Development of risk taking, perspective taking, and inhibitory control during adolescence

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Abstract

Structural and functional brain development is thought to lead to different developmental progressions of cognitive control, risk/reward processing and social cognition during adolescence. We compared these abilities in a cross-sectional sample of 90 adolescents aged 12, 15 or 17 years old, using computerised measures of inhibitory control (Go/No-go task), risk-taking (Balloon Analogue Risk Task), and social perspective-taking (Director task). Fifteen-year-olds exhibited better inhibitory control than 12-year-olds, while 17-year-olds exhibited greater perspective-taking than younger adolescents. Risk-taking was greater in older adolescents than 12-year-olds when controlling for inhibitory control. These findings are consistent with earlier findings obtained in separate samples.

Key words:

Adolescence, executive functions, response inhibition, risk-taking, social cognition

Introduction

Adolescence is defined as the transition period between childhood and adulthood (Crone & Dahl, 2012). It is characterised by hormonal, physiological and physical changes, as well as changes in social roles and responsibilities. Two decades of cognitive neuroscience research suggest that adolescence is associated with increasing use of top-down cognitive control skills, which allows adolescents to focus their attention and regulate their emotions and behaviour in order to achieve their goals (Crone & Dahl, 2012). However, adolescence is also associated with sub-optimal decisions and actions apparent in heightened substance abuse and mortality rates (Casey, Getz, & Galvan, 2008; Dahl, 2004; Steinberg, 2008; although see Willoughby, Good, Adachi, Hamza, & Tavernier, 2013). This paradox appears driven by the fact that social, reward and affective “hot” contexts influence adolescents’ cognition and behaviour to a greater extent than is observed in adults (Albert, Chein, & Steinberg, 2013; Casey & Caudle, 2013). On the basis of such observations, it has been proposed that adolescents’ risk-taking and susceptibility to peer influence may partly derive from differences in the maturational timecourse of the socio-emotional reward system and the cognitive control system in the brain (Albert et al., 2013; Casey et al., 2008).

Supporting evidence comes from longitudinal structural neuroimaging studies. Higher-order association areas in the prefrontal and temporal lobes supporting cognitive control and social cognition show prolonged changes in cortical thickness and grey matter volumes until early adulthood (Giedd & Rapoport, 2010; Gogtay et al., 2004; Mills, Goddings, Clasen, Giedd, & Blakemore, 2014; Mills, Lalonde, Clasen, Giedd, & Blakemore, 2014; Shaw et al., 2008). In contrast, earlier maturation is observed in sub-cortical regions, including the amygdala and nucleus accumbens, associated with processing socio-emotional information relating to threat, reward and social status (Forbes & Dahl, 2010; Galvan et al., 2006), although individual subcortical regions vary in their structural developmental trajectories and are differentially affected by sex and puberty (Goddings, Mills, Clasen, Giedd, Viner, & Blakemore, 2014; Mills, Goddings et al., 2014). Behavioural data have predominantly been gathered from studies using distinct participant samples and different experimental paradigms, designed to chart a single cognitive developmental trajectory, for example cognitive control (Luna, Padmanabhan, & O’Hearn, 2010), risk/reward affective processing (Casey et al., 2008) or social cognition (Blakemore, 2008). The variety of paradigms used in distinct samples of participants may have emphasised differences in the developmental trajectories for each domain. The present study therefore aimed to use three established paradigms assessing inhibitory control, risk-taking and social perspective-taking, to compare their developmental trajectories within a single sample of adolescents aged 12, 15 or 17 years-old. A secondary aim of this study was to investigate whether individual and age differences in inhibitory control were associated with differences in risk-taking and social perspective-taking.

The first developmental trajectory we wished to explore was in the domain of cognitive control. Cognitive control enables flexible, voluntary coordination of behaviour, through impulse inhibition and goal-directed action (Badre, 2008). Performance on basic cognitive control processes including working memory, inhibitory control and task switching (Crone & Dahl, 2012; Luna et al., 2010; Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015) improves sharply in childhood and then more slowly until mid- to late adolescence (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Band, van der Molen, Overtoom, & Verbaten, 2000; Dumontheil et al., 2011). Although the parietal cortex shows consistent increased engagement with age, findings in the prefrontal cortex (PFC) are more mixed, and may depend on the loads imposed by the task on different aspects of the cognitive control system (Anderson, 2002; Crone & Dahl, 2012; Luna et al., 2015). Behaviourally, a large longitudinal study of 8- to 30-year-olds used visual tasks to demonstrate that mature performance was observed around 14 years of age when the task taxed response inhibition (anti-saccade), and 19 years of age when the task taxed working memory (delayed saccade) (Luna, Garver, Urban, Lazar, & Sweeney, 2004).

To assess developmental changes in performance during adolescence when different aspects of cognitive control are combined we took advantage of commonly used variants of the Go/No-go paradigm. In "simple" Go/No-go paradigms (Simmonds, Pekar, & Mostofsky, 2008) a stimulus requiring a rapid response ('Go') is presented with high frequency to establish a dominant response, which needs to be inhibited ('No-go') when an alternative, less frequent, stimulus is shown. Children are less accurate and slower than adults on simple Go/No-go tasks; response times continue to improve during adolescence; and No-go trials PFC activation changes during childhood and adolescence (Durston, Thomas, Yang, Uluğ, Zimmerman, & Casey, 2002; Tamm, Menon, & Reiss, 2002). By adding a 1-back-type working memory load (Simmonds et al., 2008), whereby participants are asked to inhibit their response when the current and previous stimuli comply with a certain rule, "complex" Go/No-go tasks allow the assessment of developmental changes during adolescence associated with combined inhibitory control and working memory demands.
Cognitive control development does not occur in isolation, but interacts with socio-affective development. During early- to mid-adolescence the limbic system becomes functionally over-sensitised to socio-emotional stimuli, which may underpin the preoccupation with peer status exhibited by adolescents (Luna, Paulsen, Padmanabhan, & Geier, 2013). As the cognitive control system is less mature this may increase risk-taking during adolescence; particularly when peers are present (Blakemore & Mills, 2014; Casey et al., 2008; Steinberg, 2008) and working memory load is high. For example, in a driving simulation study 13- to 16-year-olds made more errors and showed increased orbito-frontal cortex activation, associated with risk/reward or affective processing, in the presence of peers, compared to adults, who exhibited greater PFC activity independent of the social context (Chein, Albert, O'Brian, Uckert, & Steinberg, 2011).

The 'dual-system' model (Steinberg, 2010) accounts for why more adolescents take risks with peers present than when alone (Arnett, 1992) and statistical trends of sudden increases in risk-taking at 13-14 years old, lowering towards the end of adolescence or early adulthood (Brooks, Magnusson, Klemera, Spencer, Morgan, 2011; National Center for Health Statistics, 2012). However dual-system models (Casey et al., 2008; Steinberg, 2010) are likely to be too simplistic. Researchers have argued there may be too much emphasis on frontal cortical immaturity and hyperactivation in the striatum as being behind adolescent risk-taking, to the detriment of a more nuanced understanding of the interplay between cognitive, affective and social processing during development (Crone & Dahl, 2012; Pfeifer & Allen, 2012; Willoughby, Tavernier, Hamza, Adachi, & Good, 2014). More recent consideration of real-life risk-taking data suggests that the highest level of risk-taking behaviours occurs in fact among emerging adults, and that the type of risk is likely to play an important role in differences in risk-taking across the lifespan (Willoughby et al., 2013).

Few studies have measured cognitive control and risk-taking in the same participants. Inhibitory control skills may play a role in adolescents' ability to resist an impulsive risky choice, or instead behaviour may be mainly driven by increased sensation- or reward-seeking (Steinberg, 2008). Both impulsiveness and sensation-seeking as measured by self-report questionnaires have been linked to risk-taking during adolescence (e.g. Romer et al., 2011). Here, we used computerised measures and compared Go/No-go performance with behaviour on a simple proxy measure of risk-taking propensity, the Balloon Analogue Risk Task (BART; Lejuez et al., 2002), which correlates well with actual risk-taking levels (Collado, MacPherson, Kurdziel, Rosenberg, & Lejuez, 2014). In this task participants 'pump-up' a series of virtual balloons. The more they pump-up the balloon, the greater the amount of money they win, but gains are forfeited if the balloon bursts, which mirrors real-world risk/gain experiences (Lejuez, Aklin, Zvolensky, & Pedulla, 2003). A greater average number of pumps indicates greater risk-taking propensity (Bornovalova et al., 2009; Lejuez et al., 2003). As the BART can measure adolescents' increased risk-taking propensity in incentivised situations (Steinberg, 2008), without disclosure, and before actual risk-taking emerges, it is useful for use with adolescents from age 11 (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Collado et al., 2014; Lejuez, Aklin, Daughters, Zvolensky, Kahler, Gwadz, 2007). Here, we compared developmental differences in inhibitory control and risk-taking during adolescence, and investigated whether individual and age differences in inhibitory control were related to risk-taking.

The third developmental trajectory we were keen to compare lies within the domain of social cognition. We specifically focused on theory of mind (ToM), or 'mentalising', the ability to attribute mental states such as beliefs, desires, emotions and intentions to oneself and to others. Cognitive ToM, the ability to make inferences about others' beliefs and intentions, typically develops early in life (e.g. when measured by False-Belief tasks, Wellman, Cross, & Watson, 2001). In contrast, mentalising regions of the "social brain" exhibit significant changes in structure (Mills, Lalonde, et al., 2014) and functional activation (Blakemore, 2008; Burnett, Sebastian, Cohen-Kadosh, & Blakemore, 2010) during adolescence. Here, we employed the 'Director task' (Apperly, Carroll, Samson, Humphreys, Qureshi, & Moffitt, 2010; Dumontheil, Apperly, & Blakemore, 2010; Keysar, Lin, & Barr, 2003), designed to explore how ToM interacts with goal-directed cognitive control processes during adolescence. The paradigm places participants in a communicative context where they need to use their mentalising abilities to take another person's perspective, and to inhibit their own perspective to complete an action. A control, rule-based, non-social condition is matched in terms of general and response inhibition demands. Using this task, Dumontheil, Apperly, & Blakemore (2010) found that an adult level of performance was achieved by age 14 in the rule-based condition, while adolescents aged 14-17 years old made more errors than adults in the social perspective-taking condition. This suggests that the social ability of taking another person's perspective into account does not mature until early adulthood and that adolescents retain a stronger egocentric bias than adults. Alternatively, it could be that adults are better at adjusting their thinking to overcome an egocentric bias, rather than that this bias no longer exists (Epley, Morewedge, & Keysar, 2004). In a recent study, Fett et al. (2014) found no age-related differences in a sample of 13-18-year-olds, but observed that performance in the Director task was significantly associated with adolescents' behaviour in a trust game with cooperative and unfair counterparts, providing evidence for the ecological validity of the Director task.

A secondary aim in this study was to investigate the role of individual and age differences in inhibitory control in the development of social perspective-taking. Executive functions, including inhibitory control, have been implicated in ToM inference in children (Devine and Hughes, 2014). We previously found that Director-task perspective-taking differences between children, adolescents and adults were in part related to differences in inhibitory control in a Go/No-go task (Symeonidou, Dumontheil, Chow, & Breheny, in press). Vetter and colleagues (Vetter, Altgassen, Phillips, Mahy, & Kliegel, 2013) found that inhibitory control in an anti-saccade task was associated with developmental differences in affective ToM between 12 and 22 years of age. Here, we were interested in identifying whether inhibitory control was specifically associated with individual and age differences in perspective-taking during adolescence, or whether the association would be found across both the social perspective-taking condition and the rule-based condition, suggesting a more general effect related to the inhibition of a dominant response.

In the present study, we assessed performance in the Go/No-go, BART and Director tasks in a cross-sectional sample including three groups of adolescents, aged 12, 15 and 17 years old. This permitted a direct comparison of age differences in cognitive control, risk/reward processing and social cognition. Our findings were expected to reflect a similar pattern to those observed in distinct participant samples in previous research. We were expecting earlier maturation of performance on the simple Go/No-go task than on the complex Go/No-go and Director tasks. On the BART task higher scores during mid-adolescence would be consistent with predictions from the dual system model (Steinberg, 2008), while a more progressive increase continuing until late adolescence would be more consistent with real-life risk-taking data as reviewed by Willoughby and colleagues (2013). In secondary analyses, we further assessed a proposed association between, on one hand, individual differences in risk-taking on the BART and inhibition of the dominant response in the Director task, and on the other hand impulsivity, as measured by the Go/No-go tasks.

Methods

Participants

Ninety participants (45 males, 45 females) were recruited in Year 7 (n = 28; 13 males, 15 females; age M = 12.33 years, SD = 0.33, range 11.83-12.83), Year 10 (n = 30; 17 males, 13 females; age M = 15.29 years, SD = 0.27, range 14.83-15.75) and Year 12 (n = 32; 15 males, 17 females; age M = 17.38 years, SD = 0.26, range 16.92-18.00) from six schools in Sussex, England. There was no difference in gender distribution between the three age groups ($X^2(2) = 0.801$, $p > .66$). Sixty-seven participants attended an 11-18 faith comprehensive, five an 11-16 non-faith comprehensive, two a sixth-form college, thirteen attended a 3-18 girls independent school and three attended two separate 3-18 mixed independent schools. Five participants were left handed. All spoke English as their main language. Fifteen were bilingual, including three whose early education was in another country. Verbal ability was measured using the vocabulary sub-test of the Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 1999). There was no significant difference between mean verbal IQ scores of the age groups ($F(2, 87) = 0.31$, $p > 0.7$, $\eta_p^2 = .007$; 12-year-olds: M = 108.9, SD = 10.8, range = 91-140; 15-year-olds: M = 106.9, SD = 9.1, range = 87-123; 17-year-olds: M = 108.4, SD = 10.1, range = 90-134).

Participants who were recruited through a school were screened for known developmental disorders by school staff using special educational needs and disabilities (SEND) and medical registers. Participants recruited individually were screened for developmental disorders through an initial verbal conversation with their parent(s). One participant reported being colour blind and did not take part in the Go/No-go task. Informed consent was obtained from parents/guardians and assent was obtained from each participant. Ethical approval was obtained prior to this study from the local ethics committee.

Design and Materials

The Go/No-go tasks and the BART were programmed in Cogent (www.vislab.ucl.ac.-uk/Cogent/ index.html) running in Matlab 7.0 (MathWorks). The Director task was programmed in E-Prime 2. Testing of these three tasks was performed individually using a *DELL* laptop computer. Participants completed in addition a 23-items paper-based questionnaire on classroom social environment, which will not be discussed here.

Inhibitory control tasks

Participants performed two Go/No-go tasks (Simple and Complex tasks). The Simple Go/No-go followed a traditional Go/No-go paradigm (Simmonds et al., 2008). The Go stimulus was a green square, the No-go stimulus a red square (adapted from Watanabe et al., 2002) (**Figure 1A**). Participants pressed the left key when the green square was shown on the left of the screen and the right key when the green square was shown on the right, using their right index and middle finger respectively. When the square was red participants were asked not to respond and wait for the next trial. A first practice block of ten green square trials established a habitual response. Participants repeated this practice if they made three errors or more. A second practice block of ten trials included seven Go trials and three No-go trials. Participants repeated this practice if they made more than one error on No-go trials. The eighty test trials comprised twenty No-go trials (25%) and were pseudo-randomly presented, with no repeat of No-go trials. The squares were presented on either side of a fixation cross for 400 ms. The fixation cross remained on the screen between stimuli, with an inter-stimuli interval of 700 ms on average (duration uniformly distributed between 600 ms and 800 ms). The Complex Go/No-go task included a 1-back working memory requirement (see Simmonds et al., 2008). Participants were required to inhibit their habitual response when a blue square (B) followed a yellow square (Y) (**Figure 1A**). A response indicating the location of the square, as in the simple Go/No-go task, was required for all other combinations (BB, YY, and YB). The task was matched to the Simple Go/No-go task in terms of the number of practice and experimental trials, and the timing of stimuli presentation. An equal number of yellow and blue squares were used in the experimental trials. Accuracy and reaction times (RT) were recorded.

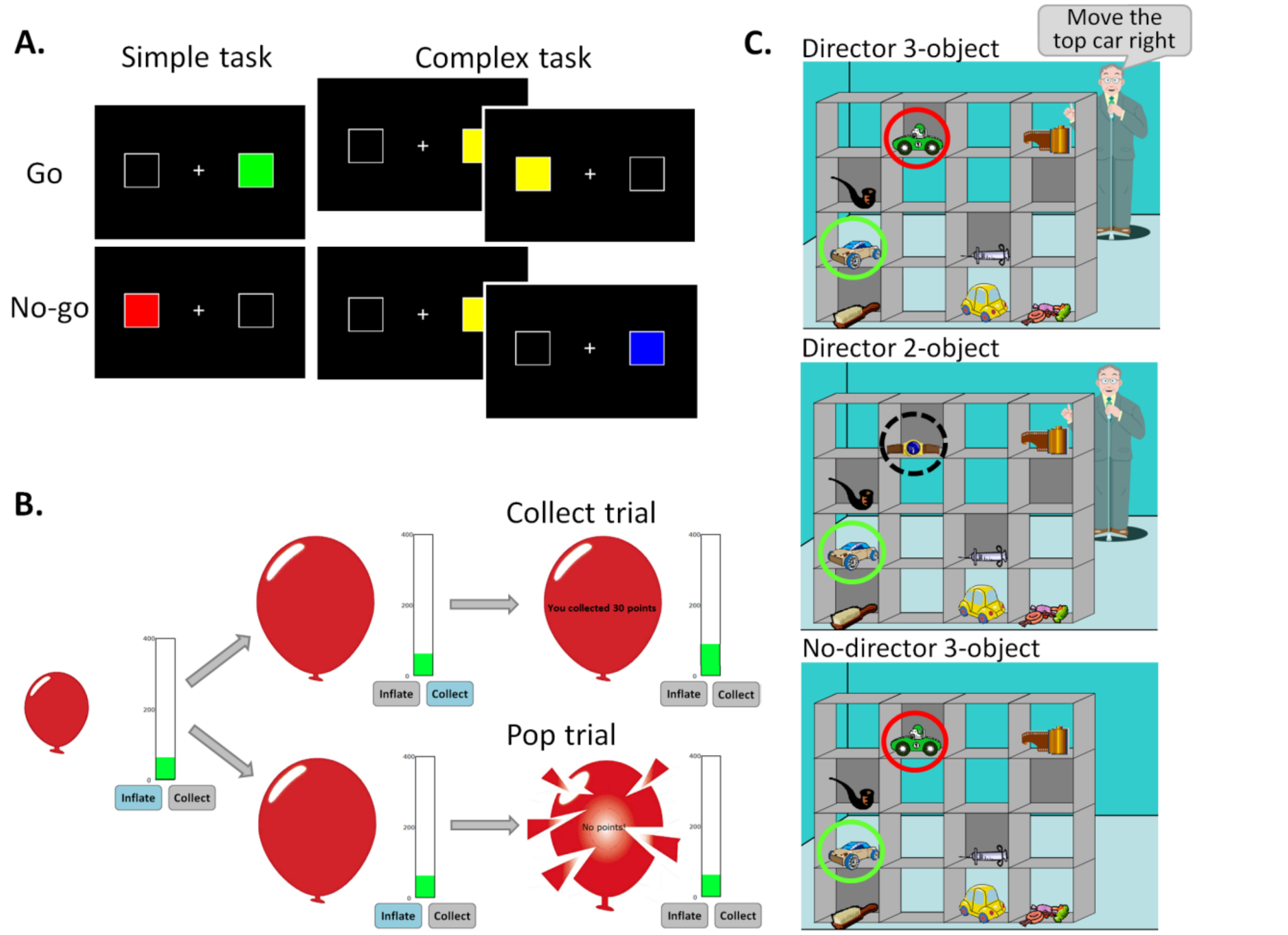

Figure 1. Experimental paradigms. **(A)** Go/No-go tasks. In the Simple task participants were asked to press on the side of the coloured square except if the square was red. In the Complex task participants were asked to press on the side of the coloured square except if the current square was blue and the previous square had been yellow. (B) Balloon Analogue Risk Task. On each trial participants were asked to decide whether to collect the points they had accumulated until then ("Collect") or to try to inflate the balloon more to increase the number of points they could win ("Inflate"), at the risk of popping the balloon. **(C)** Director task. Participants were asked to move objects on the shelves by following auditory instructions. In the Director condition participants were asked to take into account the Director's perspective. A correct response in the Director 3-object trial (top) would therefore be to move the blue car, as the director cannot see the green car. In Director 2-object trials the distractor (green car) was replaced by an irrelevant object (watch) (middle). In the No-director conditions participants were asked to ignore (i.e. not select) objects in slots with a grey back panel. A correct response in the No-director 3-object trial (bottom) would therefore again be to move the blue car. Participants saw different object configurations for the Director and No-director conditions.

Balloon Analogue Risk Task (BART)

In the BART participants were instructed to inflate a balloon presented on the screen by pressing the left key with their right index finger. Each key press (pump) inflated the balloon by a set amount and scored one point. The greater the number of pumps, the greater the number of points the balloon would be worth, should the participant choose to collect their points by pressing the right key with the right middle finger (**Figure 1B**). Points were visibly collected in a point-meter presented on the right side of the balloon

(**Figure 1B**). If the balloon was overinflated it popped and the points for that particular balloon were lost. Participants were told that if they collected enough points they would get a £5 prize voucher. No specific number of points was stated for this and the voucher was subsequently given to all participants at the end of the testing period. A point-meter was used to avoid any conceptual differences regarding monetary value (Lejuez et al., 2007). There were a total of 20 test balloons, which has been shown to provide reliable data (Lejuez et al., 2002). The task was self-paced, popping points varied (3-64 pumps) to avoid prediction, with low popping points for some balloons early in the test sequence (trials 1, 2 and 7) to emphasise uncertainty of the popping point. The sequence of balloons was fixed across participants. The main measure of interest on this task is the adjusted number of pumps, i.e. the mean number of pumps per unpopped balloon (Lejuez et al., 2002). In the present paradigm, this measure is equivalent to the mean number of points collected per unpopped balloon. Higher scores represent greater propensity for risk, although participants have been found to take too few risks on the BART overall, therefore a greater risk-taking propensity is actual advantageous in terms of leading to higher scores (Lejuez et al., 2002).

Director Task

The Director task used in this study is the experimental paradigm used by Dumontheil, Apperly, & Blakemore (2010) to first study the development of online perspective-taking. The task followed a 2 x 2 factorial design, with the factors Condition (Director, No-director) and Trial type (2-object, 3-object). Participants were presented with a visual stimulus of a 4 x 4 set of shelves containing eight objects. In the Director condition a man (the director) was shown behind the shelves. Five of the slots were occluded from his view by grey back panels (**Figure 1C**). In the No-director condition the man was not shown, but the configuration of the shelves remained the same. The task required participants to listen to instructions to move an item in the shelves and respond accordingly. In the Director condition they were asked to take into account the viewpoint of the director, who cannot see all the items, when following his instructions. In the No-director task, which was always performed second, participants were asked to only move items in clear slots, and not those in slots with grey back panels. Therefore participants followed a rule for responding, rather than thought about the director’s viewpoint.

Participants were required to move three items for each shelf/objects configuration, with sixteen configurations presented each for the Director and No-director conditions. For both conditions, there were eight critical trials where the participants had to choose a target item out of three possible items of the same type (3-object trials). Correct responses required selecting the target item which the director could see and was referring to (Director condition) or was in a clear slot (No-director condition) (e.g. the blue car, **Figure 1C**), rather than the item that best fitted the instruction from the perspective of the participant (e.g. the green car, **Figure 1C**). In a further eight trials, the participant had to choose between two items of the same type, neither of which was located in a slot with a grey back panel (2-object trials, **Figure 1C**). In both

2-object and 3-object trials, the target item was identified by relational values, i.e. bottom/top or large/small. The remaining thirty-two trials were filler trials where the director asked participants to move an object that was present in only one location on the shelves (e.g. the sweets, **Figure 1C**) and was visible from both viewpoints. Each shelf/objects configuration was associated with either one 2-object or one 3-object trial, and two filler trials. Participants were presented with different shelf/objects configurations and auditory instructions for the Director and No-director conditions. This was counterbalanced across participants. Each visual stimulus was first presented for 2 s, then the auditory instruction lasted 2.2 s and participants had a further 3.6 s to respond by clicking on an object with the computer mouse and dragging it to the correct location. Instructions were heard through the laptop speakers. A trial was considered correct when the correct object was picked by the participant; RT was measured from the start of the auditory instruction to the object selection.

Procedure

Participants were tested individually, in a school classroom or at home (for five participants). Tests were administered in the following order: Go/No-go tasks, BART, Director task, classroom social environment questionnaire. The vocabulary subtest of the WASI was then completed. The whole testing took approximately 40-50 minutes. Prior to each task standardised instructions were given and participants' questions answered.

For the Go/No-go tasks the same procedure applied for the Simple and Complex tasks. Standardised instructions appeared on the screen prior to practice and experimental trials and were read to the participants. If participants made more than three errors during practice blocks a message appeared and further practice was provided. The two tasks together took 6.5 min to complete on average. For the BART, standardised instructions appeared on the screen and were read to participants. No participants had difficulty with this task and the task took approximately 4.5 min to complete.

Next, standardised instructions were read to participants whilst sample slides of the Director task were shown on the screen. It was explained that the task was to move items in a set of shelves by following instructions from a director on the other side of the shelves. His viewpoint was shown and it was emphasised that the director could not see all items and that his viewpoint must be considered when following his instructions. To ensure understanding of the different perspectives participants were asked to indicate items that only they could see and items that the director could see as well. All participants completed this successfully. The computer mouse was used to click on objects and drag and drop them in new location. Participants were told that objects would not actually move but to act as if they did. Participants completed three practice trials (filler trials), followed by 48 test trials (eight 3-object trials, eight 2-object trials, and 32 filler trials) of the Director condition. Further standardised instructions were read to participants with sample slides on the screen to explain the No-director condition. It was explained that the task this time was to follow instructions to move items, but only items in the clear slots could be moved, and those in grey slots were to be ignored. To ensure understanding participants were asked to indicate their response for an example 3-object trial. All participants answered this practice question correctly. There was no further practice trial in this condition. Participants performed 48 test trials (eight 3-object trials, eight 2-object trials, and 32 filler trials) immediately following the instructions. The whole task took approximately 12 minutes to complete. Participants were then issued with the questionnaire, which took approximately 5 minutes to complete, after which the vocabulary subtest of the WASI was administered.

Statistical analyses

Partial eta squared was used to assess effect size in ANOVAs. Post-hoc tests were used to explore main and interaction effects. Bonferroni correction was applied when contrasting the three age groups in pairwise comparisons.

For both the Simple and Complex Go/No-go tasks, percentage error was calculated for each Trial type (Go, No-go). The median RT for correct responses was calculated for Go trials. Medians are thought to be more resistant to outliers and can be used when not comparing conditions with different number of trials (Whelan, 2008). For each task separately, a 3 x 2 mixed ANOVA with the between-subjects factor Age group (12-, 15- and 17-year-olds) and the within-subjects variable Trial type (Go, No-go) was performed on percentage error. RT was compared between age groups with one-way ANOVAs in the Simple and Complex tasks separately. One participant was colour-blind and did not complete the Go/No-go tasks (n = 89). Another participant did not respond in the Complex Go/No-go task and was therefore not included in the analyses of the Complex task (n = 88).

In the BART, the adjusted number of pumps (mean number of pumps per unpopped balloon) was calculated for each participant. A one-way ANOVA with Age group as the independent variable was performed on this measure. All participants were included in the analysis (n = 90).

Percentage error and mean RT for correct trials were calculated for each Condition and Trial type. Means were calculated rather than medians because of the low and variable number of correct trials in this task. Medians are less efficient than means at estimating the central tendency, especially for low number of cases, and it has been argued that medians should not be used to estimate RT when there are small number of trials and differing number of trials between conditions (Miller, 1988). Data from one participant were excluded from all analyses as there was a problem with data logging. Percentage error analyses were therefore performed on n = 89 participants. Data from a further six participants were excluded from RT analyses as there was no correct trial for at least one condition (n = 83). Two 3 x 2 x 2 mixed ANOVAs with Age group as the between-subjects factor and the within-subjects variables Condition (Director, No-director) and Trial type (2-object, 3-object) were performed on percentage error and RT.

All analyses were repeated with Gender included as an additional between-subjects factor, however no main effect of Gender or interaction with Gender was observed.

In a final set of analyses, hierarchical multiple regressions were performed to assess whether performance on the response inhibition tasks was associated with risk-taking on the BART and performance on the Director task, and whether they may account for differences in performance between age groups. Two measures of the Director task were entered as dependent variables: (1) the difference in percentage error between Director 3-object and No-director 3-object trials, which reflects participants' tendencies to take into account the Director's perspective; (2) the mean percentage error in Director and No-director 3-object trials, reflecting the general task and inhibitory demands of 3-object trials (in both conditions participants need to inhibit a response towards the object that at first sight correspond best to the verbal instruction). In a first step, two dummy variables coding for the age group differences (contrasting 12-year-olds to 15- and 17-year-olds, and 12- and 15-year-olds to 17-year-olds) were entered in the model (Model 1). In a second step, as multiple measures of performance of the Go/No-go Simple and Complex tasks were obtained and all showed differences between age groups, we entered all six measures (percentage error in Go and No-go trials of the Simple and Complex tasks, and median Go RT in the Simple and Complex tasks) as possible predictors of BART and Director task performance, using a stepwise approach. No-go errors are considered to be the key marker of individual differences in inhibitory control.

Results

Inhibitory control tasks

Simple Go/No-go

A 3 x 2 mixed repeated measures ANOVA with Age group (12-, 15- and 17-year-olds) as the between-subjects factor and Trial type (Go, No-go) as the within-subjects factor was performed on percentage error data. There were significant main effects of: Trial type ($F(1, 86) = 73.02$, $p < .001$, $\eta_p^2 = .459$) with fewer errors for Go trials; and Age group ($F(2, 86) = 9.69$, $p < .001$, $\eta_p^2 = .184$), with more errors made by 12-year-olds compared to 15- ($p = 0.002$) and 17-year-olds ($p < .001$), who did not differ ($p = 1$; p-values of pairwise comparisons between age groups are Bonferroni corrected). There was also a significant interaction between Age group and Trial type ($F(2, 86) = 3.72$, $p = .028$, $\eta_p^2 = .080$).

This interaction was investigated with two one-way ANOVAs assessing differences in percentage error between age groups separately in Go and No-go trials. There was a significant main effect of Age group for both trial types (Go: $F(2, 86) = 8.83$, $p < .001$, $\eta_p^2 = .170$; No-go: $F(2, 86) = 7.27$, $p = .001$, $\eta_p^2 = .145$). Post-hoc comparisons showed that 12-year-olds made more errors than both 15-year-olds (Go, $p = .004$; No-go: $p = .010$) and 17-year-olds (Go, $p < .001$; No-go: $p = .002$) in both trial types, however the difference was greater in amplitude for No-go trials than Go trials. Fifteen- and 17-year-olds did not differ (*p*s = 1) (**Figure 2A**).

Analysis of median RT for correct Go trials showed a significant main effect of Age group ($F(2, 86) = 9.15$, $p < .001$, $\eta_p^2 = .175$). Post-hoc tests indicated that 12-year-olds were significantly slower ($M = 342$ ms, $SD = 39$) than 15- ($M = 312$ ms, $SD = 24$) and 17-year-olds ($M = 313$ ms, $SD = 24$; *p*s = .001), who did not differ ($p = 1$).

Complex Go/No-go

Similarly, a 3 (Age group) x 2 (Trial type) mixed repeated measures ANOVA was performed on percentage error data of the Complex Go/No-go task. Again, there were significant main effects of Trial type ($F(1, 85) = 178.96$, $p < .001$, $\eta_p^2 = .678$), with fewer errors committed in Go trials ($M = 12.4$ %, $SD = 10.1$) than No-go trials ($M = 38.0$ %, $SD = 16.6$), and of Age group ($F(2, 85) = 6.80$, $p = .002$, $\eta_p^2 = .138$). Post-hoc tests indicated that, similarly to what was observed in the Simple task, 12-year-olds committed significantly more errors than 15- ($p = .005$) and 17-year-olds ($p = .006$), who did not differ ($p = 1$) (**Figure 2A**). However, in the Complex task the interaction between Trial type and Age group was not significant ($F(2, 85) = 1.05$, $p = .356$).

As in the Simple task, analysis of median RT for correct Go trials showed a significant main effect of Age group ($F(2, 85) = 5.26$, $p = .007$, $\eta_p^2 = .110$). Post-hoc tests indicated that 12-year-olds were significantly slower ($M = 383$ ms, $SD = 56$) than 15-year-olds ($M = 345$ ms, $SD = 25$; $p = .006$). However the difference between 12- and 17-year-olds ($M = 359$ ms, $SD = 47$) did not reach Bonferroni-corrected significance ($p = .11$). The two older age groups did not differ ($p > .7$).

In summary, both percentage error and RT measures of the Go/No-go tasks showed poorer performance in 12-year-olds than 15- and 17-year-olds. In the Simple task, 12-year-olds made relatively more errors in the No-go trials than the Go trials when compared to the other age groups. In the Complex task, which has a 1-back working memory load, age did not interact with performance on No-go vs. Go trials.

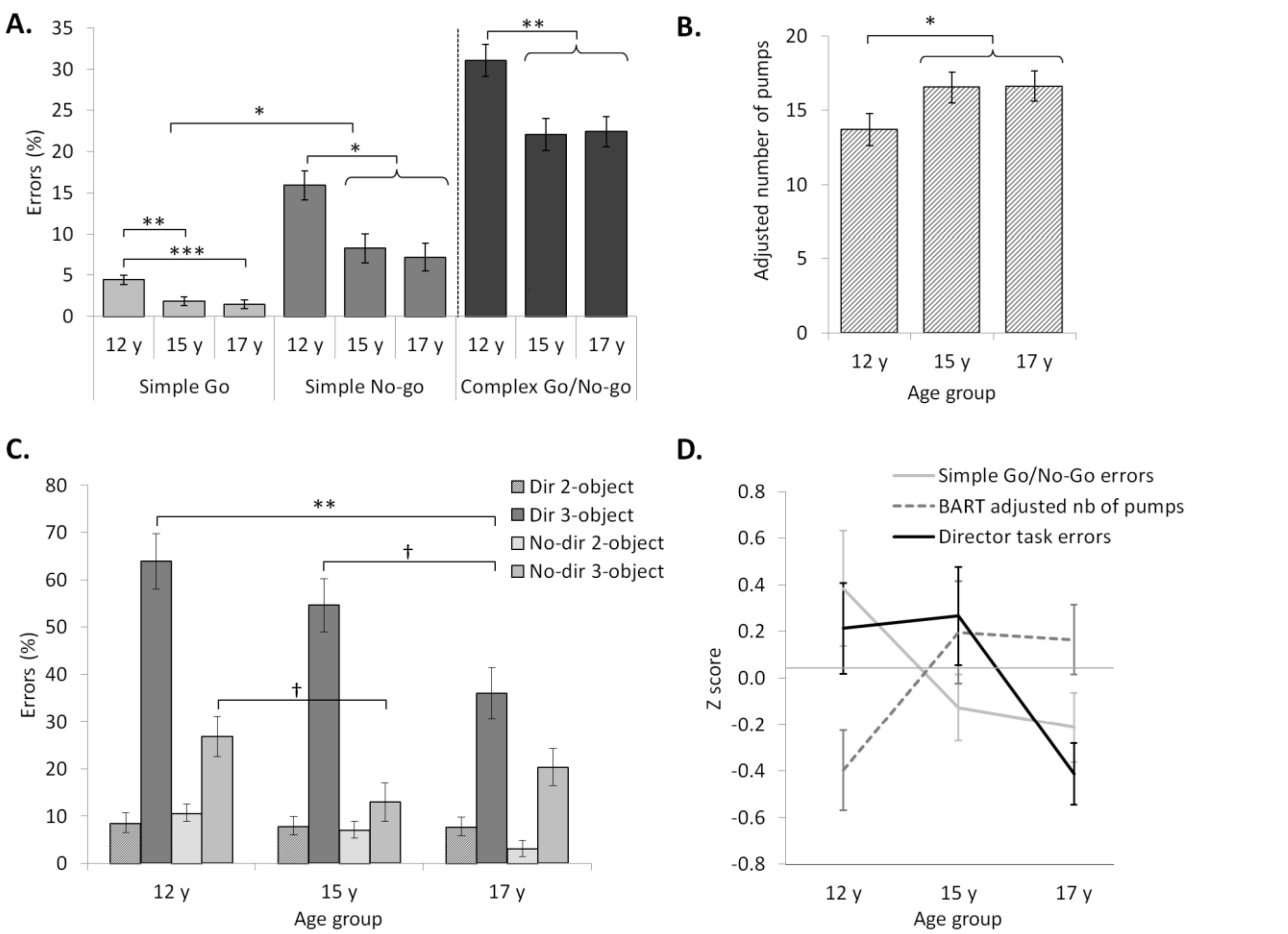

Figure 2: Age group differences in the performance of the inhibitory control, BART, and Director tasks. **(A)** Go/No-go tasks. Mean percentage error is plotted as a function of Age group for Simple Go and No-go trials, and for the mean of Complex Go and No-go trials. **(B)** BART task. The adjusted number of pumps (mean number of pumps for unpopped balloons) is plotted as a function of Age group. Pairwise comparisons were not significant but a multiple regression indicated a significant difference between 12-year-olds and older adolescents. **(C)** Director task. Mean percentage error is plotted as a function of Age group for the four different trial types. **(D)** Plot of the z-score transformed key measures of each task as a function of Age group: difference in No-go and Go percentage error in the Simple Go/No-go task, adjusted number of pumps in the BART task and difference in Director and No-director 3-object percentage error in the Director task. Errors bars represent *SE*; y = years; † $p < .1$; * $p < .05$; ** $p \leq .01$; *** $p < .001$ (pairwise comparisons are Bonferroni corrected).

BART

A one-way ANOVA was performed on the adjusted number of pumps with Age group as the between-subjects factor. There was only a trend effect of Age group ($F(2, 87) = 2.43$, $p = .094$, $\eta_p^2 = .053$). The general pattern was of greater risk-taking in 15- and 17-year-olds than 12-year-olds (**Figure 2B**); however, post-hoc tests with Bonferroni correction revealed no significant pair-wise differences between the three age groups (all *p*s > .15).

Director task

Participants made on average 4 % errors on filler trials, which were not included in the main analyses. A 3 x 2 x 2 mixed ANOVA with Age group as a between-subjects factor and the within-subjects factors Condition (Director, No-director) and Trial type (2-object, 3-object) was performed on percentage error data. There were significant main effects of Condition ($F(1, 86) = 71.69$, $p < .001$, $\eta_p^2 = .455$) and Trial type ($F(1, 86) = 165.85$, $p < .001$, $\eta_p^2 = .659$), with more errors in the Director condition and 3-object trials respectively, and a main effect of Age group ($F(2, 86) = 5.80$, $p = .004$, $\eta_p^2 = .119$). Post-hoc tests indicated that 12-year-olds made more errors on average than 17-year-olds ($p = .003$), however the other pairwise comparisons were not significant with Bonferroni correction (*p*s > .11). There were marginal two-way interactions between Condition and Age group ($F(2, 86) = 3.02$, $p = .054$, $\eta_p^2 = .066$) and Trial type and Age group ($F(2, 86) = 3.04$, $p = .053$, $\eta_p^2 = .066$), and a significant interaction between Condition and Trial type ($F(1, 86) = 62.17$, $p < .001$, $\eta_p^2 = .420$). These were qualified by a significant three-way interaction between Condition, Trial type and Age group ($F(2, 86) = 6.63$, $p = .002$, $\eta_p^2 = .134$), which was explored by performing 3 (Age group) x 2 (Condition) mixed repeated measures ANOVAs on 2-object and 3-object trials separately.
In 2-object trials there was no main effect of Condition ($F(1, 86) = 0.51$, $p = .478$) or Age group ($F(2, 86) = 2.24$, $p = .113$), nor a significant interaction between Age and Condition ($F(2, 86) = 1.83$, $p = .167$). In 3-object trials there was a significant effect of Condition ($F(1, 86) = 78.94$, $p < .001$, $\eta_p^2 = .479$), with more errors committed in the Director condition, and a main effect of Age group ($F(2, 86) = 4.91$, $p = .010$, $\eta_p^2 = .102$), with more errors committed by the 12-year-olds than the 17-year-olds ($p = .008$). The interaction between Age and Condition was significant ($F(2, 86) = 5.38$, $p = .006$, $\eta_p^2 = .111$). This interaction was followed up by running one-way ANOVAs assessing Age group differences in Director 3-object and No-director 3-object trials separately.

In the No-director condition, there was a marginal effect of Age group on percentage error in 3-object trials ($F(2, 86) = 2.83$, $p = .065$, $\eta_p^2 = .062$). Post-hoc tests indicated there was a trend for 12-year-olds to make more errors than 15-year-olds ($p = .060$). None of the other comparisons were significant (*p*s > .5) (**Figure 2C**). In the Director condition, there was a significant effect of Age group on percentage error in 3-object trials ($F(2, 86) = 6.26$, $p = .003$, $\eta_p^2 = .127$). The pattern differed from that of the No-director condition, as Bonferroni corrected post-hoc tests indicated that 12- and 15-year-olds did not differ ($p = .841$) while 17-year-olds made fewer errors than both 12- ($p = .003$) and (marginally) 15-year-olds ($p = .057$) (**Figure 2C**).

Reaction time is not a key measure of interest in the Director task. A 3 (Age group) x 2 (Condition) x 2 (Trial type) mixed repeated measures ANOVA was performed on mean RT for correct trials**.** The only significant effect was a main effect of Age group ($F(2, 80) = 3.19$, $p = .046$, $\eta_p^2 = .074$). Post-hoc tests indicated that 15-year-olds ($M = 2667$ ms, $SD = 41$) were significantly faster than 12-year-olds ($M = 2811$ ms, $SD = 41$, $p = .049$), the other two pairwise comparisons were not significant (*p*s > .23).

In summary, 3-object trials showed age differences in performance, with an overall pattern of earlier improvements in performance in the No-director condition (between 12 and 15 years of age) than in the Director condition (between 15 and 17 years of age).

Is inhibitory control associated with risk-taking and perspective-taking?

Multiple regression analyses were performed to assess whether performance on the inhibitory control tasks could account for variance in risk-taking on the BART and performance on the Director task, and whether this prediction could account for differences in performance between age groups. In the BART, Simple Go median RT significantly predicted the adjusted number of pumps, with slower RT on Simple Go trials predicting a greater number of pumps. However, Simple Go RT did not account for differences in BART performance between 12-year-olds and 15- and 17-year-olds, which in fact became stronger in Model 2 (**Table 1**).

In the Director task, none of the Go/No-go measure significantly accounted for variance in perspective-taking, i.e. the difference in percentage error between Director 3-object and No-director 3-object. However, Simple Go and Complex Go percentage errors significantly associated with overall performance in 3-object trials; participants who made more Go errors, also made more errors on 3-object trials (**Table 1**). Further, Go percentage error accounted for the difference in performance between the 12-year-olds and 15-17-year-olds, which became non-significant in Models 2 and 3.

Table 1: Results of multiple regressions assessing whether inhibitory control is associated with performance on the BART and Director task. DV: Dependent variable. Significant regressors are highlighted in bold font.

DV: BART Adjusted number of pumps		***β***	***t***	***p***
Model 1: R^2 = .241, $F(2, 85) = 2.61$, $p = .079$	**12y vs. 15-17y**	**.248**	**2.017**	**.047**
	12-15y vs. 17y	-.015	-.121	.904
Model 2: R^2 = .317, $F(3, 84) = 3.13$, $p = .030$	**12y vs. 15-17y**	**.342**	**2.636**	**.010**
ΔR^2 = .043, $p = .049$	12-15y vs. 17y	-.014	-.118	.907
	Simple Go Median RT	**.227**	**1.997**	**.049**
DV: Percentage error [Director 3-object] - [No-director 3-object]				
Model 1: R^2 = .317, $F(2, 84) = 4.70$, $p = .012$	12y vs. 15-17y	.025	.203	.839
	12-15y vs. 17y	**-.329**	**-2.732**	**.008**
DV: Percentage error [Director & No-director 3-object]				
Model 1: R^2 = .329, $F(2, 84) = 5.11$, $p = .008$	**12y vs. 15-17y**	**-.264**	**-2.205**	**.030**
	12-15y vs. 17y	-.103	-.858	.393
Model 2: R^2 = .430, $F(3, 83) = 6.28$, $p = .001$	12y vs. 15-17y	-.158	-1.302	.196
ΔR^2 = .077, $p = .006$	12-15y vs. 17y	-.082	-.713	.478
	Simple Go errors	**.301**	**2.793**	**.006**
Model 3: R^2 = .475, F(4, 82) = 5.97, $p < .001$	12y vs. 15-17y	-.130	-1.084	.282
ΔR^2 = .041, $p = .042$	12-15y vs. 17y	-.066	-.584	.561
	Simple Go errors	**.239**	**2.171**	**.033**
	Complex Go errors	**.219**	**2.071**	**.042**

In summary, errors on Go trials were found to be associated with age differences in general performance on 3-object trials of the Director task, i.e. across Director and No-director conditions, and reaction times in Simple Go trials were associated with individual differences in risk-taking in the BART. However, inhibitory control per se, as measured by No-go errors, was not found to be related to either risk-taking on the BART or perspective-taking in the Director task.

Discussion

The purpose of this study was to assess inhibitory control, risk-taking and perspective-taking within a single cross-sectional participant sample to investigate whether these cognitive abilities followed distinct patterns of development, as suggested by prior research in separate samples of participants. Broadly speaking the findings did support the theory of distinct executive functions, affective and social-cognitive developmental trajectories. Each pathway will be discussed in turn, before more general considerations of the results of this study are presented.

Development of inhibitory control during adolescence

In the Go/No-go tasks, 12-year-olds made significantly more errors in both Go and No-go trials, and were slower in correct Go trials, than the two older adolescent groups (15- and 17-year-olds). There was no significant improvement thereafter between 15- and 17-year-olds. In the Simple Go/No-go task only, there was further evidence of greater improvement in performance between the ages of 12 and 15 years old in No-go trials than Go trials, although this may have been driven by ceiling accuracy levels in Go trials. Overall, these results indicate that a simple choice RT Go/No-go task is able to detect changes in inhibitory control performance during adolescence. The pattern of age group differences was similar in the Simple and Complex Go/No-go tasks. Neuroimaging studies have shown that No-go trials of simple and complex tasks are associated with both common and specific patterns of activation (Simmonds et al., 2008). On one hand, No-go trials in both types of tasks are associated with increases in brain activation in the pre-supplementary motor area and left fusiform gyrus. On the other hand, bilateral occipital and precuneus activations are specific to simple tasks, while activations in the right middle/inferior frontal gyrus, bilateral inferior parietal regions, bilateral putamen, bilateral insula, right middle temporal gyrus and left middle frontal gyrus are specific to complex tasks (Simmonds et al., 2008). Here, the addition of a working memory load in the Complex task, although detrimental for overall performance, did not appear to provide further sensitivity for age differences associated with loading different aspects of cognitive control simultaneously.

Our results suggest that the ability to inhibit a motor response plateaus from around age 15 years old. This concurs with previous evidence from RT or accuracy measures of inhibitory control (Fisher, Biscaldi, & Gezeck, 1997; Lamm, Zelazo, & Lewis, 2006; Luna et al., 2004; see Tamm et al., 2002 for review), and the findings are in-line with developmental trajectories suggesting that executive functions continue to develop during adolescence, albeit at a slower rate than during childhood (see Band et al., 2000; Luna et al., 2010).

Development of risk-taking during adolescence

The findings from the BART showed minimal effects of age, with only a trend main effect of age group on the adjusted number of pumps measure. As in the inhibitory control task, the difference was between the younger adolescents (12-year-olds) and older adolescents (see **Table 1**). However, here, rather than an improvement in performance, the increase in adjusted number of pumps reflects increased risk-taking (Bornovalova et al., 2009; Lejuez et al., 2003). The monetary incentive was fixed and of low value (£5 voucher), which may have reduced the strength of age differences. Note that according to the dual-system model (Steinberg, 2010), sensitivity should gradually decline towards late adolescence. Our results may therefore be more consistent with the observation of increased real-life risk-taking in late adolescence or emerging adulthood (National Center for Health Statistics, 2012; see Willoughby et al., 2013 for review).

Regression analyses indicated that response times on the Simple Go/No-go task significantly accounted for variance in risk-taking in the BART, and that the difference in risk-taking between 12-and 15-year-olds became more apparent once individual differences in Go RT were accounted for. There was no association with No-go errors, the typical measure of inhibitory control. These findings support the idea that paradigms like the BART recruit to a lesser extent “cold” cognitive control, here represented by response inhibition, than affective or reward-processing systems, here related to risk-taking in the context of a monetary incentive, and that these components show independent maturational trajectories (Crone & Dahl, 2012; Luna et al., 2015; Steinberg, 2008).

Statistics show that adolescent boys are over-represented in mortality rates associated with risk-taking (National Center for Health Statistics, 2012). However, no effect of gender or interaction between gender and age group were observed in the present study. Prior research suggests that males and females are more likely to take different sorts of risks (see Amsel & Smetana, 2011), depending on the perceived social value of actions for males and females (Crone & Dahl, 2012). It is possible that the BART, by its design, is sufficiently removed from the social context and social norms that it minimises gender differences observed outside of experimental testing sessions.

Development of perspective-taking during adolescence

In the Director task more errors occurred when the cognitive load increased (deciding which of 3 vs. 2 objects needed to be moved), and specifically when decisions required taking another person’s perspective (Director condition) rather than following a pre-determined rule (No-director condition). Fifteen-year-olds tended to outperform 12-year-olds for 3-object trials of the No-director condition, indicating earlier development of general cognitive abilities required to select the correct object out of three possible options and inhibit a dominant response, i.e. the selection of the object that best fits the auditory instruction from the participant's view point (e.g. the green car in **Figure 1C**). The older adolescents performed better than the two younger year groups (trend effect between 15- and 17-year-olds) specifically in Director 3-object trials, suggesting late improvements of the use of perspective-taking and mentalising skills in a communicative context. This finding is consistent with the results from Dumontheil, Apperly, & Blakemore (2010), which indicated that performance in Director 3-object trials improved between 14-17 years of age and adulthood.

Therefore, it may be inferred that the late adolescents were performing at a more adult level than the younger groups for perspective-taking, inhibiting their egocentric bias to think about and take into account the perspective of another individual. This accords with the idea of prolonged changes in social cognitive skills during adolescence, with slow development and late maturation of the mentalising brain network including medial PFC and temporal-posterior regions supporting the processing of social information (Blakemore, 2008; Dumontheil, Apperly, & Blakemore, 2010).

In a previous study, Simple No-go errors were associated with Director task perspective-taking errors and partially accounted for differences in performance between children, adolescents and adults (Symeonidou et al., in press). Here, we investigated the role played by response inhibition in performance of the Director task within adolescence. Errors on Simple and Complex Go trials showed the strongest association with errors on Director and No-director 3-object trials. However, No-go percentage error, the key measure of response inhibition, was not found to show further association with Director task performance, suggesting that response inhibition is not a key factor of individual or age differences in Director task 3-object performance during adolescence.

The observed association between errors in Go trials and in 3-object trials of the Director and No-director conditions is likely to reflect general individual differences in cognitive ability, possibly related to the elaboration and maintenance of structured mental programs (Duncan, 2010). The Complex task made unique contribution, possibly related to its greater load on working memory-related cognitive processes also necessary in the Director and No-director 3-object trials. Indeed 3-object trials of both Director and No-director conditions require participants to inhibit a dominant response that best fits their own perspective, as well as to remember the type of object that is targeted (e.g. cars), which object should be considered (e.g. top), and the direction in which the object needs to be moved (e.g. left), in addition to the general rules of the task. Our results are consistent with findings from a neuroimaging study using a Director task variant showing that Director and No-director 3-object trials are, compared to 1-object trials, associated with slower RTs and shared greater activation of a fronto-parietal network of brain regions typically associated with cognitive control and maintenance of structured mental programs (Dumontheil, Küster, Apperly, & Blakemore, 2010; Dumontheil, Hillebrandt, Apperly, & Blakemore, 2012; Duncan, 2010).

Distinct developmental trajectories

The present study revealed different patterns of development for inhibitory control, risk-taking and perspective-taking (summarised in **Figure 2D**). These results support the findings previously obtained in distinct participant samples. Obtaining data on several tasks from a single sample of participants allowed us to reliably compare developmental performance on the three tasks by controlling for unassessed individual differences which may affect performance (e.g. socio-economic status). The use of three age groups with narrow age ranges enabled us to have more power to compare different stages of adolescence, in contrast to studies that have compared adolescents as a group to children and adults (e.g. Steinberg et al., 2008), or divided adolescents into two groups, early and late (e.g. Dumontheil, Apperly, & Blakemore, 2010), or using age as a continuous measure (e.g. Fett et al., 2014). Using three age groups within this study enabled exploration which showed that mid-adolescents were similar to the young adolescents for perspective-taking (i.e. more child-like) and more similar to the late adolescents for inhibitory control (i.e. more adult-like), with greatest differences between trajectories for the mid-adolescents (15 years old). A weak age difference in risk-taking found between 12-year-olds and older adolescents was enhanced when individual differences in RT on a Simple Go/No-go task were taken into account. In this way, the findings support distinct developmental trajectories during adolescence for cognitive control, risk/reward processing and social cognition.

The focus of this study was adolescence. It has been argued that puberty may be linked to particular aspects of cognitive development during adolescence (Blakemore, Burnett, & Dahl, 2010). On the basis of the literature, it is likely that stage of pubertal development would be more strongly associated with risk-taking measures, which target the affective system, than to response inhibition or cognitive ToM (Blakemore, Burnett, & Dahl, 2010; Crone & Dahl, 2012). Although no puberty stage measure was collected for the present study, the age groups assessed here may not have allowed a clear distinction of puberty and age effects, as although 12-year-olds may have showed varied puberty stages, 15- and 17-year-olds would have most likely been classified as in late or post-puberty. A limitation of our focus on adolescent participants is that it did not allow the plotting of more complete developmental trajectories. For example, we could not test how different the 12-year-olds were to younger children, nor how close the 17-year-olds were to adult performance, although the 17-year-old group in our findings exhibited similar performance to that of young adults included in previous studies on the Director task (Apperly et al., 2010; Dumontheil, Apperly, & Blakemore, 2010). The inclusion of adult participants of varied ages could also have revealed a peak in risk-taking on the BART in young adulthood (Willoughby et al., 2013). A further limitation of this study is the use of a cross-sectional design, which is considerably weaker than longitudinal designs with regards to assessing developmental trajectories.

The BART has been validated as a proxy measure for real-world risk-taking (Collado et al., 2014), and in the present study, like in most BART studies, participants were tested individually. However, adolescents are more likely to engage in risky behaviours in the presence of peers (e.g. Arnett, 1992; Gardner & Steinberg, 2005). Cavalca et al. (2013) observed that adolescent smokers showed a greater increase in risk-taking on the BART when in the presence of peers than alone, compared to non-smokers. Future research could investigate the impact of peer presence on the BART across different age groups within adolescence and early adulthood, to help map the decline of peer-group influence on risk-taking during late adolescence.

Future work could include affective variants of the Go/No-go and ToM tasks used here, to further investigate the distinct developmental trajectories of cognitive control measured within or outside an affective context. For example, emotional Go/No-go paradigms have been used to investigate the interplay between the cognitive control and affective processing systems and show later maturation of performance than non-emotional Go/No-go paradigms, as well as adolescent-specific activations (e.g. in the amygdala, Hare et al., 2008). Similarly, a distinction has been made between cognitive ToM and affective ToM, contrasting the ability to make inferences about beliefs and intentions, to the ability to infer what a person is feeling, respectively (Shamay-Tsoory, Harari, Aharon-Peretz, & Levkovitz, 2010). Affective ToM appears to show a more protracted development in late adolescence that cognitive ToM (e.g. Goddings, Burnett Heyes, Bird, Viner, & Blakemore, 2012; Sebastian et al., 2012). Future work including both affective and cognitive variants of the Go/No-go and ToM tasks used in this study could enhance our current understanding of typical adolescent development.

Conclusion

This cross-sectional study aimed to directly compare the development of social cognition, risk/reward processing and cognitive control during adolescence. Our results within a single sample of adolescents provide supporting evidence for previous findings in separate samples. We observed earliest improvement in performance for cognitive control, as measured by response inhibition tasks, while social cognition, as measured by a social perspective-taking task, matured later in adolescence. Risk/reward processing showed a different trajectory, with only a trend increase in risk-taking observed during early adolescence. These findings enhance our understanding of the interplay between social and affective processing on one hand and cognitive control and decision-making on the other, and are a step towards charting the development of adolescent functioning in the real-world.

References

Aklin, W. M., Lejuez, C. W., Zvolensky, M. J., Kahler, C. W., & Gwadz, M. (2005). Evaluation of behavioral measures of risk taking propensity with inner city adolescents. *Behavior Research and Therapy, 43*, 215-228. doi: 10.1016/j.brat.2003.12.007

Albert, D., Chein, J., & Steinberg, L. (2013). Peer influences on adolescent decision making. *Current Directions in Psychological Science*, *22*, 114–120. doi: 10.1177/0963721412471347

Amsel, E., & Smetana, J. G. (Eds.). (2011). *Adolescent Vulnerabilities and Opportunities: Developmental and Constructivist Perspectives* (Vol. 38). New York, NY: Cambridge University Press.

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, *8*, 71-82. doi: 10.1076/chin.8.2.71.8724

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*, 385-406. doi: 10.1207/S15326942DN2001_5

Apperly, I. A., Carroll, D. J., Samson, D., Humphreys, G. W., Qureshi, A., & Moffitt, G. (2010). Why are there limits on theory of mind use? Evidence from adults' ability to follow instructions from an ignorant speaker. *The Quarterly Journal of Experimental Psychology*, *63*, 1201-1217. doi: 10.1080/17470210903281582

Arnett, J. (1992). Reckless behavior in adolescence: A developmental perspective. *Developmental Review, 12*, 339-373. doi: 10.1016/j.dr.2007.08.002

Band, G. P. H., van der Molen, M. W., Overtoom, C. C. E., & Verbaten, M. N. (2000). The ability to activate and inhibit speeded responses: Separate developmental trends. *Journal of Experimental Child Psychology*, *75*, 263–290. doi: 10.1006/jecp.1999.2538

Badre, D. (2008). Cognitive control, hierarchy, and the rostro–caudal organization of the frontal lobes. *Trends in Cognitive Sciences*, *12*, 193-200. doi: 10.1016/j.tics.2008.02.004

Blakemore, S. J. (2008). The social brain in adolescence. *Nature Reviews Neuroscience*, *9*, 267–277. doi: 10.1038/nrn2353

Blakemore, S.-J., Burnett, S., & Dahl, R. E. (2010). The role of puberty in the developing adolescent brain. *Human Brain Mapping*, *31*, 926–33. doi:10.1002/hbm.21052

Blakemore, S.-J., & Mills, K. L. (2014). Is adolescence a sensitive period for sociocultural processing? *Annual Review of Psychology*, *65*, 187–207. doi: 10.1146/annurev-psych-010213-115202

Bornovalova, M. A., Cashman-Rolls, A., O'Donnell, J. M., Ettinger, K., Richards, J. B., Dewit, H., & Lejuez, C. W. (2009). Risk taking differences on a behavioral task as a function of potential reward/loss magnitude and individual differences in impulsivity and sensation seeking. *Pharmacology Biochemistry and Behavior*, *93*, 258-262. doi: 10.1016/j.pbb.2008.10.023

Brooks, F. M., Magnusson, J., Klemera, E., Spencer, N., Morgan, A. (2011). *Health Behaviour in school-aged children (HBSC): World Health Organisation collaborative cross national study: Findings from the 2010 HBSC study for England.* Hatfield. University of Hertfordshire.

Burnett, S., Sebastian, C., Cohen-Kadosh, K., & Blakemore, S.-J. (2010). The social brain in adolescence: Evidence from functional magnetic resonance imaging and behavioural studies. *Neuroscience and Biobehavioral Reviews*, *35*, 1654–1664. doi: 10.1016/j.neubiorev.2010.10.011

Cavalca, E., Kong, G., Liss, T., Reynolds, E. K., Schepis, T. S., Lejuez, C. W., & Krishnan-Sarin, S. (2013). A preliminary experimental investigation of peer influence on risk-taking among adolescent smokers and non-smokers. *Drug and Alcohol Dependence*, *129*, 163-166. doi: 10.1016/j.drugalcdep.2012.09.020

Casey, B., & Caudle, K. (2013). The teenage brain: Self control. *Current Directions in Psychological Science*, *22*, 82–87. doi: 10.1177/0963721413480170

Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review, 28*, 62-77. doi: 10.1016/j.dr.2007.08.003

Chein, J., Albert, D., O'Brien, L., Uckert, K., & Steinberg, L. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science, 14*, F1-F10. doi: 10.1111/j.1467-7687.2010.01035.x

Collado, A., MacPherson, L., Kurdziel, G., Rosenberg, L. A., & Lejuez, C. W. (2014). The relationship between puberty and risk taking in the real world and in the laboratory. *Personality and Individual Differences*, *68*, 143-148. doi: 10.1016/j.paid.2014.04.019

Crone, E. A., & Dahl, R. E. (2012). Understanding adolescence as a period of social–affective engagement and goal flexibility. *Nature Reviews Neuroscience, 13*, 636-650. doi: 10.1038/nrn3313

Dahl, R. E. (2004). Adolescent brain development: a period of vulnerabilities and opportunities. Keynote address. *Annals of the New York Academy of Sciences*, *1021*, 1-22. doi: 10.1196/annals.1308.001

Devine, R. T., & Hughes, C. (2014). Relations between false belief understanding and executive function in early childhood: A meta-analysis. *Child Development, 85*, 1777–1794. doi:10.1111/cdev.12237

Dumontheil, I., Apperly, I. A., & Blakemore, S. J. (2010). Online usage of theory of mind continues to develop in late adolescence. *Developmental Science, 13*, 331-338. doi: 10.1111/j.1467-7687.2009.00888.x

Dumontheil, I., Roggeman, C., Ziermans, T., Peyrard-Janvid, M., Matsson, H., Kere, J., & Klingberg, T. (2011). Influence of the COMT genotype on working memory and brain activity changes during development. *Biological Psychiatry*, *70*, 222–9. doi: 10.1016/j.biopsych.2011.02.027

Dumontheil, I., Hillebrandt, H., Apperly, I. A., & Blakemore, S.-J. (2012). Developmental differences in the control of action selection by social information. *Journal of Cognitive Neuroscience*, *24*, 2080–2095. doi: 10.1162/jocn_a_00268

Dumontheil, I., Küster, O., Apperly, I. A., & Blakemore, S.-J. (2010). Taking perspective into account in a communicative task. *Neuroimage*, *52*, 1574–1583. doi: 10.1016/j.neuroimage.2010.05.056

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. *Trends in Cognitive Science*. *14*, 172–179. doi: 10.1016/j.tics.2010.01.004

Durston, S., Thomas, K. M., Yang, Y., Uluğ, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5*, F9-F16. doi: 10.1111/1467-7687.00235

Epley, N., Morewedge, C. K., & Keysar, B. (2004). Perspective taking in children and adults: Equivalent egocentrism but differential correction. *Journal of Experimental Social Psychology*, *40*, 760-768. doi: 10.1016/j.jesp.2004.02.002

Fett, A.-K. J., Shergill, S. S., Gromann, P. M., Dumontheil, I., Blakemore, S.-J., Yakub, F., & Krabbendam, L. (2014). Trust and social reciprocity in adolescence - A matter of perspective-taking. *Journal of Adolescence*, *37*, 175–84. doi:10.1016/j.adolescence.2013.11.011

Fischer, B., Biscaldi, M., & Gezeck, S. (1997). On the development of voluntary and reflexive components in human saccade generation. *Brain Research, 754,* 285-297. doi: 10.1016/S0006-8993(97)00094-2

Forbes, E. E., & Dahl, R. E. (2010). Pubertal development and behavior: hormonal activation of social and motivational tendencies. *Brain and Cognition*, *72*, 66-72. doi: 10.1016/j.bandc.2009.10.007

Galvan, A., Hare, T. A., Parra, C. E., Penn, J., Voss, H., Glover, G., & Casey, B. J. (2006). Earlier development of the accumbens relative to orbitofrontal cortex might underlie risk-taking behavior in adolescents. *Journal of Neuroscience*, *26*, 6885-6892. doi: 10.1523/JNEUROSCI.1062-06.2006

Gardner, M., & Steinberg, L. (2005). Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: an experimental study. *Developmental Psychology, 41*, 625. doi: 10.1037/0012-1649.41.4.625

Giedd, J. N., & Rapoport, J. L. (2010). Structural MRI of pediatric brain development: what have we learned and where are we going? *Neuron, 67*, 728-734. doi: 10.1016/j.neuron.2010.08.040

Goddings, A. L., Burnett Heyes, S., Bird, G., Viner, R. M., & Blakemore, S. J. (2012). The relationship between puberty and social emotion processing. *Developmental Science*, *15*(6), 801-811. doi: 10.1111/j.1467-7687.2012.01174.x

Goddings, A.-L., Mills, K. L., Clasen, L. S., Giedd, J. N., Viner, R. M., & Blakemore, S.-J. (2014). The influence of puberty on subcortical brain development. *Neuroimage*, *88*, 242–51. doi: 10.1016/j.neuroimage.2013.09.073

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences U.S.A*, *101*, 8174–8179. doi: 10.1073/pnas.0402680101

Hare, T. A., Tottenham, N., Galvan, A., Voss, H. U., Glover, G. H., & Casey, B. J. (2008). Biological substrates of emotional reactivity and regulation in adolescence during an emotional go-nogo task. *Biological Psychiatry*, *63*, 927–934. doi: 10.1016/j.biopsych.2008.03.015015

Keysar, B., Lin, S., & Barr, D. J. (2003). Limits on theory of mind use in adults. *Cognition*, *89*, 25-41. doi: 10.1016/S0010-0277(03)00064-7

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*, 2139-2148. doi: 10.1016/j.neuropsychologia.2005.10.013

Lejuez CW, Aklin W, Daughters S, Zvolensky M, Kahler C, Gwadz M (2007). Reliability and validity of the youth version of the balloon analogue risk task (BART-Y) in the assessment of risk-taking behavior among inner-city adolescents. *Journal of Clinical Child and Adolescent Psychology, 36*, 106-111. doi: 10.1080/15374410709336573

Lejuez, C. W., Aklin, W. M., Zvolensky, M. J., & Pedulla, C. M. (2003). Evaluation of the Balloon Analogue Risk Task (BART) as a predictor of adolescent real-world risk-taking behaviours. *Journal of Adolescence*, *26*, 475-479. doi: 10.1016/S0140-1971(03)00036-8

Lejuez, C. W., Read, J. P., Kahler, C. W., Richards, J. B., Ramsey S. E., Stuart, G. L., et al. (2002). Evaluation of a behavioural measure of risk taking: the Balloon Analogue Risk Task (BART). *Journal of Experimental Psychology: Applied, 8*, 75-84. doi: 10.1037/1076-898X.8.2.75

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*, 1357-72. doi: 10.1111/j.1467-8624.2004.00745.x

Luna, B., Marek, S., Larsen, B., Tervo-Clemmens, B., & Chahal, R. (2015). An integrative model of the maturation of cognitive control. *Annual Review of Neuroscience*, *38*, 151–70. doi: 10.1146/annurev-neuro-071714-034054

Luna, B., Padmanabhan, A., & O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain and Cognition*, *72*, 101–113. doi: 10.1016/j.bandc.2009.08.005

Luna, B., Paulsen, D. J., Padmanabhan, A., & Geier, C. (2013). The teenage brain cognitive control and motivation. *Current Directions in Psychological Science*, *22*, 94-100. doi: 10.1177/0963721413478416

Miller, J. (1988). A warning about median reaction time. *Journal of Experimental Psychology: Human Perception and Performance*, *14,* 539–543. doi: 10.1037/0096-1523.14.3.539

Mills, K. L., Goddings, A.-L., Clasen, L. S., Giedd, J. N., & Blakemore, S.-J. (2014). The developmental mismatch in structural brain maturation during adolescence. *Developmental Neuroscience*, *36*, 147–160. doi: 10.1159/000362328

Mills, K. L., Lalonde, F., Clasen, L. S., Giedd, J. N., & Blakemore, S.-J. (2014). Developmental changes in the structure of the social brain in late childhood and adolescence. *Social Cognitive and Affective Neuroscience*, *9*, 123–131. doi: 10.1093/scan/nss113

National Center for Health Statistics (US). (2012). *Health, United States, 2012, with special feature on emergency care.* http://www.cdc.gov/nchs/data/hus/hus12.pdf

Pfeifer, J. H., & Allen, N.B (2012). Arrested development? Reconsidering dual-systems models of brain function in adolescence and disorders. *Trends in Cognitive Sciences, 16,* 322–329. doi: 10.1016/j.tics.2012.04.011

Romer, D., Betancourt, L. M., Brodsky, N. L., Giannetta, J. M., Yang, W., & Hurt, H. (2011). Does adolescent risk taking imply weak executive function? A prospective study of relations between working memory performance, impulsivity, and risk taking in early adolescence. *Developmental Science, 14*, 1119–1133. doi:10.1111/j.1467-7687.2011.01061.x

Sebastian, C. L., Fontaine, N. M. G., Bird, G., Blakemore, S.-J., De Brito, S. A., McCrory, E. J. P., & Viding, E. (2012). Neural processing associated with cognitive and affective Theory of Mind in adolescents and adults. *Social Cognitive and Affective Neuroscience*, *7*, 53–63. doi: 10.1093/scan/nsr023

Shamay-Tsoory, S. G., Harari, H., Aharon-Peretz, J., & Levkovitz, Y. (2010). The role of the orbitofrontal cortex in affective theory of mind deficits in criminal offenders with psychopathic tendencies. *Cortex*, *46*, 668–677. doi: 10.1016/j.cortex.2009.04.008

Shaw, P., Kabani, N. J., Lerch, J. P., Eckstrand, K., Lenroot, R., Gogtay, N., et al. (2008). Neurodevelopmental trajectories of the human cerebral cortex. *Journal of Neuroscience*, *28*, 3586–3594. doi: 10.1523/JNEUROSCI.5309-07.2008.

Simmonds, D. J., Pekar, J. J., & Mostofsky, S. H. (2008). Meta-analysis of Go/No-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, *46*, 224-232. doi:10.1016/j.neuropsychologia.2007.07.015

Steinberg, L. (2008). A social neuroscience perspective on adolescent risk-taking. *Developmental Review*, *28*, 78-106. doi: 10.1016/j.dr.2007.08.002

Steinberg, L. (2010). A dual systems model of adolescent risk-taking. *Developmental Psychobiology, 52*, 216-224. doi: 10.1002/dev.20445

Symeonidou, I., Dumontheil, I., Chow, W.-Y., & Breheny, R. (in press). Development of online use of theory of mind during adolescence: An eye-tracking study. *Journal of Experimental Child Psychology.* doi: 10.1016/j.jecp.2015.11.007

Tamm, L., Menon, V., & Reiss, A. L. (2002). Maturation of brain function associated with response inhibition. *Journal of the American Academy of Child & Adolescent Psychiatry*, *41*, 1231-1238. doi: 10.1097/00004583-200210000-00013

Vetter, N. C., Altgassen, M., Phillips, L., Mahy, C. E. V, & Kliegel, M. (2013). Development of affective theory of mind across adolescence: disentangling the role of executive functions. *Developmental Neuropsychology, 38*, 114–25. doi:10.1080/87565641.2012.733786

Watanabe, J., Sugiura, M., Sato, K., Sato, Y., Maeda, Y., Matsue, Y., et al. (2002). The human prefrontal and parietal association cortices are involved in NO-GO performances: An event-related fMRI study. *Neuroimage*, *17*, 1207-1216. doi: 10.1006/nimg.2002.1198

Wellman, H. M., Cross, D., & Watson, J. (2001). Meta-analysis of theory-of-mind development: The truth about false belief. *Child Development*, *72*, 655–684. doi: 0009-3920/2001/7203-0001

Wechsler, D., (1999) *Wechsler Abbreviated Scale of Intelligence*. Psychological Corp, San Antonio, TX.

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record, 58,* 475–482.

Willoughby, T., Tavernier, R., Hamza, C., Adachi, P.J.C., & Good, M. (2014). The triadic systems model perspective and adolescent risk taking. *Brain and Cognition, 89,* 114–115. doi: 10.1016/j.bandc.2013.11.001

Willoughby, T., Good, M., Adachi, P.J.C., Hamza, C., & Tavernier, R. (2013). Examining the link between adolescent brain development and risk taking from a social-developmental perspective. *Brain and Cognition, 83,* 315–323. doi:10.1016/j.bandc.2013.09.008