences on any of the WCST indices. The WCST requires problem solving in the absence of an affective component and normative data suggest that by age 10, children perform as well as adults on the task (Chelune & Baer, 1986). Age differences in successful performance were not expected. The measure was included in this investigation for the purpose of exploring individual differences in the use of feedback to learn and apply rules. In particular, because it is considered a measure of cognitive flexibility, it was thought that performance on the WCST might be correlated with FRN ratio scores (Bilder at al., 2004).

FRN and between age differences in executive function

There were no observed differences in DDT or WCST performance between adults and adolescents; therefore it was not possible to investigate an explanatory relationship between the FRN and age group differences in these measures. There were subtle differences in IGT performance for adults and adolescents, but, FRN amplitude, latency and ratio scores were not correlated with any of the indices on which differences were observed. Therefore, it is not likely that maturational changes in the FRN explain these differences.

FRN and within-age differences in executive function

One of the few specific hypotheses tested with regard to FRN and individual differences was that FRN ratio scores might be related to cognitive flexibility (Bilder et al., 2004), such that smaller ratio scores would be predictive of weaker performance on the WCST due to perseverative errors. This hypothesis was not supported. However, the WCST was designed primarily to assess clinically significant deficits in cognitive flexibility (Lezak et al, 2004), and therefore, ceiling effects can substantially reduce the variance in scores among normal participants (e.g., Arffa et al., 1998). In addition, the 64-card version of the task further reduces the normal range of scores that can be obtained. In retrospect, considering that several participants did perform poorly on the test, it might have been more useful to have used the longer (128-card) version of the test to increase both the range and the reliability of the scores obtained. Nonetheless, the WCST still might not be a sensitive enough measure of cognitive flexibility to use in a neurologically intact population. It is possible that the FRN would show a correlation with impaired performance on the test, if neurologically impaired participants were studied (e.g., Egan et al., 2001).

While ratio scores were not predictive of performance on the WCST, the number of trials required to complete the first category on the task was related to FRN amplitude after losses for adolescents, but not for adults. This effect remained only marginally significant after controlling for IQ; nonetheless, it seems reasonable to conclude that in comparison to other adolescents, those with smaller physiological responses to losses might show slower learning. van der Helden, Boksem & Blom (2010) have shown that, in adults, the amplitude of FRNs after a mistake on a reinforcement learning task was predictive of whether the incorrect action would be repeated; specifically, smaller FRNs after mistakes were associated with a higher likelihood to repeat an incorrect response. As discussed earlier, expectancy (i.e., performance) confounds are inherent in reinforcement learning tasks. The findings from the current study—because it used an independent measure of learning (WCST) that was correlated with FRN elicited in a separate non-RL task—lend support for the direction of the relationship between FRN amplitude and learning: namely, that smaller FRNs lead to poorer learning. Importantly, however, this effect was only marginally significant after controlling for IQ and was specific only to the adolescents in this study.

None of the indices of the FRN were predictive of individual differences on the DDT, but it is possible that this is because in this sample there was very little individual variability in discounting in general. The discounting parameters for all participants clustered fairly close to the overall sample mean.

Perhaps the most interesting finding from these analyses was that FRN latency in the high loss condition predicted disadvantageous card choices on the IGT in teenagers but not in adults. Specifically, longer latency for high losses (delayed FRNs) was associated with increased picks from Deck A (disadvantageous) and fewer advantageous picks in Block five.

Deck A is typically avoided by healthy participants who realize quickly, by virtue of its high loss to win ratio, that it is disadvantageous. Anecdotal data from discussions with a handful of participants who were observed to have made choices from Deck A later in the game, suggests that these participants knew it was risky to select from the deck, but were hoping for one more big win before the game was over. Selecting from disadvantageous decks in block 5 also suggests a willingness for risk taking, as presumably, by block 5 the contingencies of the decks have been learned. The adolescents who choose more from disadvantageous decks at block 5 might be more likely to engage in risk-taking behaviors than others.

Given that adolescents had more variable latencies in the high loss condition than the adults, this particular index might be important in understanding within-age differences in disadvantageous option selection. The effect of midbrain dopamine on the facilitation of learning is dependent on the timing of the dopamine response (e.g., Wicken, Begg & Arbuthnett, 1996). If a delayed FRN in some adolescents is an indication that the phasic decrement in dopamine is delayed with respect to the action that produced the negative outcome, then avoidance behaviors might not become as well established for those teens. At the very least, these results suggest that FRN latency might be an important index for identifying those teenagers that are at increased risk for poor decision-making among their more mature peers.

Perhaps as interesting as what was correlated with the IGT, was what was not correlated. Neither FRN amplitude nor FRN ratio scores were related to performance on the IGT. This was somewhat unexpected. Lamm, Zelazo and Lewis (2006) reported that N200 amplitude explained the effect of age on net advantageous picks in their sample of children and adolescents, and similar neural processes are thought to generate both the N200 and the FRN (Holroyd et al., 2009). One possible explanation for this discrepancy is that there were performance confounds related to ERP task used by Lamm and colleagues (2009). Whereas there was no performance component to the gambling task used in this study, the Go/NoGo task used by Lamm and colleagues (2009) required that participants' inhibit their responses to particular stimuli. If correct performance was more effortful for younger compared to older participants, the relationship between N200 amplitude and IGT performance could be related primarily to similarities in task difficulty. However, other investigators have also reported an association between FRN amplitude and independent risk taking behaviors in adolescent clinical populations (e.g., Crowley et al., 2009; Segalowitz et al. 2011). In adolescents with trait surgency smaller FRNs have been associated with increased risk taking in the presence of peers during a computerized driving game (Segalowitz et al., 2009). Also, in a sample of adolescents who had been exposed prenatally to cocaine, Crowley et al., (2008) reported a relationship between FRN loss-gain differentiation and risk – taking, assessed independently with the Balloon Analog Risk Task (BART; Lejuez et al., 2002). In that study, males with smaller differentiation of the FRN were more likely than females or males with larger FRN differentiation to take risks on the task (Crowley at al., 2008).

Apart from a marginally significant effect of high loss FRN amplitude on trials to complete first category on the WCST in adolescents, in this study FRN amplitude was not correlated with performance on any of the tests of EF. As discussed earlier, the FRN likely reflects an extremely fast and relatively coarse dopamine response that differentiates between good and bad events. This first stage of this investigation revealed that the FRN in adolescents does not differentiate as well between losses and gains as it does in adults. It seems reasonable to assume from this that the dopaminergic signal received in the ACC, does not discriminate as well between good and bad events, implying that adolescents' brains do not process feedback as efficiently or as well as adults' brains. Nonetheless, neither FRN amplitude nor ratio scores predicted performance differences between the adults and adolescents on the tests of EF in this study. Furthermore, with the exception of WCST trials to first category, FRN amplitude and ratio scores were not related to individual differences on the measures used in this study either. The difference between the results of this present study and those of others who show a relationship between FRN amplitude and independent measure of behavior might be related to the different age ranges of the participants studied and/or to differences in the populations from which the samples were selected.

With regard to the former reason, FRN might simply be a better predictor of behavior in younger participants than in adults. Among the relationships that were found between the FRN and EF in the present study, most were specific to the adolescents. It is important to remember that the way that the dopamine signal is used to modify future behavior depends on the integrity and maturity of the post-synaptic structures it activates, especially within the PFC (Schultz, 2002). Given that the prefrontal cortex (which mediates regulatory and control systems) is less mature in adolescents than adults, the “more bottom-up” dopamine error-prediction signals at the ACC might be more directly tied to observed behavior in teenagers than in adults. This could explain why FRN latency (or amplitude in the case of WCST trials to first category) better predicted performance within adolescents than adults. Presumably, in adults, for whom the PFC is mature, there are more top-down mechanisms contributing to the modulation of the system that generated the FRN. Poor performance in adults might be related to other top-down, cortically-mediated processes that were not assessed in this study and that might be better predictors of adult performance.

For the teenagers in this study, it appears that at least for some of the EF indices examined, the bottom-up processes dominate: among those teens for whom the system works less well, deficits in performance become apparent. This does not mean that the FRN is not important to adult behavior; shorter latency in the high loss condition was related to a preference for Deck D on the IGT in both groups. These data do suggest, however, that with development the top-down modulation of the neural processes that generate the FRN may become more pronounced. If this is the case, the effects should be even stronger among younger age groups, perhaps explaining the discrepancies between this study and others who showed a more robust relationship between FRN amplitude and independent measures of behavior in children and adolescents (i.e., Crowley et al., 2009; Lamm et al., 2006; Segalowitz et al., 2011)

With regard to the latter point about population differences, it has been shown that the amplitude of the FRN and the differentiation of the FRN between positive and negative outcomes is moderated by top-down processes such as expectancy and by individual differences in personality (e.g., extraversion)(Marco-Pallarés et al., 2009; Smillie et al., 2010). The adults and adolescents used in this study were not randomly sampled and in general, they represent a segment of the population that is not engaging in particularly risky behaviors. Indeed, participants self-selected and were further screened for risk-taking behaviors such as substance abuse, and for psychological disorders associated with impulsivity and risk-taking, such as ADHD. The relative homogeneity of the sample likely attenuated the relationships that were measured between FRN amplitude and EF. It is quite possible a wider range of scores would have been obtained on the measures of EF used, and possibly for FRN amplitude and ratio score measurements as well, had a wider, more representative sample been used.

CHAPTER 11: GENERAL DISCUSSION

This dissertation had two aims. The first aim was to establish normative age-related differences in the FRN with an all-male sample of adolescents, ages 14 to 16 years, and young adults. The second aim was to investigate whether the FRN could be used as an index of functional brain maturation to explain developmental differences in behavior on executive function tasks more precisely than chronological age. This dissertation concludes with a discussion of how these findings, in conjunction with proposed future studies, might be useful to policy makers who are ultimately responsible for deciding how the law views and responds to adolescents who offend.

Study one of this dissertation revealed that there are differences between adolescents and young adults in the size of the FRN elicited in response to losses and gains in a simple gambling task. Specifically, adolescents had larger FRNs than adults, and when baseline differences were taken into account, adults showed a greater difference in FRN amplitude between losses and gains. The absolute difference in FRN amplitude between losses and gains might not be as important a predictor of signal efficacy as the relative difference, especially if the DA signal has to reach a certain threshold in order for it to signal when a “good event” has occurred. If this is the case, it is possible that feedback of larger magnitudes might be required by teens, compared to adults, to elicit an equally effective DA response. In addition to larger amplitudes and smaller relative differentiation between losses and gains, the adolescents also had a broader FRN after high loss feedback. This phenomenon is probably indicative of less efficient processing in this condition. Taken together, the FRN data suggest that the neural networks that underlie rapid processing of external feedback are still developing in this adolescent age group. This might partially explain why adolescents are vulnerable to poor decision making in pressured and emotionally charged situations: Effective decision making in these contexts typically requires the ability to very rapidly differentiate between good and bad outcomes without extensive top-down elaboration (Grose-Fifer, Hoover, Zottoli & Rodrigues, 2011).

The second study in this dissertation attempted to link these neurophysiological differences to observable behavior on independent measures of executive function. Differences in observable behavior between adults and adolescents were modest, but consistent with analogous published reports. By middle adolescence, adult-like capacity has generally been reached for abstract analytical EF tasks that do not include motivationally salient outcomes such as losses and gains (Prencipe et al., 2011). In contrast, when making decisions in emotional contexts, deficits in the performance of adolescents become more apparent (see Steinberg, 2007, for review). This is seen in both in real-life decision making (Steinberg, 2007) and also on EF tests, such as the IGT, which include an affective component (Cauffman et al., 2010; Hooper et al., 2004; Overman et al., 2004). In this study, no age group differences were obtained on the WCST, an abstract analytical task, but differences were found on the IGT, a task with more emotionally salient outcomes. The most striking age-related difference between the adults and teenagers was the tendency of the adolescents to choose from high risk decks late in the game, after contingencies of risk were learned.

Of most relevance here was the finding that longer FRN latency to a loss in teenagers was related to poorer performance on the IGT. Adolescents who started choosing from risky decks late in the game were distinguished from those who did not by the latency of their FRNs. Adolescents with delayed FRNs were more likely to engage in this behavior. Likewise, the latency of the FRN was able to distinguish between adolescents who were inclined to choose frequently from the riskiest deck (Deck A) from those who were not; again, those with delayed FRNs were more likely to select from this deck. Deck A is associated with big wins, but also with big and high frequency losses; therefore, choosing from this deck is a short-sighted strategy. Since the adolescents who performed poorly on the IGT were also likely to show immaturities in their FRN, the strategies adolescents use to play the IGT may be particularly helpful in understanding risk taking or poor decision making in this population. For example, the adolescents who switch back to disadvantageous decks later in the game might be more likely to engage in risk-taking behaviors in real-life situations.

Direct ecologically-valid behavioral correlates are still needed to understand how these results are translated into real-life situations, but it is not unreasonable to speculate that in contexts of real-life decision-making, adolescents with slower FRNs after losses might be more vulnerable to making poor choices. Specifically, they may be more prone to choosing options with immediate pay offs than are adults or other adolescents whose FRNs are not as delayed. Although this is, at present, speculative, these adolescents may also be at higher risk for involvement in the criminal justice system because they may be more prone to engaging in risky behaviors such as drug or alcohol use, be more easily influenced by the suggestions of peers and be less capable of weighing the long term consequences of their behavior against more immediate pay-offs of excitement, notoriety or peer acceptance. Ironically, these same teens might also be more vulnerable to waiving their rights (when not in their best interest), when in legal custody. Such adolescents might be more inclined to agree to talking to the police in return for incentives rather than waiting for an attorney, or to be more likely to refuse a plea bargain when it is in the adolescent's long term best interest but entails immediate punishment.

Policy Implications

Overall, this study sheds new light on how a neurophysiological correlate of the dopaminergic signal that differentiates between good and bad environmental events is related to executive function in 14-16 year old males. These results add to a growing body of research that demonstrates immaturities in adolescent decision making and that associates these differences with maturational changes in the brain during this period of development. As such, these data have the potential to contribute to policy relevant discourse in areas of juvenile justice and child advocacy.

First, this study has revealed evidence of neural immaturity in a population of normally developing, healthy teenagers, with no histories of substance abuse, psychiatric or neurological disorder, abuse or neglect. These neural immaturities were linked with poor choices on a test of EF that has an affective component (IGT). It is quite possible that the effects obtained in this study would be even more dramatic in a more heterogeneous sample of teenagers with more variable intellectual functioning and diverse psychiatric histories (i.e., better reflecting the population of juvenile offenders). Policy makers should consider the probability that juvenile offenders will show more pronounced EF deficits in comparison to the sample used in this study.

Second, until recently, most of the studies that have examined decision making capacities of adolescents have used behavioral measures or structured interviews, without affective components, in laboratory settings where participants had time to think about their answers free from any emotional or motivational pressures. However, it has been generally shown that, when given adequate time, adolescents tend to reason about risk in much the same way as adults (Fischoff et al., 2000), but that in emotionally charged situations their capacity to make good choices is compromised (e.g., Gardner & Steinberg, 2010; Segalowitz et al., 2009). This study employed behavioral tasks (i.e., DDT; IGT) with emotionally salient outcomes which are likely to have greater sensitivity to the immaturities that might lead to risky decision making. As predicted, modest age-related differences were found on the IGT, and importantly, the FRN was associated with performance on the task among the adolescents. However, a question that remains open is how performance on a "hot" EF task, such as the IGT, relates to actual day-to-day behaviors of the participants. Any cogent scientific argument for a change in juvenile justice policy would benefit from research that makes these links.

The IGT data from this present study hint that there is likely to be a link between performance on "hot" EF tasks and real life decision-making. A substantial number of adolescents, but not adults, began to choose from risky decks late in the game after contingencies for risk had been learned. The procedure used in this study was unique in that it had a real, tangible and motivationally salient outcome for success; for every $500 they won on the task, participants received a raffle ticket for a $100 drawing. As a consequence, the "heat" of this "hot" task was increased, and the task became a more ecologically valid investigation of how adolescents approach monetary risk. Under these unique conditions, many of the adolescents began to gamble on the high risk decks late in the game, after they learned risk contingencies. As described above in detail, these teens might be more likely to engage in risky behavior than those who did not gamble towards the end of the game. Of relevance to policy decisions, is that this pattern of behavior was true for teens but not for adults, suggesting that for the teenagers, short-term risk for gains were more salient in comparison to long-term losses. In real-life situations, this might mean that teens are less able to resist the immediate rewards associated with risky behavior.

Nonetheless, whether or not adolescents who took that gamble on the laboratory task would be more prone to risk taking behavior in day-to-day life is question that must be answered empirically. A planned follow-up study will investigate this phenomenon by manipulating the external monetary reward for performance on the IGT and comparing performance on the IGT with real-life risk taking behavior, as measured by self report (e.g., Youth Risk Behavior Survey). Although logistically more difficult, future studies that examine EF performance and physiological data (e.g., FRN) of adjudicated adolescent offenders, in relation to documented decisions they have made (e.g., waiving Miranda), would provide a useful validation of the relationship among these laboratory measures and real-life decision making or risk taking. Nevertheless, the strength of this present study with regard to its implications for public policy is that it has demonstrated observable age-related differences in risk taking behavior between young adults and 14 to 16 year olds because it employed tasks that more closely simulate the emotional context of real world decision-making.

Third, by using a physiological measure of brain activity, this study was able to highlight the rather large degree of variability in neural maturity among 14 to 16 year old males. This variability in brain activity appears to have contributed significantly to the variability in test performance among these adolescents. Namely, risk taking on the IGT was positively correlated with FRN latency after high losses for teenagers. These data suggest that during middle-adolescence, the chronological age of an adolescent is not necessarily the best indication of neural maturity. Nonetheless, as a result of sweeping legislative changes in the 80s and 90s, adolescent offenders between the ages of 14 and 16 are far more likely today to be tried as adults for their crimes than they would have been decades earlier (Fagan & Zimring, 2000). This is in large part a result of offense-based statutory exclusion from juvenile court jurisdiction, which obviates the perceived need for an individual assessment of an adolescent's blameworthiness and amenability to rehabilitation (Fagan & Zimring, 2000). Given the considerable inter-individual variability found among adolescents, policy makers should consider whether individual evaluation of adolescent offenders (i.e., traditional waiver) is preferable to statutory exclusion for deciding which, if any, adolescents deserve adult sanction.

Neuroscientific and clinical evidence have already been considered by some state legislatures that have made their juvenile justice policies less punitive. Neuroscientific evidence was also introduced in amicus briefs that may have impacted the Supreme Court's *Roper v. Simmons* (2005) decision that abolished capital punishment for offenders who committed their crimes as adolescents. It appears increasingly likely that the legal system is open to input from the scientific community about the neurobiological changes across development that make adolescents susceptible to errors in decision-making.

At present, data from this study warrant reconsideration of the statutory exclusion of adolescents from juvenile court, which eliminates the individual evaluation of offenders that accompany traditional juvenile waiver decisions. The law operates under the principle of proportional justice, which means that punishment should fit the severity of the crime. But, proportionality is also balanced with the culpability, or blameworthiness, of the actor. These data suggest that some adolescents who commit crimes, or engage in risky behavior that can lead to criminal acts, might do so because of developmental immaturity. If this is the case, it implies that some teenagers ought to be considered less culpable for their crimes than adults by virtue of developmental immaturity. Indeed, many jurisdictions allow an adolescent offender charged as an adult to submit a motion for his or her case to be heard in juvenile court, on the grounds of developmental immaturity (Fagan & Zimring, 2000). In practice, however, this process is rarely used (Feld, B., 2006 as cited by Brannen et al., 2006) and places the burden on the defendant to show developmental immaturity. Again, whether adolescent offenders should continue to be tried as adults on the basis of offense type or whether traditional waiver (i.e., individual evaluation of the offender before transfer decision is made) should be reinstated, is a legal decision, not a scientific one. However, science has a great deal to offer policy makers. Adolescence is not a disease or defect, but a normal developmental stage. Moreover, it is an impressionable stage, during which perturbations can have long term consequences (e.g., Crews, He & Hodge, 2007). It has been argued elsewhere that adult sanction has adverse consequences on recidivism rates of adolescent offenders (Bishop et al., 1996; Winner, et al., 1997). In addition, while the general public may be more aware of the sensational crimes involving juveniles, most adolescent offenders who are tried as adults have not committed violent crimes (Arya, 2011). The weight of the research to date suggests that a separate system of justice, rather than criminal court, is appropriate for most adolescent offenders. It should also be noted that in some states (e.g., New York; North Carolina) the legal limit for juvenile justice jurisdiction is set at 15 years, therefore all 16 year olds are tried as adults. Although this section has focused on statutory exclusion and juvenile waiver, it goes without saying that the data from this present study are incongruent with the suggestion that the brains of 16 year olds have reached adult maturity.

The results of this study should also lead to the reasonable conclusion that better safeguards ought to be in place throughout the processing of juvenile offenders from intake through adjudication; for example, interrogation protocols for adolescents should take into account whether the developmentally enhanced effects of emotionally salient immediate inducements might make adolescent more likely than an adults to waive their Miranda rights. Adolescent offenders arrested and charged as adults do not have the same protections afforded to adolescents in juvenile court. The pressures of interrogation and the emotional inducements offered by interrogators might very well have undue effects on teenagers by virtue of their developmental stage. Nonetheless, providing these protections (some states already do) yields an apparent inconsistency: An arrested juvenile no longer has the capacity to make appropriate decisions that have long term consequences, whereas before he was arrested he had the mental faculty necessary to engage in a crime with long term consequences. This inconsistency should make it evident that culpability under the law and the legal capacities of adolescents in police custody are not independent. This study suggests that adolescents between the ages of 14 and 16 are more likely than adults to show deficits in feedback processing and executive function that might render them vulnerable to making decisions that are not in their best legal interests.

Finally, while the results of this study were in line with theoretical expectations, they should not be over-interpreted. This study was the first to examine the relationship of FRN and EF in adults, and only the second study to attempt to examine developmental differences in EF using an ERP component as an index of neural maturity. As such, the hypotheses were, for the most part, exploratory in nature. Results were modest and many relationships were tested within the same, relatively small, sample; a process that inevitably increases the likelihood for type 1 error. Replication of these findings in different and larger samples is therefore of great importance.

It is also important to note that this is a normative study that investigated feedback processing in healthy, normally developing, non-delinquent adolescents. Normative studies are necessary to pave the way for future research that can examine factors that could moderate the neural response to feedback. Future studies should examine whether and how the relationship between the FRN and EF is changed by abuse and neglect, substance abuse and developmental/learning disability, as the base rate of these conditions is reportedly higher among offending populations (e.g., Currie & Tekin, 2006; Leone, Zaremba, Chapin & Iseli, 1995; Teplin, Abram, McClelland, Mericle, Dulcan & Washburn, 2002).

APPENDIX

Table 1

Participant Demographics

		Adults (*SD*)	Adolescents (*SD*)
Age		23.8 (*1.1*)	15.0 (*.86*)
Education		15.7 (*1.1*)	9.2 (*1.2*)
Est. IQ*		113.6 (*9.5*)	103.5 (*12.1*)
Ethnicity			
	White	n=9 (34.6%)	n=11 (45.8%)
	Black	n=4 (15.4%)	n=5 (20.8%)
	Hispanic	n=4 (15.4%)	n=4 (16.7%)
	Other	n=9 (34.6%)	n=4 (16.7%)

* The discrepancy between adult and adolescent estimated IQ is unreliable. IQ estimates for half of the adult sample were made using the AMNART and are likely over-estimates; all adolescents and remaining adults were assessed using the Matrix Reasoning subtest of the WAIS-III.

Table 2

Mean FRN Amplitude (in μV) by Age and Condition

	Adults (*SD*)	Adolescents (*SD*)
High Gain	-2.0 (*2.0*)	-4.7 (*2.4*)
Low Gain	-4.3 (*2.2*)	-6.9 (*2.7*)
High Loss	-5.6 (*1.6*)	-8.5 (*3.4*)
Low Loss	-5.9 (*2.2*)	-9.2 (*3.4*)

Table 3

Mean Ratio Scores ([Loss-Gain]/Loss) by Age and Condition

	Adults (*SD*)	Adolescents (*SD*)
High Magnitude	.66 (*.34*)	.48 (*.20*)
Low Magnitude	.36 (*.21*)	.29 (*.15*)

Table 4

Mean FRN Latency (in ms) by Age and Condition

	Adults (*SD*)	Adolescents (*SD*)
High Gain	265.4 (*36.4*)	281.6 (*39.3*)
Low Gain	266.4 (*36.3*)	277.0 (*28.1*)
High Loss	297.2 (*38.6*)	309.8 (*45.9*)
Low Loss	282.3 (*26.1*)	284.2 (*22.8*)

Table 5

Frequency and Magnitude of Wins and Losses for Each IGT Deck

	Wins		Losses	
	Frequency	Magnitude	Frequency	Magnitude
Deck A*	High	Moderate to High	High	Moderate
Deck B*	High	Moderate to High	Low	High
Deck C+	High	Low	High	Low
Deck D+	High	Moderate	Low	Moderate

*Long term disadvantageous decks +Long term advantageous decks

Table 6.

Means and Standard Deviations for Adults and Adolescents for Executive Function Measures

	Adults		Adolescents	
EF Index	Mean	SD	Mean	SD
WCST				
Categories	3.2	1.6	2.9	0.9
Trials to 1st	16.3	6.6	15.3	5.9
FMS	0.7	0.9	0.4	0.5
Total Perseverative Errors	8.8	3.9	8.6	2.3
IGT				
Net Advantageous Picks				
Block 1	-1.1	5.2	-1.9	3.3
2	2.62	3.9	1.0	2.5
3	4.2	4.7	4.0	7.6
4	5.5	8	3.6	6.5
5	7.1	7.9	1.7	5.7
# Picks From Deck				
Deck A	15.8	5.3	15.7	4.6
B	25.4	5.9	28.4	7.0
C	25.8	7.7	19.8	5.3
D	31.5	5.9	33.0	11.2
DDT				
Discounting parameter (k)	0.00447	0.00118	0.00375	0.00085

Categories=Total number of sorting categories completed; Trials to 1st=Total number of trials to learn and complete the first sorting category; FMS=Failure to Maintain Set

Figure 1. A representative sequence of events during a gambling task trial. Participants were presented with a choice between two colored cards, one of which was selected by pressing the corresponding mouse button. The selected card was highlighted with a white border for 500 ms, and then the value for the selected card was shown for 1000 ms.

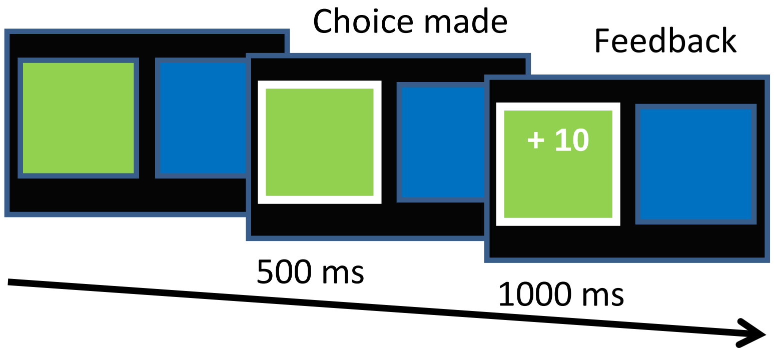


Figure 2a and 2b. Grand average waveforms for the FRN at the 6 frontocentral electrodes used in the analysis, plotted as a function of reward magnitude and valence, for adults (2a) and adolescents (2b). HG = High Gain; HL = High Loss; LG = Low Gain; LL = Low Loss.

Figure 2a. Young Adults

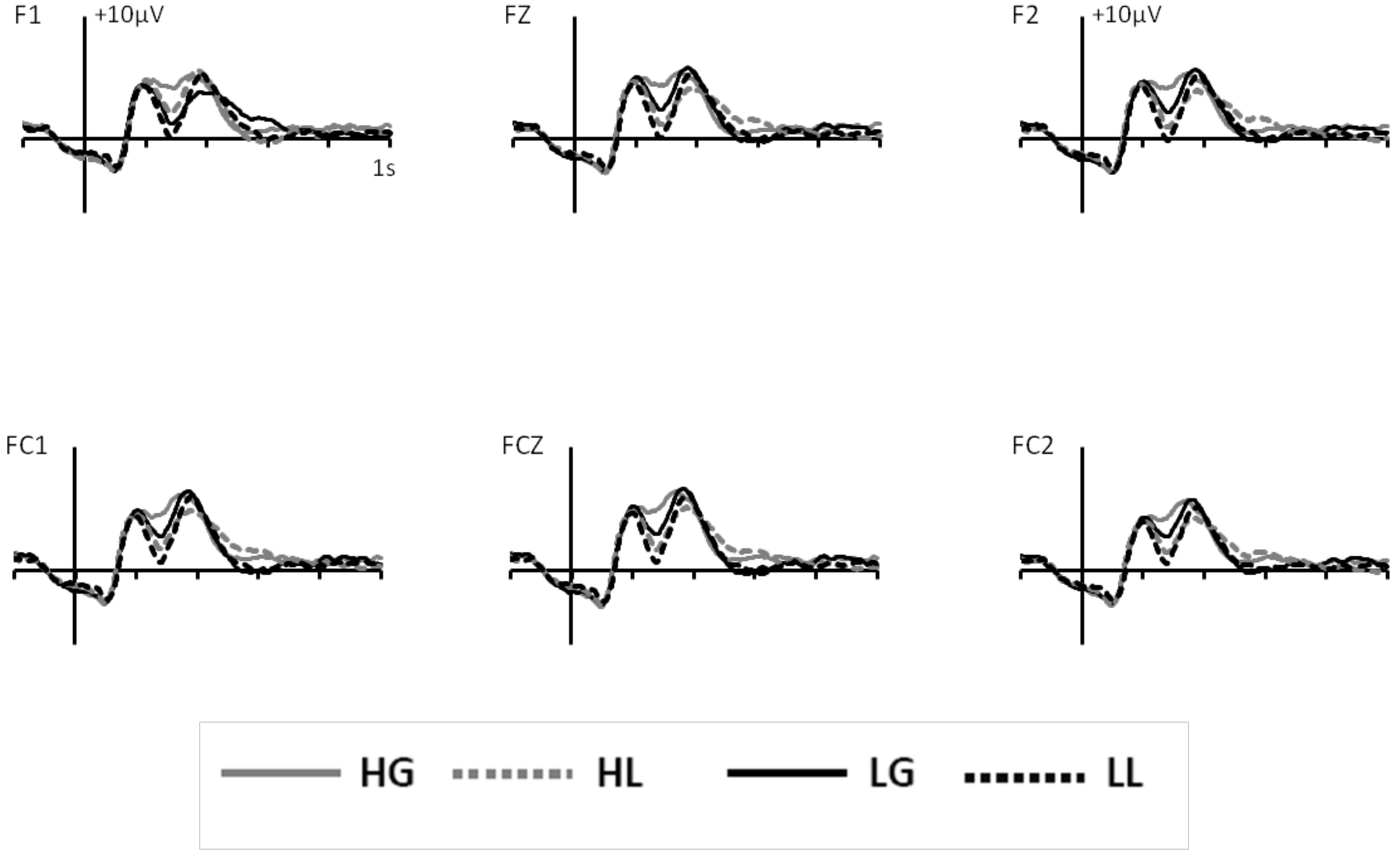


Figure 2b. Adolescents

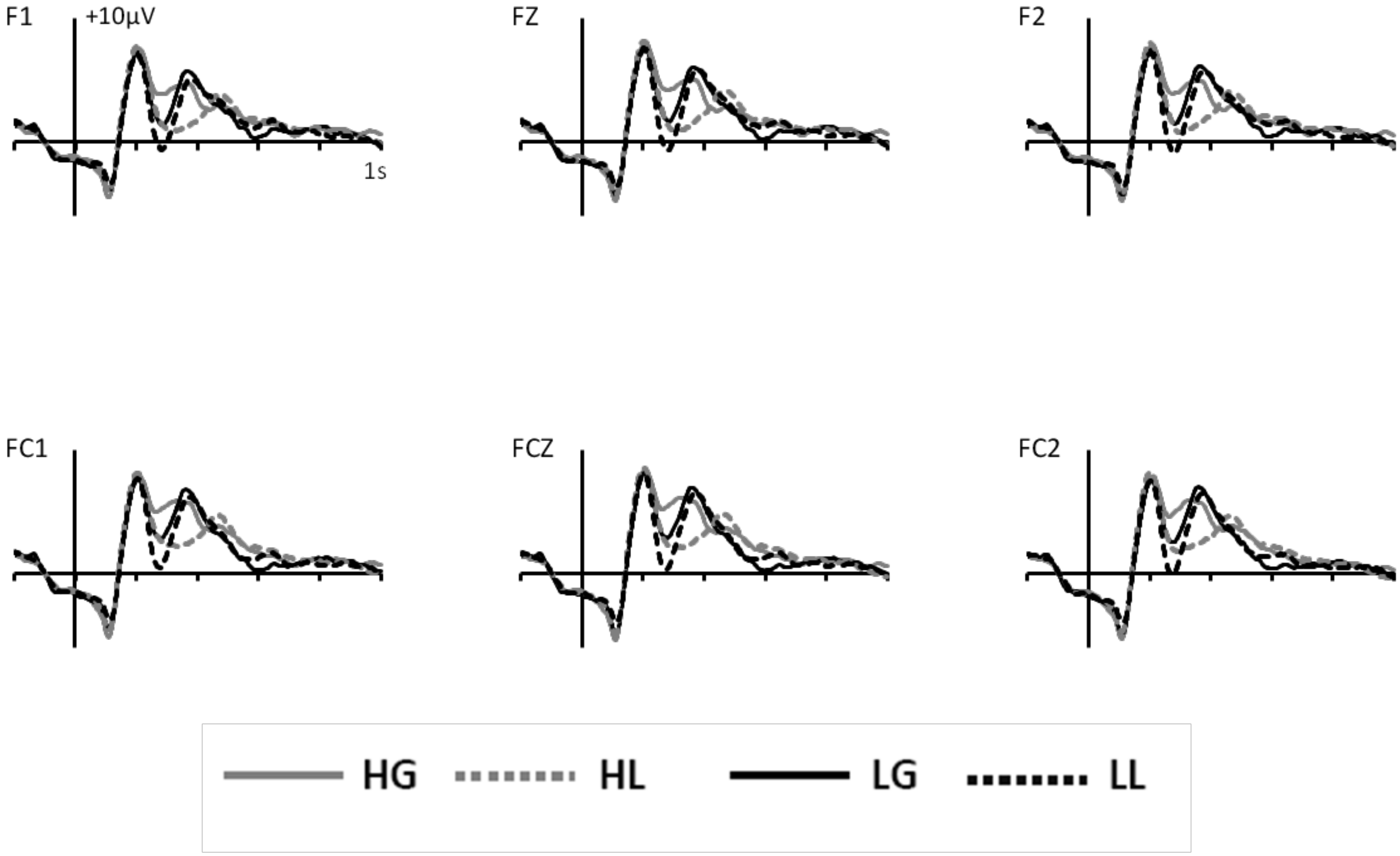


Figure 3. Scalp topography of voltage differences between losses and gains, for high and low magnitude conditions.

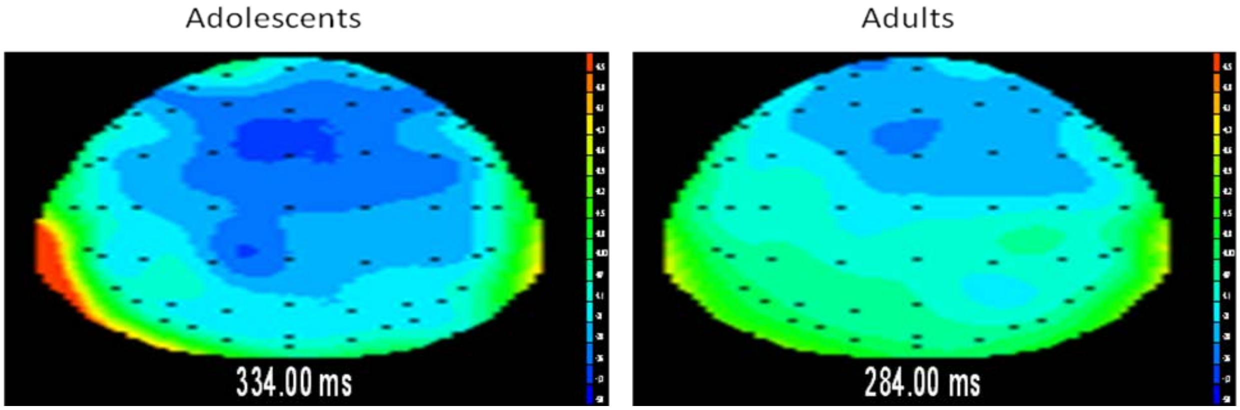
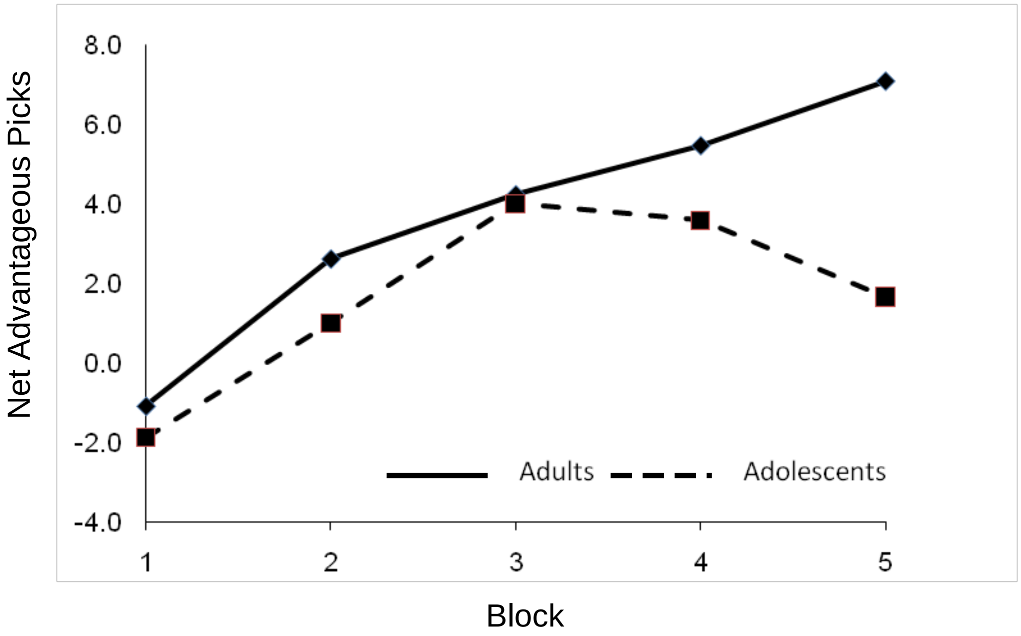


Figure 4. IGT net advantageous picks plotted as a function of block for adults and adolescents.



REFERENCES

Adleman, N. E., Menon, V., Blasey, C. M., White, C. D., Warsofsky, I. S., Glover, G. H., et al. (2002). A developmental fMRI study of the stroop color-word task. *NeuroImage, 16*(1), 61.

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of executive functions through late childhood and adolescence in an australian sample. *Developmental neuropsychology, 20*, 385.

Anderson, V., Northam, E., Hendy, J., & Wrennal, J. (2001) Developmental Neuropsychology: A Clinical Approach. London: Psychology Press.

Andersen, S. L., Rutstein, M., Benzo, J. M., Hostetter, J. C., & Teicher, M. H. (1997). Sex differences in dopamine receptor overproduction and elimination. *Neuroreport, 8*(6), 1495-1498.

Arffa, S., Lovell, M., Podell, K., & Goldberg, E. (1998). Wisconsin Card Sorting Test performance in above average and superior school children: Relationship to intelligence and age. *Archives of Clinical Neuropsychology*, 13(8), 713-720.

Arya, N. (2011). *State Trends: Legislative Changes from 2005 to 2010 Removing Youth from the Adult Criminal Justice System,* Washington, DC: Campaign for Youth Justice.

Baird, A., Fugelsang, J., & Bennett, C. (2005, April). *What were you thinking: An fMRI study of adolescent decision-making.* Poster presented at the annual meeting of the Cognitive Neuroscience Society.New York, USA

Baron, R. M., & Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology*, 51(6), 1173-1182.

Bechara, A. (2007). *Iowa Gamling Task: Professional Manual.* Lutz, Fl: Psychological Assessment Resources, Inc.

Bechara, A., Damasio, A., Damasio, H., & Anderson, S. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition*, *50*(1), 7-15.

Bechara, A., Tranel, D., & Damasio, H. (2000). Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions. *Brain: A Journal of Neurology, 123*(11), 2189-2202.

Bench, C. J., Frith, C. D., Grasby, P. M., & Friston, K. J. (1993). Investigations of the functional anatomy of attention using the Stroop test. *Neuropsychologia*, 31(9), 907-922.

Berg, E. (1948). A simple objective technique for measuring flexibility in thinking. *Journal of General Psychology*, *39*, 15-22.

Bilder, R. M., Volavka, J., Lachman, H. M., & Grace, A. A. (2004). The catechol-O-methyltransferase polymorphism: Relations to the tonic-phasic dopamine hypothesis and neuropsychiatric phenotypes. *Neuropsychopharmacology : Official Publication of the American College of Neuropsychopharmacology, 29*(11), 1943-1961.

Bishop, D. M., Frazier, C. E., Lanza-Kaduce, L., & Winner, L. (1996). The transfer of Juveniles to criminal court: Does it make a difference?. *Crime & Delinquency,* 42(2), 171-191.

Blakemore, S., and Choudhury, S. (2006). Development of the adolescent brain: implications for executive function and social cognition. *Journal or Child Psychology and Psychiatry*, 47(3/4), 296-312

Bolla, K. M. (2003). Orbitofrontal cortex dysfunction in abstinent cocaine abusers performing a decision-making task. *Neuroimage*, 191085-1094.

Bolla, K. L. (2004). Sex-related differences in a gambling task and its neural correlates. *Cerebral Cortex*, 141226-1232.

Brand, M., Recknor, E. C., Grabenhorst, F., & Bechara, A. (2007). Decisions under ambiguity and decisions under risk: correlations with executive functions and comparisons of two different gambling tasks with implicit and explicit rules. *Journal of Clinical and Experimental Neuropsychology*, 29, 86–99.

Buelow, M. T., & Suhr, J. A. (2009). Construct validity of the Iowa Gambling Task. *Neuropsychology Review*, 19(1), 102-114.

Byrnes, J. P., Miller, D. C., & Schafer, W. D. (1999). Gender differences in risk taking: A meta- analysis. *Psychological Bulletin*, *125*(3), 367-383.

Cauffman, E., Shulman, E. P., Steinberg, L., Claus, E., Banich, M. T., Graham, S., et al. (2010). Age differences in affective decision making as indexed by performance on the Iowa Gambling Task. *Developmental Psychology*, 46(1), 193-207.

Cauffman, E., & Steinberg, L. (2000). (Im)maturity of judgment in adolescence: Why adolescents may be less culpable than adults. *Behavioral Sciences & the Law, 18*(6), 741-760.

Chelune, G., & Baer, R. (1986). Developmental norms for the Wisconsin Card Sorting Test. *Journal of Clinical and Experimental Neuropsychology*, *8*(3), 219-228.

Chelune, G., & Thompson, L. (1987). Evaluation of the general sensitivity of the Wisconsin Card Sorting Test among younger and older children. *Developmental Neuropsychology*, *3*(1), 81-89.

Christakou, A., Brammer, M., & Rubia, K. (2011). Maturation of limbic corticostriatal activation and connectivity associated with developmental changes in temporal discounting. *NeuroImage*, 54(2), 1344-1354.

Christakou, A., Brammer, M., Giampietro, V., & Rubia, K. (2009). Right ventromedial And dorsolateral prefrontal cortices mediate adaptive decisions under ambiguity by integrating choice utility and outcome evaluation. *The Journal of Neuroscience*, 29(35), 11020 - 11028.

Clark, L., Manes, F., Antoun, N., Sahakian, B. J., & Robbins, T. W. (2003). The contributions of lesion laterality and lesion volume to decision-making impairment following frontal lobe damage. *Neuropsychologia*, 41(11), 1474-1483.

Crone, E., Vendel, I., & van der Molen, M. (2003). Decision-making in disinhibited adolescents and adults: Insensitivity to future consequences or driven by immediate reward?. *Personality and Individual Differences*, *35*(7), 1625-1641.

Crone, E., & van der Molen, M. (2004). Developmental changes in real life decision making: Performance on a gambling task previously shown to depend on the ventromedial prefrontal cortex. *Developmental Neuropsychology*, *25*(3), 251-279.

Crone, E. A., & van der Molen, M. W. (2007). Development of decision making in school-aged children and adolescents: Evidence from heart rate and skin conductance analysis. *Child Development*, 78(4), 1288-1301.

Crowley, M. J., Wu, J., Crutcher, C., Bailey, C. A., Lejuez, C. W., & Mayes, L. C. (2009). Risk-taking and the feedback negativity response to loss among at-risk adolescents. *Developmental Neuroscience*, 31(1-2), 137-148.

Davies, P. L., Segalowitz, S. J., & Gavin, W. J. (2004). Development of error-monitoring event-related potentials in adolescents. *Annals of the New York Academy of Sciences, 1021*, 324.

Egan, M.F., Goldberg, T.E., Kolachana, B.S., Callicott, J.H., Mazzanti, C.M., Straub, R.E., et al. (2001). Effect of COMT Val108/158 Met genotype on frontal lobe function and risk for schizophrenia. *Proceedings of the National Academy of the Sciences*. 98(12), 6917-22.

Eppinger, B., Mock, B., & Kray, J. (2009). Developmental differences in learning and error processing: Evidence from ERPs. *Psychophysiology, 46*(5), 1043-1053.

Ernst M, Nelson EE, Jazbec S, McClure EB, Monk CS, Leibenluft E, et al.(2005). Amygdala and nucleus accumbens in responses to receipt and omission of gains in adults and adolescents. *Neuroimage.* 25(4), 279-91.

Ernst M., & Paulus, M. (2005). Neurobiology of decision making: A selective review from a neurocognitive and clinical perspective. *Biological Psychiatry* 58, 597 – 604

Ernst, M., Pine, D., & Hardin, M. (2006). Triadic model of the neurobiology of motivated behavior in adolescence. *Psychological Medicine, 36*(3), 299-312.

Falkenstein, M., Hohnsbein, J., & Hoormann, J. (1995). Event-related potential correlates of errors in reaction tasks. *Electroencephalography and Clinical Neurophysiology. Supplement*, *44*, 287-296.

Falkenstein M, Hoormann J, & Hohnsbein J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica*. 101(2-3), 267-91

Farrington, D. P. (1986). Age and crime. *Crime and Justice, 7*, 189-250.

Fry, J., Greenop, K., Turnbull, O., & Bowman, C. (2009). The effect of education and gender on emotion-based decision-making. *South African Journal of Psychology*, 39(1), 122-132.

Furby, L., & Beyth-Marom, R. (1992). Risk taking in adolescence: A decision-making perspective. *Developmental Review, 12*(1), 1-44.

Galvan, A., Hare, T. A., Parra, C. E., Penn, J., Voss, K., Glover, G., et al. (2006). Earlier development of the accumbens relative to orbitofrontal cortex might underlie risk-taking behavior in adolescents. *Journal of Neuroscience, 26*(25), 6885-6892.

Gardner, M. and Steinberg, L. (2005). Peer influence of risk taking, risk preference, and risky decision making in adolescence and adulthood: An experimental study. *Developmental Psychology* 41(4), 625-635

Gehring, W. J., & Willoughby, A. R. (2002). The medial frontal cortex and the rapid processing of monetary gains and losses. *Science*, *295*(5563), 2279.

Giedd, J.N. (2004). Structural magnetic resonance imaging of the adolescence brain. *Annals of the New York Academy of Sciences* 1021: 77-85

Giedd, J., Blumenthal, J., Jefferies, N., Catellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence. A longitudinal MRI study. *Nature Neuroscience, 2*, 861.

Gogtay, N., Gıedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaıtuzıs, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Science U S A, 101*(21), 8174-8179.

Green, L., Fry, A. F., & Myerson, J. (1994). Discounting of delayed rewards: A life-span comparison. *Psychological Science*, 5(1), 33-36.

Green, L., Myerson, J., Lichtman, D., Rosen, S., & Fry, A. (1996). Temporal discounting in choice between delayed rewards: The role of age and income. *Psychology and Aging*, 11(1), 79-84.

Greve, K. W., Ingram, F., & Bianchini, K. J. (1998). Latent structure of the Wisconsin Card Sorting Test in a clinical sample. *Archives of Clinical Neuropsychology*, 13(7), 597-609.

Grober, E., & Sliwinski, M. (1991). Development and validation of a model for estimating premorbid verbal intelligence in the elderly. *Journal of Clinical and Experimental Neuropsychology*, 13(6), 933-949.

Goyer, J. P., Woldorff, M. G., & Huettel, S. A. (2008). Rapid electrophysiological brain responses are influenced by both valence and magnitude of monetary rewards. *Journal of Cognitive Neuroscience, 20*(11), 2058-2069.

Grisso, T. (1997). The competence of adolescents as trial defendants. *Psychology, Public Policy, and Law*, *3*(1), 3-32.

Grisso, T., Steinberg, L., Woolard, J., Cauffman, E., Scott, E., Graham, S., et al. (2003). Juveniles' competence to stand trial: A comparison of adolescents' and adults' capacities as trial defendants. *Law and human behavior, 27*(4), 333-363.

Grisso, T., & Schwartz, R. (2000). *Youth on trial: A developmental perspective on juvenile justice*. Chicago, IL, US: University of Chicago Press.

Grose-Fifer, J., Hoover, S., Zottoli, T.M. & Rodriguez, A. (2011). Expecting the unexpected: An N400 study of risky sentence processing in adolescents. *Psychophysiology*. Advance online publication. doi: 10.1111/j.14698986.2011.01197.x

Grose-Fifer, J., Saul, S., Yuksel-Sokmen, O., Zottoli, T.M., Hoover, S. & Navarro, K. (April, 2011). *Gender differences in the feedback-related negativity (FRN) in a simple gambling task.* Poster to be presented at the annual meeting of the Cognitive Neuroscience Society, San Francisco, CA

Hajcak, G., Holroyd, C. B., Moser, J. S., & Simons, R. F. (2005). Brain potentials associated with expected and unexpected good and bad outcomes. *Psychophysiology*, *42*, 161.

Hajcak, G., Moser, J. S., Holroyd, C. B., & Simons, R. F. (2006). The feedback-related negativity reflects the binary evaluation of good versus bad outcomes. *Biological Psychology, 71*(2), 148-154.

Hajcak, G., Moser, J. S., Holroyd, C. B., & Simons, R. F. (2007). It's worse than you thought: The feedback negativity and violations of reward prediction in gambling tasks. *Psychophysiology*, 44(6), 905-912

Hammerer, D., Li, S. C., Muller, V., & Lindenberger, U. (2011). Life span differences in electrophysiological correlates of monitoring gains and losses during probabilistic reinforcement learning. *Journal of Cognitive Neuroscience, 23*(3), 579-592.

Heilbrun, K., Leheny, C., Thoma, L., & Huneycutt, D. (1997). A national survey of U.S. statutes on juvenile transfer: Implicatioins for policy and practice. *Law and Human Behavior,* 15(2), 125-149

Hillyard, S.A. & PIcton, T.W. (1987). Electrophysiology of cognition. In F. Plum (Ed.), Handbook of Physiology: Section 1. The Nervous System: Volume 5. Higher Functions of the Brain,Part 2. pp. 519-584. Bethseda, MD: Waverly Press.

Heaton, R.K. (1981). *Wisconsin Card Sorting Test Manual.* Odessa,Fl. Psychological Assessment Resources Inc.

Hogan, A. M., Vargha-Khadem, F., Kirkham, F. J., & Baldeweg, T. (2005). Maturation of action monitoring from adolescence to adulthood: An ERP study. *Developmental Science, 8*(6), 525-534.

Holroyd, C.B., Baker, T.E., Kerns, K.A. & Müller, U. (2008). Electrophysiological evidence of atypical motivation and reward processing in children with attention deficit hyperactivity disorder Neuropsychologia, 46 (8), 2234-2242

Holroyd, C. B., & Coles, M. G. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109*(4), 679-709.

Holroyd, C. B., Nieuwenhuis, S., Yeung, N., & Cohen, J. D. (2003). Errors in reward prediction are reflected in the event-related brain potential. *Neuroreport, 14*(18), 2481-2484.

Holroyd, C. B., Pakzad-Vaezi, K. L., & Krigolson, O. E. (2008). The feedback correct-related positivity: Sensitivity of the event-related brain potential to unexpected positive feedback. *Psychophysiology, 45*(5), 688-697.

Hooper, C. J., Luciana, M., Conklin, H. M., & Yarger, R. S. (2004). Adolescents' performance on the development of decision making and ventromedial prefrontal cortex. *Developmental Psychology*, *40*, 1148-58.

Huizenga, H. M., Crone, E. A., & Jansen, B. J. (2007). Decision-making in healthy children, adolescents and adults explained by the use of increasingly complex proportional reasoning rules. *Developmental Science*, 10(6), 814-825.

Jenkinson, P. M., Baker, S. R., Edelstyn, N. J., & Ellis, S. J. (2008). Does autonomic arousal distinguish good and bad decisions? Healthy individuals’ skin conductance reactivity during the Iowa Gambling Task. *Journal of Psychophysiology*, 22(3), 141-149

Jonkman, L. M., Lansbergen, M. M., & Stauder, J. A. (2003). Developmental differences in behavioral and event-related brain responses associated with response preparation and inhibition in a go/nogo task. *Psychophysiology*, 40(5), 752-761.

Kamarajan, C., Porjesz, B., Rangaswamy, M., Tang, Y., Chorlian, D. B., Padmanabhapillai, A., et al. (2009). Brain signatures of monetary loss and gain: Outcome-related potentials in a single outcome gambling task. *Behavioural Brain Research*, *197*(1), 62-76.

Kamarajan, C., Rangaswamy, M., Tang, Y., Chorlian, D. B., Pandey, A. K., Roopesh, B. N., et al. (2010). Dysfunctional reward processing in male alcoholics: An ERP study during a gambling task. *Journal of Psychiatric Research, 44*(9), 576-590.

Kelley, A. E., Schochet, T., & Landry, C. F. (2004). Risk taking and novelty seeking in adolescence: Introduction to part I. In R. E. Dahl, L. Spear, R. E. Dahl, L. Spear (Eds.), *Adolescent brain development: Vulnerabilities and opportunities* (pp. 27-32). New York, NY US: New York Academy of Sciences

Kenny, D. A., Kashy, D. A., & Bolger, N. (1998). Data analysis in social psychology. In D. T. Gilbert, S. T. Fiske, G. Lindzey, D. T. Gilbert, S. T. Fiske, G. Lindzey (Eds.) , *The handbook of social psychology, Vols. 1 and 2 (4th ed.)* (pp. 233-265). New York, NY US: McGraw-Hill.

Kheramin, S., Body, S., Ho, M. -., Velázquez-Martinez, D. N., Bradshaw, C. M., Szabadi, E., et al. (2003). Role of the orbital prefrontal cortex in choice between delayed and uncertain reinforcers: A quantitative analysis. *Behavioural Processes, 64*(3), 239-250.

Kirby, K., & Marakovic, N. (1996). Delay-discounting probabilistic rewards: Rates decrease as amounts increase. *Psychonomic Bulletin & Review*, *3*(1), 100-104.

Kizilbash, A., & Donders, J. (1999). Latent structure of the Wisconsin Card Sorting Test after pediatric traumatic head injury. *Child Neuropsychology*, *5*(4), 224-229.

Kongs, S.K., Thompson, L.L., Iverson, G.L. & Heaton, R.K. (2000). *Wisconsin Card Sorting Test –64 Card Version, Professional Manual.* Lutz, FL: Psychological Assessment Resources, Inc.

Kruglanski, A. W., & Gigerenzer, G. (2011). Intuitive and deliberate judgments are based on common principles. *Psychological Review*, 118(1), 97-109

Kwon, H., Reiss, A. L., & Menon, V. (2002). Neural basis of protracted developmental changes in visuo-spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 13336- 13341.

Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and adolescence: Disentangling the contributions of age and executive function. *Neuropsychologia, 44*(11), 2139-2148.

Leon-Carrion, J., Garcia-Orza, J., & Perez-Santamaria, F. J. (2004). Development of the inhibitory component of the executive functions in children and adolescents. *Int J Neurosci*, *114*, 1291

Leone, P.E., Zaremba, B.A., Chapin, M.S. & Iseli, C. (2005). Understanding the Over Representation of Youths With Disabilities in Juvenile Detention. 3 District of Columbia, Law Review 389 Retrieved from http://heinonline.org/HOL/Page?handle=hein.journals/udclr3&div=23&g_sent=1&collection=journals#415

Lejuez, C. W., Read, J. P., Kahler, C. W., Richards, J. B., Ramsey, S. E., Stuart, G. L., et al. (2002). Evaluation of a behavioral measure of risk taking: The Balloon Analogue Risk Task (BART). *Journal of Experimental Psychology: Applied*, 8(2), 75-84

Levin, H.S., Culhane, J.H., Hartman, J., Evankovich, K., and Mattson, A.J. et al. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology* 7(3), 377-395

Lezak, M. D., Howieson, D. B., Loring, D. W., Hannay, H., & Fischer, J. S. (2004). *Neuropsychological assessment (4th ed.)*. New York, NY US: Oxford University Press.

Loughran, T. A., Mulvey, E. P., Schubert, C. A., Chassin, L. A., Steinberg, L., Piquero, A. R., et al. (2010). Differential effects of adult court transfer on juvenile offender recidivism. *Law and Human Behavior*, 34(6), 476-488.

Luck, J. (2005). An Introduction to the Event Related Potential Technique. Cambridge, MA: MIT Press

Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A., & Sweeney, J. A. (2004). Maturation of cognitive processes from late childhood to adulthood. *Child development, 75,* 1357.

Manes, F., Sahakian, B., Clark, L., Rogers, R., Antoun, N., Aitken, M., et al. (2002). Decision-making processes following damage to the prefrontal cortex. *Brain: A Journal of Neurology*, 125(3), 624-639.

Marco-Pallarés, J., Cucurell, D., Cunillera, T., Krämer, U. M., Càmara, E., Nager, W., et al. (2009). Genetic variability in the dopamine system (dopamine receptor D4, catechol-O-methyltransferase) modulates neurophysiological responses to gains and losses. *Biological Psychiatry, 66*(2), 154.

Matsumoto, M., & Hikosaka, O. (2009). Two types of dopamine neuron distinctly convey positive and negative motivational signals. *Nature, 459*(7248), 837-841.

Mayzer, R., Bradley, A. R., Rusinko, H., & Ertelt, T. W. (2009). Juvenile competency to stand trial in criminal court and brain function. *Journal of Forensic Psychiatry & Psychology*, 20(6), 785-800

Mishra, S., Lalumière, M. L., & Williams, R. J. (2010). Gambling as a form of risk taking: Individual differences in personality, risk-accepting attitudes, and behavioral preferences for risk. *Personality and Individual Differences*, 49(6), 616-621.

Moffitt, T. E.,&Harrington, H. L. (1996). Delinquency: The natural history of antisocial behaviour. In P. A. Silva & W. R. Stanton (Eds.), *From child to adult: The Dunedin multidisciplinary health and development study* (pp. 163-185). Oxford, UK: Oxford University Press.

Monk, C. S., McClure, E. B., Nelson, E. E., Zarahn, E., Bilder, R. M., Leibenluft, E., et al. (2003). Adolescent immaturity in attention-related brain engagement to emotional facial expressions. *NeuroImage, 20*, 420-428.

Monterosso, J., Ehrman, R., Napier, K. L., O'Brien, C. P., & Childress, A. (2001). Three decision-making tasks in cocaine-dependent patients: Do they measure the same construct? *Addiction*, 96(12), 1825-1837.

Müller, S. V., Möller, J., Rodriguez-Fornells, A., & Münte, T. F. (2005). Brain potentials related to self-generated and external information used for performance monitoring. *Clinical Neurophysiology, 116*, 63.

Murphy, K. & Garavan, H. (2010) Artifactual fMRI group and condition differences driven by performance confounds. *Neuroimage.* 21(1), 219-28.

Niedermayer, E. & Da Silva, L. (2005). Electroencephalography Basic Principles, Clinical Applications, and Related Fields 5th Edition. Philadelphia: Lippincott Williams & Wilkins

Nieuwenhuis, S., Holroyd, C. B., Mol, N., & Coles, M. G. (2004). Reinforcement-related brain potentials from medial frontal cortex: Origins and functional significance. *Neuroscience and Biobehavioral Reviews*, *28*, 441.

Nieuwenhuis, S., Slagter, H. A., von Geusau, H. J., Heslenfeld, D. J., & Holroyd, C. B. (2005). Knowing good from bad: Differential activation of human cortical areas by positive and negative outcomes. *European Journal of Neuroscience, 21*, 3161.

Northoff, G., Grimm, S., Boeker, H., Schmidt, C., Bermpohl, F., Heinzel, A., et al. (2006). Affective judgment and beneficial decision making: Ventromedial prefrontal activity correlates with performance in the Iowa Gambling Task.. *Human Brain Mapping*, 27(7), 572-587.

Nyhus, E., & Barceló, F. (2009). The Wisconsin Card Sorting Test and the cognitive assessment of prefrontal executive functions: A critical update. *Brain and Cognition*, 71(3), 437-451.

United States. Department of Justice. Office of Justice Programs. *Office of Juvenile Justice and Delinquency Prevention*. OJJDP Statistical Briefing Book. Available Online: http://ojjdp.ncjrs.org/ojstatbb/crime/JAR_Display.asp?ID=qa05200. October 31, 2009.

United States. Department of Justice. Office of Justice Programs. Bureau of Justice Statistics Bulletin (2006). Prison and jail inmates at midyear 2005 by Harrison, P.M. & Beck, A. J. Washington DC: Office of Justice Programs (NCJ 213133)

United States. Department of Justice. Office of Justice Programs. Office of Juvenile Justice and Delinquency Prevention. Juvenile Offenders and Victims, National Report Series (2004). Juveniles in corrections by Sickmund, M. Washington DC:

Office of Justice Programs (NCJ 202885)

United States. Department of Justice. Office of Justice Programs. Office of Juvenile Justice and Delinquency Prevention Juvenile Offenders and Victims, National Report Series (1999). Juveniles in Corrections by Snyder, H. & Sickmund, M. Washington DC: Office of Justice Programs. (NCJ 178257)

Oliveira, F. T. P., McDonald, J. J., & Goodman, D. (2007). Performance monitoring in the anterior aingulate is not all error related: Expectancy deviations and the representations of action-outcome associations. *Journal of Cognitive Neuroscience*, 19, 1994-2004.

Olson, E. A., Collins, P. F., Hooper, C. ., Muetzel, R., Lim, K. O., & Luciana, M. (2009). White matter integrity predicts delay discounting behavior in 9- to 23-year-olds: A diffusion tensor imaging study. *Journal of Cognitive Neuroscience*, 21(7), 1406-1421.

Olson, E. A., Hooper, C. J., Collins, P., & Luciana, M. (2007). Adolescents' performance on delay and probability discounting tasks: Contributions of age, intelligence, executive functioning, and self-reported externalizing behavior. *Personality and Individual Differences, 43*(7), 1886-1897.

Pfabigan, D. M., Alexopoulos, J., Bauer, & Sailer, U. (2010). Manipulation of feedback expectancy and valence induces negative and positive reward prediction error signals manifest in event-related brain potentials. *Psychophysiology*, 1-9 Advance online publication. doi: 10.1111/j.1469-8986.2010.01136.x

Picton, T. W., Bentin, S. S., Berg, P. P., Donchin, E. E., Hillyard, S. A., Johnson, R. ,et al. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology*, 37(2), 127-152

Potts, G. F., Martin, L. E., Burton, P., & Montague, P. R. (2006). When things are better or worse than expected: The medial frontal cortex and the allocation of processing resources. *Journal of Cognitive Neuroscience, 18*(7), 1112-1119.

Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods, Instruments & Computers*, 36(4), 717-731.

Psychological Corporation, The. (1999). *WASI: Wechsler Abbreviated Scale of Intelligence*.

Reyna, V. F., Adam, M. B., Poirier, K. M., LeCray, C. W., & Brainerd, C. J. (2005). Risky Decision Making in Childhood and Adolescence: A Fuzzy-Trace Theory Approach. In J. E. Jacobs, P. A. Klaczynski, J. E. Jacobs, P. A. Klaczynski (Eds.), *The development of judgment and decision making in children and adolescents* (pp. 77-106). Mahwah, NJ US: Lawrence Erlbaum Associates Publishers

Reynolds, B. (2006). A review of delay-discounting research with humans: Relations to drug use and gambling. *Behavioural Pharmacology*, 17(8), 651-667.

Roper v. Simmons, 543 U.S. 551 (2005)

Rubia, K., Smith, A.B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., et al. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Human Brain Mapping,* 27, 973-993

Santesso, D.L, Evins A. E, Frank, M. J., Schetter, E. C., Bogdan, R. & Pizzagalli, D.A. (2009). Single dose of a dopamine agonist impairs reinforcement learning in humans: Evidence from event-related potentials and computational modeling of striatal-cortical function.*Human Brain Mapping.* 30(7), 1963–1976

Santesso, D. L., & Segalowitz, S. J. (2008). Developmental differences in error-related ERPs in middle- to late-adolescent males. *Developmental Psychology, 44*(1), 205-217.

Santesso, D. L., Segalowitz, S. J., & Schmidt, L. A. (2005). ERP correlates of error monitoring in 10-year olds are related to socialization. *Biological Psychology, 70*(2), 79-87.

Sato, A., Yasuda, A., Ohira, H., Miyawaki, K., Nishikawa, M., Kumano, H., et al. (2005). Effects of value and reward magnitude on feedback negativity and P300. *Neuroreport: An International Journal for the Rapid Communication of Research in Neuroscience, 16*(4), 407-411.

Scheres, A., Dijkstra, M., Ainslie, E., Balkan, J., Reynolds, B., Sonuga-Barke, E., et al. (2006). Temporal and probabilistic discounting of rewards in children and adolescents: Effects of age and ADHD symptoms. *Neuropsychologia*, 44(11), 2092-2103.

Schultz, W. (2002). Getting formal with dopamine and reward. *Neuron, 36*, 241.

Schubert, C. A., Mulvey, E. P., Loughran, T. A., Fagan, J., Chassin, L. A., Piquero, A. R., et al. (2010). Predicting outcomes for youth transferred to adult court. *Law and Human Behavior*, 34(6), 460-475.

Segalowitz, S. J., & Davies, P. L. (2004). Charting the maturation of the frontal lobe: An electrophysiological strategy. *Brain and Cognition, 55*(1), 116-133.

Segalowitz, S. J., Santesso, D. L., Willoughby, T., Reker, D. L., Campbell, K., Chalmers, H., et al. (2011). Adolescent peer interaction and trait surgency weaken medial prefrontal cortex responses to failure. *Social Cognitive and Affective Neuroscience*. Advance online publication. doi: 10.1093/scan/nsq090

Senkowski, D., & Herrmann, C. S. (2002). Effects of task difficulty on evoked gamma activity and ERPs in a visual discrimination task. *Clinical Neurophysiology*, 113(11), 1742-1753.

Strauss, E., Sherman, E., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary (3rd. ed)*. New York, NY, US: Oxford University Press.

Smillie, L. D., Cooper, A. J., & Pickering, A. D. (2010). Individual differences in reward-prediction-error: Extraversion and feedback-related negativity. *Social Cognitive and Affective Neuroscience,* Advance online publication. *d*oi:10.1093/scan/nsq078

Somsen, R. M. (2007). The development of attention regulation in the Wisconsin Card Sorting Task. *Developmental Science*, 10(5), 664-680

Spear, L. P. (2000). The adolescent brain and age-related behavioral manifestations. *Neuroscience and Biobehavior Review, 24*(4), 417.

Steinberg, L., & Cauffman, E. (1996). Maturity of judgment in adolescence: Psychosocial factors in adolescent decision making. *Law and Human Behavior*, 20(3), 249-272

Steinberg, L., Graham, S., O'Brien, L., Woolard, J., Cauffman, E., & Banich, M. (2009). Age differences in future orientation and delay discounting. *Child Development*, 80(1), 28-44.

Steinberg, L., & Scott, E. S. (2003). Less guilty by reason of adolescence: Developmental immaturity, diminished responsibility, and the juvenile death penalty. *American Psychologist, 58*(12), 1009-1018.

Stroop, J. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643-662.

Tamnes, C. K., Østby, Y., Walhovd, K. B., Westlye, L. T., Due-Tønnessen, P., & Fjell, A. M. (2010). Neuroanatomical correlates of executive functions in children and adolescents: A magnetic resonance imaging (MRI) study of cortical thickness. *Neuropsychologia*, 48(9), 2496-2508.

Tanida, T., Warita, K., Mitsuhashi, T., Ishihara, K., Yokoyama, T., Kitagawa, H., et al. (2009). Morphological analyses of sex differences and age-related changes in C3H mouse midbrain. *The Journal of Veterinary Medical Science / the Japanese Society of Veterinary Science, 71*(7), 855-863.

Tekin, E. & Currie, J. (2006). Does Child Abuse Cause Crime? *Andrew Young School of Policy Studies Research Paper No. 06-31*; IZA Discussion Paper No. 2063. Available at SSRN: http://ssrn.com/abstract=895178

Teplin, LA, Abram, KM, McClelland, GM, Dulcan, MK & Mericle, AA. (2002). Psychiatric disorders in youth in juvenile detention. *Archives of General Psychiatry* 59: 1133-1143.

van Duijvenvoorde, A. K., Jansen, B. J., Visser, I., & Huizenga, H. M. (2010). Affective and cognitive decision-making in adolescents. *Developmental Neuropsychology*, 35(5), 539-554.

VanMeel, C. S., Oosterlaan, J., Heslenfeld, D. J., & Sergeant, J. A. (2005). Telling good from bad news: ADHD differentially affects processing of positive and negative feedback during guessing. *Neuropsychologia, 13*, 1946-1954.

Verdejo-Garcia, A. I. (2007). The differential relationship between cocaine use and marijuana use on decision-making performance over repeat testing with the Iowa gambling task. *Drug & Alcohol Dependence,* 902-11.

Wahlstrom, D., White, T., & Luciana, M. (2010). Neurobehavioral evidence for changes in dopamine system activity during adolescence. *Neuroscience & Biobehavioral Reviews*, *34*(5), 631-648.

Wechsler, D. (1997). Wechsler Adult Intelligence Scale-III. San Antonio: The Psychological Corporation

Wilcox, R. (2003). Applying Contemporary Statistical Techniques. San Diego, CA: Academic Press

Winner, L., Lanza-Kaduce, L., Bishop, D. M., & Frazier, C. E. (1997). The transfer of juveniles to criminal court: Reexamining recidivism over the long term. *Crime & Delinquency*, 43(4), 548-563

Whelan, R., & McHugh, L. A. (2009). Temporal discounting of hypothetical monetary rewards by adolescents, adults, and older adults. *The Psychological Record,* 59(2), 247-258.

Wiersema, J. R., van der Meere, J. J., & Roeyers, H. (2007). Developmental changes in error monitoring: An event-related potential study. *Neuropsychologia, 45*(8), 1649-1657.

Wickens, J.R., Begg, A.J., & Arbuthnett, G.W. (1996). Dopamine reverses the depression of rat corticostriatal synapses which normally follows high-frequency stimulation of cortex in vitro. *Neuroscience.* 70(1), 1-5.

Wilson, M., & Daly, M. (2006). Are Juvenile Offenders Extreme Future Discounters? *Psychological Science*, 17(11), 989-994.

Xu, J., Kochanek, K.D., Murphy, S.L. & Tejada-Vera, B. (2010). Deaths: Final data for 2007. National Vital Statistics Report, 58, 19.

Yasuda, A., Sato, A., Miyawaki, K., Kumano, H., & Kuboki, T. (2004). Error-related negativity reflects detection of negative reward prediction error. *Neuroreport, 15*(16), 2561-2565.

Yeung, N., Holroyd, C. B., & Cohen, J. D. (2005). ERP correlates of feedback and reward processing in the presence and absence of response choice. *Cerebral Cortex*, *15*, 535.

Yeung, N., & Sanfey, A. G. (2004). Independent coding of reward magnitude and valence in the human brain. *Journal of Neuroscience*, *24*(28), 6258-6264.

Yu, R., & Zhou, X. (2006). Brain response to outcome of one's own and other's performance in a gambling task. *Neuroreport*, *17*, 1747-1751.