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Considerations of a Dual-systems Model of Cognitive Development and Risky Driving

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Abstract

The dual-systems model of adolescent risk-taking postulates that risk-taking during adolescence partially results from an imbalance in the development of the executive and the socio-emotional cognitive systems. While supported by behavioral and neuroanatomical data, translational research linking the model with real-world driving or laboratory driving simulation is sparse. This paper discusses the model as it relates to adolescent driving and reviews empirical studies that have applied it in a driving-specific context. While, the studies reviewed provided partial support, each lacked a critical component necessary to fully test the model. Thus, a strong test has yet to be implemented; however, the dual-systems model holds promise for advancing the understanding of teen driving risk and guiding applications for prevention and policy.

Recent research in developmental neuroscience highlights relationships among neuroanatomical development and corresponding social, emotional, and cognitive changes that hold promise for an improved understanding of risky behavior during adolescence (Eshel, Nelson, Blair, Pine, & Ernst, 2007; Galvan et al., 2006; Galvan, Hare, Voss, Glover, & Casey, 2007; Giedd et al., 1999; Gogtay et al., 2004; Toga, Thompson, & Sowell, 2006; but see Berns, Moore, & Capra, 2009). A dominant theme of this work has been the emergence of a dual-systems model of adolescent risk (Casey, Jones, & Somerville, 2011; Steinberg, 2008; Galvan et al., 2007; Dahl, 2004; Giedd, 2010; Keating & Halpern-Felsher, 2008; Pharo, Sim, Graham, Gross, & Hayne, 2011). The present paper provides a conceptual discussion of the dual-systems model, discusses supporting developmental theory and research, and explains how the theory relates to the dangerous but common real-world

behavior of teenage driving. The paper first presents the model by providing an initial overview of the evolutionary-developmental context of adolescent risk behavior and insights from neuroscience that have led to its development. This is followed by an illustration of the model's key content and major perspectives. Next the paper presents a review and qualitative analysis of existing empirical applications (Chein, Albert, O'Brien, Uckert, & Steinberg, 2011; Gardner & Steinberg, 2005; Jongen et al., 2012; Mäntylä, Karlsson, & Marklund, 2009; Shepherd & Lane, 2011) that illustrate the utility of the theory with respect to teenage driving. The final sections identify critical gaps in translational research and consider public policy aimed at positive youth development in light of what is known and what remains to be learned.

The Dual-System Model of Adolescent Risk

Across cultures and time, adolescence is marked by increased risk behavior (Arnett, 1992; Blum & Nelson-Mmari, 2004; Kloep, Güney, Çok, & Simsek, 2009) that often results in negative health and social outcomes (Dahl, 2004). While alarming, increased risk behavior in adolescence may, in part, be developmentally advantageous. Recent interpretations have suggested that adolescent risk behavior may serve the developmentally-adaptive purpose of facilitating adolescents' transition from a family dependent social context to a more independent and peer-oriented one (Casey, Jones, & Hare, 2008; Ellis et al., 2011; Steinberg, 2008) because adolescence is a time of increased independence and decreased supervision when opportunities that afford risk behavior become more frequent. This change in contextual exposure co-occurs with psychological and neurophysiological changes during a critical period of the lifespan when, in our evolutionary past, risk and independence may have improved the likelihood of survival and reproduction. As Steinberg and Belsky (1996) write, "The willingness to take risks, even life-threatening risks, might well have proved advantageous to our ancestors when refusing to incur such risk was in fact even more dangerous to survival or reproduction" (p. 96). The convergence of these evolutionary social-contextual factors with emerging evidence from developmental neuro-science helps to explain how neuro-developmental changes may predispose individuals to be more open or attracted to risk during adolescence than during other life stages. Adolescence marks a neuro-developmental period in which the neuro-network responsible for deliberate controlled processing (the executive system) is underdeveloped compared to the neuro-network responsible for reward sensitivity (the socio-emotional system). This developmental imbalance may incline adolescents to risk behavior. Dahl (2004) argues that the discrepancy between the development of the executive system and the socio-emotional system may have increased over time in relation to improvements in nutrition and standards of living.

To illustrate this dual-systems model, we present a heuristic overview of the divergent neuro-development of the executive system and the socio-emotional system. While the account simplifies complex neuroanatomical functions, it highlights the neuroanatomical development that specifically informs the dual-systems model. It should be noted, however, that the distinctions between the two systems are not as clearly delineated as the model suggests and there is much interplay and overlap between the two cognitive systems (for examples, see Krawczyk, Gazzaley, & D'Esposito, 2007; Padmala & Pessoa, 2010; Szatkowska, Bogorodzki, Wolak, Marchewka, & Szeszkowski, 2008).

Figure 1 describes key aspects of the dual-systems model. The upper left side of the figure depicts the general nature of the relationship between the executive system and the socio-emotional system, and notes critical brain regions associated with each. The executive system, largely mediated by lateral prefrontal and parietal cortex, represents a constellation of cognitive processes that allow us to control our thoughts and actions (Alvarez & Emory, 2006; Engle, 2002; Goldman-Rakic, 1987; Miyake et al., 2000; Rubia, Smith, Brammer, & Taylor, 2003). The socio-emotional system, largely mediated by limbic and paralimbic brain regions is strongly implicated in reward sensitivity (Steinberg, 2010). In optimal conditions, the executive system regulates the socio-emotional system in a top-down fashion. In other words, the executive system controls, interprets, and utilizes the information received from the highly activated socio-emotional system, typically over-riding or moderating the influence of that system. While the development of the socio-emotional system peaks during adolescence, the executive system does not fully develop until early adulthood due to the prolonged development of prefrontal brain regions.

The upper right side of Figure 1 conceptually depicts the developmental trajectories of these two systems. Studies of neuroanatomical brain development show that the human brain continues to mature throughout adolescence and well into young adulthood (Blakemore & Choudhury, 2006). The development of the executive system is largely reflected in prefrontal cortex development, the seat of the executive function. This developmental trajectory is particularly prolonged. While there is much individual variability (Semrud-Clikeman, 2012), for most, this brain region does not reach maturity until the mid-twenties (Durston et al., 2006; Luna et al., 2001; Steinberg, 2009; Watson, Lambert, Miller, & Strayer, 2011).

The developmental trajectory of the socio-emotional system is somewhat different. Evidence suggests that the sensitivity of the socio-emotional system peaks during mid-adolescence and is higher during this time than any other developmental period (Steinberg, 2009). For example, studies employing functional magnetic resonance imaging (fMRI) have shown increased activity during adolescence in the nucleus accumbens, a subcortical structure involved in the socio-emotional system associated with the processing of reward salience (Galvan et al., 2006). Further, relative to adults, adolescents show less coordinated simultaneous activity of cortical and subcortical regions when presented with emotional stimuli, suggesting immature emotion regulation (Steinberg, 2009). Accordingly, reward salience is highest in early adolescence when executive function is not well developed. Indeed, parity between the social-emotional system and the executive system is not reached until the early to mid-twenties, after which the executive system is mature enough to regulate the now attenuated activity of the socio-emotional system.

This dual-systems model posits that this imbalance between the early-adolescence peak in the sensitivity of the socio-emotional neural system and the prolonged maturation of the executive system make adolescents particularly vulnerable to risk (Casey et al., 2011; Dahl, 2004; Giedd, 2010; Keating & Halpern-Felsher, 2008; Pharo et al., 2011; Steinberg, 2005; 2007; 2008; 2010; 2011a). In situations where socio-emotional reward salience is low or moderate, the executive system is likely mature enough to inhibit risky decisions and facilitate behaviors that are consistent with adolescents' accurate risk assessment. However,

as illustrated in the bottom panel of Figure 1, because the executive system develops more gradually throughout adolescence, in socially or emotionally rewarding contexts (such as driving in the presence of peers, late at night, or when emotionally aroused) the executive system may be insufficiently robust to down-regulate (override or moderate) the highly activated socio-emotional system.

The dual-systems model has received much support within adolescent developmental psychology. For example, Steinberg (2010) lays out the model's organization and presents supporting evidence from a large sample ($N = 935$). This paper has been widely cited to explain a range of risky phenomenon in adolescence including substance use (Quinn & Harden, 2013), suicide ideation (Ortin, Lake, Kleinman, & Gould, 2012), emotionality (Centifanti & Modecki, 2013), and the link between sleep quality and risky behavior (Telzer, Fuligni, Lieberman, & Galván, 2013) to reference only a few. One paper even relies heavily on the dual-systems model in its call for a paradigm shift in our understanding of adolescent motivation (Luciana & Collins, 2012). Evidence to support the model is accumulating rapidly. Pharo et al. (2011) examined the relationship between the functionality of the executive system and risk behavior. They found that risk-taking and neuropsychological scores of executive function were negatively correlated, supporting the hypothesis that adolescent risky behavior may be due, in part, to developmental changes in the prefrontal cortex. Further support comes from research on the timing of adolescent brain development and corresponding reward sensitivity. Steinberg (2010) showed that reward sensitivity, preference for immediate rewards, and self-reported sensation seeking increase in preadolescence before peaking during mid-adolescence and declining thereafter. Research on reward salience and peer influence in decision making during adolescence is also consistent. It appears that, for many adolescents, the presence of peers introduces a salient, socially and emotionally rewarding context where the preference for immediate reward is strong. For example, using a delayed discounting task, which measures preferences for immediate versus delayed reward, O'Brien, Albert, Chein, and Steinberg (2011) found that the presence of peers increased adolescents' preference for immediate reward gratification compared to when they were alone.

Applications to Driving Safety

A highly relevant and commonly cited example of a context in which the dual-systems model is particularly applicable is driving in the presence of peers (Allen & Brown, 2008; Steinberg, 2008; Gardner & Steinberg, 2005; Keating & Halpern-Felsher, 2008). Automobile crashes are the leading cause of death for adolescents (Centers for Disease Control and Prevention, 2012; World Health Organization, 2012) and fatal teen crashes tend to occur late at night, at high speeds, and in the presence of other teenage passengers (Braitman, Kirley, McCartt, & Chaudhary, 2008; Preusser, Ferguson, & Williams, 1998; Williams, Ali, & Shults, 2010; Ouimet et al., 2010). This situation fits well within the theoretical framework of the dual-systems model where, in the presence of peer passengers, the highly sensitive and activated socio-emotional system may be particularly likely to override the regulatory influence of the executive system (Gardner & Steinberg, 2005).

Gardner and Steinberg (2005) reported the first empirical test of the dual-systems model applied to adolescent risky driving. In their study, 306 participants from three age groups (adolescents: 13-16 years of age, youths: 18-22 years of age, and adults: 24+ years of age) provided self-reported ratings of risk preference and risky decision making. The participants completed a computer game-based risky driving task where they made decisions about whether to stop a car when a traffic signal changed from green to yellow. These measures were collected either alone or in the presence of two friends. As predicted by the dual-systems model, risk-taking, risk preference, and risky decision-making decreased with increasing age. Further, in the presence of peers, participants took more risks and reported greater risk preference and risky decisions. This group effect was greatest among early adolescents (compared to older adolescents, young adults, and adults), presumably due to the relative immaturity of their executive control networks in relation to the hypersensitivity of their reward circuitry. These findings converge with more recent research by Shepherd and Lane (2011), who found that adolescents randomized to play a driving video game alone or with two peers (who could tell the driver how to react to the proposed scenario) took more risks, focused more on the benefits of risky behavior, and made riskier decisions when in peer groups than when alone. Also, Ouimet et al. (2013) reported greater inattention to potential driving hazards, but not more risky driving in the presence of a peer passenger with a risk-accepting appearance compared with a peer passenger with a risk-averse appearance (whose risk acceptance was appropriately perceived by participants).

While these findings provide initial empirical support for the dual-systems model of adolescent risk applied to driving, these studies have several important limitations. The computer game-based risky driving tests did not provide immersive simulated driving experiences. Decision trials in Gardner and Steinberg (2005) were presented on a computer monitor from a third person perspective and graphical representations of cars and traffic signals took the form of simple low-resolution images. Thus, while participants were required to make driving-relevant decisions, they were not doing so within a driving-relevant environment. Further, the studies lacked measures of individual differences in executive function (though Chein et al. examined activity in brain regions associated with cognitive control). Thus, we can only assume that the age-group differences they observed were moderated by corresponding differences in executive function. Given that there is much individual variability in adolescent cognitive development (Semrud-Clikeman, 2012), this assumption is a large one.

Mäntylä et al. (2009) evaluated relationships among three core executive control processes (mental shifting, behavioral inhibition, and working memory updating) and risky teenage driving using a latent variable approach. They found that individual differences in executive functioning were related to simulated driving performance, however, the relationship was only statistically significant for working memory updating tasks. Participants with weaker memory updating skills produced more lateral deviations while driving in a low-fidelity driving simulator during a lane-change task where they used a steering wheel to stay in their lane and to change lanes when traffic signs indicated. This study demonstrated that the updating component of executive function may be relevant to adolescent driving performance; however, it only assessed two highly related components of driving ability (lateral deviation and lateral variability) and did not measure risk-taking in the form of risky

driving. These variables were collected using a low-fidelity driving simulator that only required steering input. The lack of additional driving performance indices (e.g. brake and steering response time) and risky driving decision data (e.g. running stop signals, speeding, late braking, gap acceptance, and tailgating) limits the generalizability and applied implications of their results.

To date, Jongen et al. (2012) present perhaps the most complete empirical application of the dual-systems model to adolescent driving. In their study, the researchers hypothesized that lower executive function, specifically inhibitory control, would interact with a rewarding context and that this interaction would be predictive of risky driving. They recruited participants of two age groups (adolescents 17-18 years of age and young adults 22-24 years of age) with equal driving experience. All participants completed two drives in a high-fidelity driving simulator. In their first drive, participants were instructed to drive normally. In their second drive, they were told that they would be competing for a monetary reward and encouraged to drive as quickly as possible while still avoiding collision. During these drives, measures of standard deviation of lane position, number of collisions, speeding, and red light running were collected as dependent variables. A stop signal reaction time task measured individual differences in inhibitory control. They found that inhibitory control increased with increasing age and that low inhibitory control was associated with more lane variability (larger standard deviation of lane position). However, inhibitory control was not associated with any of the risky driving variables. Not surprisingly, speeding and red-light running were more likely in the second drive which included a rewarding context, but these effects did not interact with age or inhibitory control. The absence of this interaction defies predictions of the dual-systems model.

Gaps and Future Directions

Taken together, these studies provide some support for the dual-systems model of adolescent risk-taking applied to teenage driving. Gardner and Steinberg's (2005) study supported the idea that risky driving may be more likely in the presence of peers because participants were more likely to run red lights when their friends were present. Shepherd and Lane (2011) reported that peer presence increased risk taking in a driving video game. Chein et al. (2011) found that teenagers had greater activation in reward-related brain regions and engaged in more risky decision when observed by peers than alone. Mäntylä et al. (2009) and Jongen et al. (2012) studies linked individual differences in executive attention to driving quality, finding that weaker executive function was associated with greater lateral variability during simulated driving.

However, in many respects, these studies only provide partial support as all studies lacked at least one critical component. The dual-systems model would suggest that a) adolescent risk-taking should be more likely in rewarding contexts, namely in the presence of peers and b) this effect should be moderated by the maturity of the executive system, thereby accounting for individual differences in cognitive maturation. Thus, any complete test of the model must both manipulate peer context and measure executive function. While Gardner and Steinberg (2005) showed increases in overtly risky driving (running red lights) in the presence of peers, they did not assess executive function. Chein et al. (2011) provided

evidence from brain imaging that teenager reward sensitivity is greater in the presence of peers, but did not assess executive function. Mäntylä et al. (2009) rigorously assessed executive function, but did not manipulate peer presence. Jongen et al. (2012) came closest to fully testing the dual-systems model by including a measure of executive attention (stop-signal task) and a reward context manipulation; however, the reward context in their study was not socio-emotional in nature. Instead of manipulating peer presence, Jongen et al. (2012) introduced a monetary reward for quickly completing the drive. In addition to not being socio-emotional in nature this manipulation also represents a situation that is unlikely to occur in the real world. As such, it is unclear the extent to which their adolescent participants would have reacted differently to the rewarding salience of their peers' presence than they did to the monetary reward. Therefore, a strong test of the dual-systems model has yet to be implemented and preliminary attempts suggest the hypothesized relationships among adolescent risk-taking behind the wheel, peer presence, and cognitive maturation may be more difficult to demonstrate than initially thought.

If the dual-systems model of adolescent risk is to be effectively applied to adolescent driving, much additional work is necessary. First, in-lab replication of the relationships among critical factors of the model is essential. This proposed research would rigorously assess executive function and reward sensitivity by including multiple objective (non-self-report) measures of controlled processing, as was done by Mäntylä et al. (2009), to account for individual differences in cognitive development. Similarly, it would be equally rigorous in its assessment of risky driving, employing high-fidelity, virtual reality driving simulation technology able to collect multiple measures of both driving quality (e.g. lane position, lateral deviation, following distance, braking response time, etc.) and risky driving judgment (e.g. running stop signals, speed, unsafe gap judgment). Next, while rigorous behavioral assessment of individual differences in executive function as they relate to risk-taking represents a good starting point, given the strong incorporation of neuroanatomical development in the dual-systems model of risk, validation of the model would require additional neuroimaging work. Neuroimaging methodologies, such as fMRI, in conjunction with behavioral measures of executive function and reward sensitivity, provide modern methods for evaluating the dual-systems model. Future research linking neural activity in the hypothesized brain regions during rewarding peer contexts with risky driving outcomes would greatly strengthen the dual-systems framework. A recent investigation by Falk et al. (2012) takes a strong step in this direction. They found that heightened neural responses to social exclusion, measured using fMRI, were associated with individual susceptibility to social influences and predicted risky driving in a driving simulator one week later. Cross-sectional samples allow rapid data collection and analysis, however, they are insufficient to model change across time (Singer & Willett, 2003). While costly and time consuming, longitudinal pan-adolescence investigations that follow a single cohort, regularly (e.g. every 6 months), collecting waves of data on executive function and risk could enable statistical modeling of how the key components of the dual-systems theory change over time. Further, a complete understanding of teenage risk-taking in context would necessarily entail research outside the confines of the lab, for example, in-car video monitoring to record naturalistic teenage driving (Simons-Morton et al., 2011a).

In addition to these immediate basic and applied research plans, we must also begin to address some seemingly straight forward but hitherto elusive questions about the exact nature of social-contextual factors hypothesized to play an important role in risk prediction. Descriptively, the contextual components of a fatal crash involving a teenage driver are known. Teenage fatal crashes typically occur late at night or during the pre-dawn hours of the morning, at very high speeds, and involve multiple adolescent passengers (Braitman et al., 2008; Preusser et al., 1998; Williams et al., 2010). However, the extent to which these factors are independent or interactive is unknown. While fatal crashes involving adolescent drivers have been associated with peer presence (Ouimet et al., 2010), data patterns for non-fatal crashes are more complex. In fact, data on non-fatal crashes suggest that teenage passengers pose no risk for less severe crashes (Simons-Morton et al., 2011a; 2011b). Simons-Morton et al. (2011a) equipped the vehicles of 42 newly licensed drivers with in-car video monitoring systems to examine factors associated with risky driving. They found that risky driving was actually 18% lower in the presence of teenage passengers compared to driving alone. However, risky driving was 109% higher among those with risk-prone friends, suggesting an effect of social norms and possibly reward sensitivity. Other research has shown that male teenage passengers are associated with increased risky driving while female passengers are associated with decreased risk among male teenage drivers (Simons-Morton, Lerner, & Singer, 2005). Thus, some passengers may increase risk and other passengers may decrease risk.

These results suggest that the mere presence of peers does not, on its own, lead to risky driving. This may be because additional contextual factors, such as individual differences in driver and passenger characteristics, aspects of the trip purpose, or the emotional atmosphere within the vehicle may be a prerequisite for peer presence to produce risky driving behavior. In an editorial accompanying the paper by Simons-Morton and colleagues (2011a), Steinberg (2011b) notes that, “one cannot understand adolescent risk-taking behavior without taking into account the context in which it occurs” (p. 557). Steinberg (2011b) goes on to acknowledge that, while he and others have argued that adolescent risk-taking can be attributed to a combination of increased sensation seeking (i.e. high reward sensitivity of the social emotional network) and immature self-regulation (i.e. slowly developing executive system), he concedes that, despite this natural proclivity, manifestation of risk-taking behavior will critically depend on the opportunities they are afforded. Clearly, context must be taken into account and to do so, a clearer understanding of the contexts that lead to risky driving, near collisions, non-fatal collisions, and fatal collisions is crucial. The role of passengers is one of many important questions. Under what conditions does the presence of teenage passengers increase or decrease risk? To what extent is this due to social influence or distraction, or to driver executive control and socio-emotional regulation within the driving context?

Future research efforts might evaluate associations of specific combinations of drivers and passengers, executive function, reward sensitivity, emotional regulation, and relevant brain activity. Because driving simulation combines assets of traditional laboratory contexts (e.g. measurement precision and environmental control) with strengths of applied field research (dependent measures that are relevant to “real world” risky driving, like speeding, running stoplights, etc.), studies employing driving simulation could be especially useful in

experiments that carefully control driver and passenger characteristics. This would allow researchers to evaluate how the manipulation of these characteristics may influence a relevant applied outcome, specifically, risky driving.

Promoting Positive Youth Development by Reducing Risk

Assuming the dual-systems model holds up to more rigorous testing, it carries substantial promise as a guide for prevention policy and practice. Currently in the U.S., most resources in the field are devoted to teaching teenagers to operate the vehicle – which is only a small aspect of driving safety. Driving safety is not about managing the vehicle so much as the driver managing oneself in relation to the inherent risk associated with driving. The dual-systems model suggests that the relative timing of the slow maturation of the executive system against the faster maturation of the socio-emotional reward system may play an important role in explaining why risky driving behavior tends to increase during adolescence and then decrease during young adulthood. However, as Steinberg (2008) points out, the adolescent socio-emotional network does not exist in a constant state of high activation. Much of the time this network is not highly active. In these contexts, it is likely that the executive system is strong enough to effectively regulate risky impulses. Thus, the model suggests that policies and practices that reduce contexts that are known to heighten socio-emotional network activity (such as driving in the presence of peers) and increase contexts where socio-emotional network activity is low (such as driving alone or in the presence of adult passengers) take advantage of adolescents' strengths and have great potential to reduce risk and save lives.

As such, the dual-systems model is consistent with prevention approaches that seek to engineer social contexts to reduce risk. The current thrust of public policy is designed to limit teenage driving exposure to less risky driving conditions and, as a byproduct, appears to delay licensure somewhat. Graduated Driver Licensing policies, the dominant policies in the United States regarding teenage driving restrictions, aim to reduce risk by limiting teenage driving to lower risk contexts and gradually increasing their driving privileges over time. These policies have been shown to be highly effective (Shope, 2007); however, the degree to which they have been implemented varies widely from state to state. Similarly, parental management programs have shown great promise in reducing exposure to higher risk driving conditions (Simons-Morton, Hartos, Leaf, & Preusser, 2005), although, adoption of these programs is in its infancy (Zakrajsek, Shope, Ouimet, Wang, & Simons-Morton, 2009). The implementation of research-backed Graduated Driver Licensing policies in the United States represents a promising step in the right direction. However, to fully reap the life-saving benefits of matching sound science with research-backed, developmentally informed interventions, like Graduated Drivers Licensing and parental management programs, more uniformed policy implementation and adherence will be critical.

Conclusions

The present paper provided a conceptual discussion of a popular emerging dual-systems model of adolescence risk. While research in neuroscience and brain behavior relationships largely supports the model, translational work linking the model to real-world outcomes,

specifically risky driving, has been less definitive. The existing research linking the dual-systems model to risky driving provides some support; however, a strong test of the model has yet to be implemented and preliminary attempts suggest the hypothesized relationships may be more complicated and situational in nature than initially thought. Future research aimed at rigorously assessing key factors of the model and testing their hypothesized relationships within virtual reality driving simulation environments would represent a strong step forward. Further, neuroimaging methodologies in conjunction with behavioral measures could afford sophisticated methods for evaluating the model. Finally, longitudinal as well as naturalistic observational investigations could enhance understanding of the model's applied utility. If the dual-systems model is supported by rigorous future research endeavors, it suggests that risk intervention efforts, like Graduated Driver Licensing policies, that are aimed at engineering the social-contextual environment may be particularly effective in reducing risk and, ultimately saving lives.

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Figure 1.

Conceptual illustration of the dual-systems model as it applies to risky adolescent driving. The graph of developmental trajectories is meant to be a conceptual approximation of the functional development of the two cognitive systems.