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Affective and Deliberative Processes in Risky Choice: Age Differences in Risk Taking in the Columbia Card Task

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The authors investigated risk taking and underlying information use in 13- to 16- and 17- to 19-year-old adolescents and in adults in 4 experiments, using a novel dynamic risk-taking task, the Columbia Card Task (CCT). The authors investigated risk taking under differential involvement of affective versus deliberative processes with 2 versions of the CCT, constituting the most direct test of a dual-system explanation of adolescent risk taking in the literature so far. The "hot" CCT was designed to trigger more affective decision making, whereas the "cold" CCT was designed to trigger more deliberative decision making. Differential involvement of affective versus deliberative processes in the 2 CCT versions was established by self-reports and assessment of electrodermal activity. Increased adolescent risk taking, coupled with simplified information use, was found in the hot but not the cold condition. Need-for-arousal predicted risk taking only in the hot condition, whereas executive functions predicted information use in the cold condition. Results are consistent with recent dual-system explanations of risk taking as the result of competition between affective processes and deliberative cognitive-control processes, with adolescents' affective system tending to override the deliberative system in states of heightened emotional arousal.

Keywords: risk taking, adolescence, affective and deliberative decision making, dual system, cognitive control

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Everyday risk taking shows a typical developmental trajectory. Comparatively low during childhood, risk taking increases when individuals reach puberty, peaks in adolescence and early adulthood, and decreases again during adulthood. This age pattern has been documented in different risk-taking behaviors, such as the use of licit and illicit substances, dangerous behavior in traffic, unsafe sexual practices, delinquent behaviors, and risky recreational sports (Boyer, 2006; Casey, Getz, & Galvan, 2008; Reyna & Farley, 2006; Rivers, Reyna, & Mills, 2008; Steinberg, 2008). Although for many adolescents increased risk taking is a transient phenomenon, it can have a negative impact on adult life. For example, adolescent alcohol, nicotine, or drug use is a powerful predictor for later substance use and other behavioral problems (e.g., Ellickson, D'Amico, Collins, & Klein, 2005; Grant et al., 2006). It is therefore important to explore the causes and mechanisms of risk taking in adolescents, which are currently not well understood.

Psychological research has investigated risk taking with different methods. Most common have been risky decision-making tasks in the laboratory and self-report questionnaires of everyday risk-taking behaviors. Results from studies using these methods have sometimes observed the typical age (and gender[1]) patterns, but other times not (Boyer, 2006; Reyna & Farley, 2006). Shedding some light on this inconsistency, Byrnes, Miller, and Schafer (1999) found that the kind of measure used to assess risk taking

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[1] When gender differences are observed, male adolescents typically take even greater risks than do female adolescents (e.g., Elander, West, & French, 1993; Gullone, Moore, Moss, & Boyd, 2000; Turner & McClure, 2003; Wilson & Daly, 1985). However, this pattern is not consistent across domains, and gender differences have been reported to have grown smaller over the last decades (Byrnes et al., 1999).

plays an important role, with hypothetical choice scenarios eliciting smaller age/gender differences than actual everyday behavior. This finding is consistent with more recent, so-called dual-system models of adolescent risk taking (e.g., Casey et al., 2008; Steinberg, 2008). These models claim that, in contrast to traditional cognitive–developmental models in the tradition of Jean Piaget (see, e.g., Baird & Fugelsang, 2004), increased risk taking is not caused by characteristics of adolescent cognitive processes alone but that affective processes—particularly the balance between affective and deliberative processes—are crucial in adolescent risk taking. Consistent with these dual-system models and based on behavioral and developmental neuroscience research findings, our hypothesis is that increased adolescent risk taking is more likely to occur when affective and motivational processes are involved (e.g., Bischof, 1975, 1985; Byrnes et al., 1999; Casey et al., 2008; Galvan, Hare, Voss, Glover, & Casey, 2007; Loewenstein, Weber, Hsee, & Welch, 2001; Steinberg, 2008; Weber, Shafir, & Blais, 2004; Wilson & Daly, 1985). Because hypothetical risky choice scenarios, such as choices between monetary lotteries without outcome feedback, typically trigger only minor affective processes, our hypothesis predicts that increased adolescent risk taking would not usually be found with such measures. Although there has been substantial theorizing and indirect evidence for a dual-system explanation of adolescent risk taking (e.g., Casey et al., 2008; Rivers et al., 2008; Steinberg, 2008), to our knowledge, we are the first to directly address these claims by using two versions of a risky decision-making task that triggers differential amounts of affective versus deliberative processing.

Cognitive Development Explanations

Cognitive–developmental psychology rooted in the work of Piaget and Inhelder (1975) argues that adolescent risk taking stems from deficits in decision making and other cognitive skills that develop rather late during childhood and may not have fully matured by adolescence (see, e.g., Baird & Fugelsang, 2004). Some of these basic skills assumed to be required for good decisions include reasoning (DeLoache, Miller, & Pierroutsakos, 1998), efficiency of strategies (Siegler, 1996), and metacognitive skills (Kuhn, Garcia-Mila, Zohar, & Andersen, 1995). More directly related to risky decision making, work by Piaget and Inhelder and others (e.g., Hoemann & Ross, 1971) suggests that probability understanding develops late in childhood, typically only around age 12. Accordingly, one could argue that if probabilities are not well understood or if risk-relevant information (such as potential gains and losses) is neglected, it is likely that the resulting behavior in a risky situation will be suboptimal, for example too risk-seeking because the probability of losses is underappreciated. However, the finding that abilities, such as probability understanding, are maturing only at around age 12 might be due to the specific choice methodology that was typically used by Piaget and others. Falk and Wilkening (1998) argued that these methods assess explicit understanding and knowledge that develop relatively late. In contrast, research in the framework of information integration theory (Anderson, 1996) uses judgment tasks that tap into intuitive processes and implicit knowledge. With these functional measurement methods, children as young as 4–7 years have been shown to exhibit understanding of probability and expected value that comes strikingly close to mathematically correct normative solutions (e.g., Acredolo, O'Connor, Banks, & Horobin, 1989; Schlottmann & Wilkening, in press; see also Reyna & Ellis, 1994). On the basis of these findings, it appears rather unlikely that adolescents' risk taking is caused by an immaturity of the more general cognitive abilities required for good risky decisions. Traditional cognitive–developmental explanations of adolescent risk taking have been further undermined by recent studies that have shown that logical reasoning abilities together with basic information processing abilities, as well as their neural substrates, are basically fully developed by age 16 and do not change substantially beyond this age (e.g., Casey, Galvan, & Hare, 2005; Keating, 2004). If risk taking were caused by such cognitive immaturities, it would be expected to decrease substantially at age 16 (however, see, e.g., Baird & Fugelsang, 2004, and Yurgelun-Todd, 2007, for explanations of adolescent risk taking more consistent with traditional cognitive–developmental views). Moreover, there is little evidence that adolescents differ from adults when asked to evaluate risks, consequences, and relative costs and benefits of dangerous behaviors (Beyth-Marom, Austin, Fischhoff, Palmgren, & Jacobs-Quadrel, 1993).

Dual-System Explanations

Recent neuroscience theory views risk taking as the result of a competition between two neural systems, a phylogenetically older affective system and a phylogenetically younger, deliberative, cognitive-control system (Casey et al., 2008; Cohen, 2005; Steinberg, 2008). The affective system has been shown to rely on brain structures present in both humans and lower animals, specifically on midbrain dopaminergic centers such as the ventral tegmentum area and its various targets, including both subcortical structures (amygdala and ventral striatum) and cortical structures (medial and orbital regions of the frontal cortex and the insular cortex; e.g., Cohen, 2005; McClure, Laibson, Loewenstein, & Cohen, 2004). Affective processing is spontaneous and automatic, operates by principles of similarity and contiguity, and influences behavior by affective impulses (Weber et al., 2004). The cognitive-control system is assumed to rely on brain structures more developed in higher animals, including the dorsal and ventral portions of lateral prefrontal cortex and posterior parietal cortex. It serves two purposes relevant in the context of our article. First, it is the neural basis of deliberative processing, which is effortful, controlled, and operates according to formal rules of logic (Weber et al., 2004). Second, it is the neural basis of inhibitory control, a mechanism that can block affective impulses and therefore enables deliberative decision making even in affect-charged situations (Cohen, 2005; Knoch & Fehr, 2007; McClure et al., 2004).[2]

The affective and deliberative neural systems have been shown to mature at different speeds. The affective system's responsiveness (particularly of its subcortical parts) increases rapidly at puberty, whereas the deliberative cognitive-control system matures later and more gradually over the course of adolescence and young adulthood (Casey et al., 2008; Steinberg, 2008). Within the

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[2] Although some authors refer only to the second function—inhibitory control—as "cognitive control," we use the terms deliberative or cognitive-control system to refer to the whole neural network and specify whether we talk about deliberative processes or the inhibition of affective impulses.

cognitive-control network, deliberative processing abilities, such as abstract thought, mature earlier than the potential for inhibitory control (Keating, 2004; Kuhn, 2006). Accordingly, adolescents and adults can be expected to differ less in their potential for deliberative processing (e.g., use of all relevant information), particularly in the absence of affective involvement. In contrast, they can be expected to differ more in their potential to control affective impulses in situations of high affective involvement. The difference in maturational speed is assumed to result in a developmental imbalance between the two systems during adolescence, with the affective network being easily triggered, for example by the expectation of a reward (Galvan et al., 2006, 2007) or the presence of peers (Gardner & Steinberg, 2005). Because the very active affective system is not yet sufficiently counterbalanced by the still-maturing cognitive-control network, adolescents are assumed to be susceptible to risk taking in situations of heightened emotional arousal. A similar imbalance between these two systems is thought to be present in mental disorders such as substance abuse and pathological gambling (Bechara, 2005).

The theorizing about these dual-system mechanisms underlying adolescent risk taking is, to our knowledge, based mostly on *indirect* empirical evidence: Galvan et al. (2007), for example, showed that in adolescents and adults, but not in children, activity of the nucleus accumbens in response to rewards was highly correlated with self-reported likelihood of engaging in risk-taking behaviors in everyday life, providing correlational evidence for the affective portion of the dual-system explanation. Eshel, Nelson, Blair, Pine, and Ernst (2007), on the other hand, showed that increased prefrontal activity during risky decision making was correlated with less risk taking in both adults and adolescents. In addition, adults overall showed more prefrontal activity than adolescents during risky choices. In adults, causal evidence for a dual-system explanation of risk taking has been provided by recent studies using brain stimulation techniques. Temporarily disrupting functioning of the right dorsolateral prefrontal cortex by means of transcranial magnetic stimulation resulted in increased risk taking in a laboratory gambling task (Knoch et al., 2006), whereas increasing activity in the same brain area by means of transcranial direct current stimulation decreased risk taking (Fecteau et al., 2007).

Similar to Casey et al.'s (2008) and Steinberg's (2008) dual-system models, fuzzy-trace theory (Reyna & Brainerd, 1995; Reyna & Farley, 2006; Rivers et al., 2008) assumes that increased risk taking in adolescents can be caused by a maturational lack of inhibition, particularly in situations of heightened emotional arousal. However, in addition to this "reactive route," fuzzy-trace theory posits that adolescent risk taking can also be caused by a second mechanism, the "reasoned route." Here, adolescents' risk taking is based on too much deliberative reasoning about pros and cons of risk, whereas adults' less detail-oriented and more gist-based thinking leads them to avoid many risks.

Goals

This article had two goals. The first was to test the dual-system explanation of adolescent risk taking. We conducted four experiments investigating risk taking and use of relevant information by adolescents and adults in both a "hot" affective and a "cold" deliberative condition. We hypothesized increased risk taking in adolescents only in the affective condition, consistent with the assumption that impulsive risk taking occurs in adolescents when the affective neural network is triggered and an immature cognitive-control network is not yet capable of overriding strong affective impulses. In contrast, we expected no age differences in the cold condition, which served to investigate age differences in risk taking and the quality of deliberative processes (i.e., the number of relevant informational factors considered in their decisions) in the *absence* of affective involvement. If adolescents suffered from more general cognitive deficits in making risky decisions, we should see differences in information use between adolescents and adults not only in the hot affective but also the cold deliberative condition. Cognitive immaturities in adolescents can be ruled out as the explanation for their increased risk taking if adolescents do not differ from adults in information use in the cold condition.

The second goal of this article was to introduce a novel risky decision-making task, the Columbia Card Task (CCT). Both Slovic's (1966) risk-taking task and the Balloon Analogue Risk Task (BART; Lejuez et al., 2002) are similar to our task in the dynamic nature in which risk increases over time within a trial. Risk taking in all of these tasks is assessed via participants' voluntary stopping point in a series of incrementally increasingly risky choices. In contrast, many other risk-taking tasks (e.g., Brand et al., 2005; Levin & Hart, 2003; Reyna & Ellis, 1994; Rogers et al., 1999) involve the choice between a gamble with static risk and a safe riskless option (often of the same expected value) as a dependent measure. The CCT differs in two important ways from other dynamic and nondynamic risk-taking tasks, such as the BART (e.g., Lejuez et al., 2002), the Cambridge Gambling Task (CGT; Rogers et al., 1999), the Cups Task (Levin & Hart, 2003), the Game of Dice Task (GDT; e.g., Brand et al., 2005), the Iowa Gambling Task (IGT; e.g., Bechara, Damasio, Damasio, & Anderson, 1994), and other tasks such as the one used by Reyna and colleagues (e.g., Reyna & Ellis, 1994) to study risky decision making in children. First, in addition to assessing risk-taking level, the CCT assesses the complexity of the decision maker's information use and determines which of three factors that should be affecting risk taking have been taken into account (outcome probability, gain amount, and loss amount). Second, it is the first task that exists in two versions that differentially trigger affective versus deliberative decision-making processes.[3] In four experiments, we (a) compared behavior (risk taking and information use) across the hot and cold CCT[4] versions, (b) compared adolescents' versus adults' task performance, and (c) used individual differences measures to establish convergent validity for our dual-system explanation of adolescent risk taking versus alternative explanations.

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[3] The General Discussion provides additional comparisons of the CCT to other risk-taking tasks.

[4] "Cold" and "hot" cognition, respectively, hence the names of the CCT versions; see Metcalfe and Mischel (1999) and Steinberg (2005).

Columbia Card Task (CCT)

General Design

As shown in Figure 1, both the hot and the cold versions of the CCT involve 32 cards, displayed in four rows of 8 cards each. At the beginning of each trial, all cards are shown face down. The rules of the game are as follows: Within a given trial, cards can be turned over as long as gain cards are encountered. Each gain card adds a specified gain amount to the trial payoff, and the player can voluntarily stop the trial at any point and claim the obtained payoff. As soon as a loss card is encountered, the trial terminates; that is, no more cards can be turned over and a specified loss amount is subtracted from the previous payoff. The top of the screen displays the following information for a given trial: number of hidden loss cards (out of 32), amount of gain per gain card, amount of loss, and current trial number.

A full factorial within-subject design varied the three game parameters or factors between trials: (a) probability of a loss (1, 2, or 3 loss cards), (b) gain amount (10, 20, or 30 points per gain card), and (c) loss amount (250, 500, or 750 points). Presenting each of the 27 combinations of factor levels twice resulted in 54 trials, with the trials randomly ordered within each of the two blocks of 27 trials.

Risk Taking

Because both the gain and the likelihood of experiencing a loss increased with each card that was turned over, turning over more cards was associated with greater outcome variability and therefore was a riskier strategy than turning over fewer cards. Thus, the average number of cards turned over across trials was used as an indicator of a participant's level of risk taking.

Information Use

A normative analysis of the CCT suggests that participants should turn over cards as long as the expected value for turning over the next card is positive. An optimal strategy to maximize point total therefore needs to take into account all three factors: probability, gain amount, and loss amount.[5] In the information-use analysis, we were interested in how the levels of each of the three informational factors influenced the number of cards chosen, irrespective of the overall number of cards chosen. In the risk-taking analysis, in contrast, we were interested in the overall number of cards chosen, irrespective of the influence of the different factor levels.

Information use in the CCT can be analyzed at both the group and the subject level, following standard functional measurement analysis (see, e.g., Anderson, 1996; Figner & Voelki, 2004). At the age-group level, a repeated-measures analysis of variance (ANOVA) with the number of cards chosen in each trial as the dependent variable and the factors probability, gain amount, and loss amount as independent variables determines information use. A significant effect of an independent variable indicates that this factor has been taken into account in participants' responses (e.g., when a participant chooses more cards in trials with 500-point loss amounts in contrast to trials with 750-point loss amounts but fewer cards in contrast to trials with 250-point loss amounts); a nonsignificant effect indicates that this factor has not been taken into account, that is, that it did not influence the number of cards that were turned over. At the individual-subject level, such an ANOVA can be calculated for each participant separately.[6] From the results of these individual-subject ANOVAs, we derived a simple one-dimensional measure of the complexity of each participant's information use by counting how many factors each participant had taken into account (ignoring *which* factors had been taken into account), with values ranging from 0 (*no factor*) to 3 (*all factors*) indicating increasing complexity of information use.[7]

Hot and Cold CCT Versions

To trigger affective processes in the hot version, we allowed players to make stepwise incremental decisions about turning over an additional card and provided them with immediate feedback. Clicking on a card turned it over, revealing whether it was a gain or a loss card (see Figure 1, left panel). As long as gain cards were turned over, participants could decide after each card to either go on to another card or to terminate the trial and to collect all obtained gain points. Once a loss card was turned over, the incurred loss was subtracted from the previous point total and the trial was terminated. Participants could see their current point total for the trial, which changed with every card they turned over. If a participant decided to stop the current trial, or if he or she clicked on a loss card, all of the remaining cards were turned over to show which were gain cards and which were loss cards. The participant could then start the next trial.[8] Recent neuroimaging studies (e.g., Aron et al., 2004; Shohamy et al., 2004) have shown that such task characteristics reliably trigger activity in the affective system.

In the cold CCT, decisions were not made stepwise and there was no immediate feedback, in order to avoid triggering affective processes. Instead, participants were asked to indicate only the *number* of cards that they wanted to turn over on a given trial, not which cards they would choose. The game screen (see Figure 1, right panel) provided a string of 33 small buttons labeled 0 to 32, from left to right, just above the top row of the 32 cards. Participants indicated how many cards they wanted to turn over on a given trial by clicking 1 of these 33 buttons, thus indicating their decision on a type of analogue scale, without receiving any feedback about the result of their decision until the end of the session. These two characteristics—no immediate feedback and a single, final decision instead of stepwise decisions—were assumed to trigger predominantly deliberative information processing. In both the hot and the cold CCT, the dependent variable was the number of cards chosen in each of the 54 trials.

Learning Demands in the Hot and Cold CCT

Our manipulation checks, as shown in Experiments 3 and 4, were consistent with the hypothesized differential involvement of affective versus deliberative processes in the CCT versions. How-

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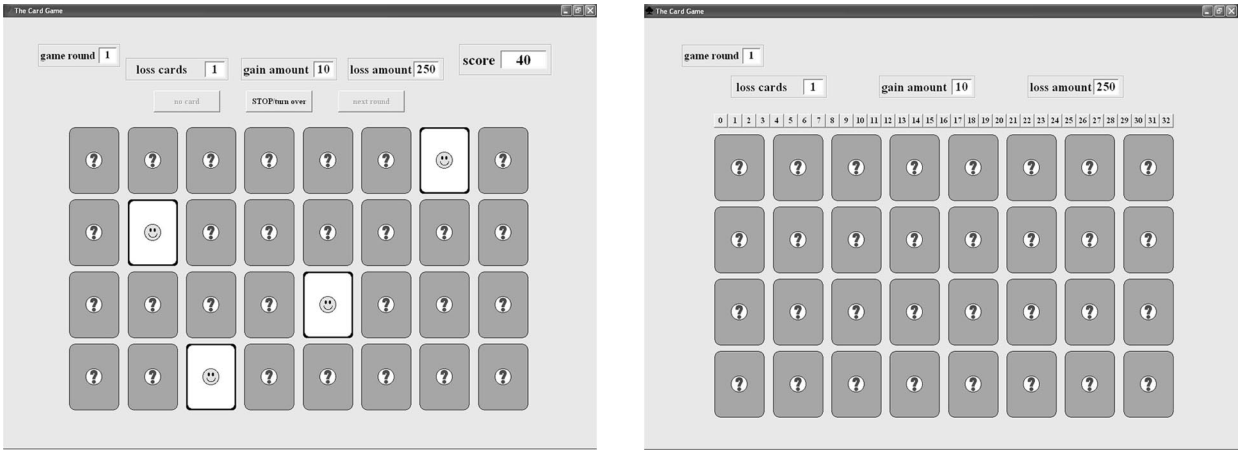
[5] See supplemental materials for details.

[6] An alpha level of $p < .10$ instead of $p < .05$ was used to minimize the probability of beta errors, that is, to reduce the chance of overlooking more complex information use (Falk & Wilkening, 1998).

[7] If, for example, the individual-level ANOVA for a participant showed significant main effects for probability and gain amount and a nonsignificant effect for loss amount, this participant's score was 2. If the ANOVA for a different participant showed significant main effects for gain amount and loss amount, but not for probability, this participant received a score of 2 as well.

[8] See supplemental materials for details.



game round 1
loss cards 1
gain amount 10
loss amount 250
score 40

game round 1
loss cards 1
gain amount 10
loss amount 250

Figure 1. Screenshots of the hot (left panel) and cold (right panel) Columbia Card Task.

ever, one could argue that the tasks also differ in learning demands. In the hot version, the probability of turning over loss cards within a trial increases with each card turned over. To make an optimal decision, the participant has to keep track of this changing probability.[9] In the cold version, participants could take into account all three factors in the beginning of each trial to make one single decision per trial, without having to keep track of changing probabilities within trials. This difference could explain age differences in hot CCT performance. Working memory span has been shown to increase from adolescence to adulthood, particularly when assessed with tasks requiring manipulation and not just storage of information (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Kwon, Reiss, & Menon, 2002). To investigate how working memory span relates to task performance in both CCT versions and whether greater learning demands were a valid alternative explanation for age differences in the hot CCT, we included two tasks assessing working memory span in Experiment 3, one task requiring only storage and one task requiring storage and manipulation.

Fixed Feedback

Our main variable of interest with respect to participants' risk taking was how many cards they chose to turn over (on average, across the 54 trials) before they stopped. Trials in which participants stop voluntarily are more informative than trials in which they are stopped involuntarily by turning over a loss card, because only the former gives full information about their risk preference. In the cold version, people did not receive immediate feedback; therefore, their decisions always reflected voluntary stopping. In order to maximize the assessment of voluntary stopping in the hot CCT, we fixed the feedback in the 54 experimental trials. The game was programmed in such a way that the loss cards would always be the last possible cards (e.g., in the case of two hidden loss cards, only the last of 31 cards chosen would be a loss card). To maintain the impression that respondents were playing a game of chance, 9 additional trials were randomly interspersed among the 54 experimental trials. These 9 additional loss trials were programmed so that every participant clicked on a loss card with very high probability (independent of the participant's choice; in the 9 loss trials this preprogrammed loss card ranged from the 2nd to the 25th card turned over. Because the loss trials served only to maintain the impression of a real game of chance, these data were not included in the analyses.) Although the fixed feedback in the hot condition was introduced to maximize the assessment of voluntary stopping, and thereby increasing comparability to the cold CCT, it introduced an additional difference between the two CCT versions that could potentially explain differences between adolescents' and adults' performance in the hot CCT. If adolescents were better at detecting the rigged nature of the feedback, this could be an alternative explanation for age differences in hot CCT performance. We tested this alternative "rigged-feedback" explanation with multiple approaches: In Experiment 1, we redid our main analyses with a reduced sample from which participants were excluded who exceeded a specified threshold of turned over cards to compare whether the results differed from those obtained with the full sample. Additionally, we tested for the presence of learning effects by comparing the first and second blocks of the hot CCT. In Experiment 3 we asked participants to what extent they had the suspicion that the game was rigged. We tested whether this suspicion differed across age groups and redid our main analyses with a reduced sample that excluded participants whose suspicion exceeded a certain threshold.

Individual Differences Measures

Several measures were used to (a) establish convergent support for our dual-system interpretation of our main results, (b) validate hypothesized differences in affective versus deliberative processes in the two CCT versions, and (c) investigate alternative explanations of our results. Based on our dual-system explanation of adolescent risk taking, we had specific hypotheses as to which of

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[9] Of course, participants were free to use the same "overall" decision strategy as in the cold CCT. That is, before turning over the first card in a trial, they could have decided how many cards they wanted to turn over and then just have turned over this number of cards without reconsidering their decision within a trial. Task characteristics make this a less obvious strategy, however.

the individual differences measures should correlate with risk taking and/or information use either in the hot or the cold CCT. All measures were administered with both the hot and cold CCT.

Need-for-Arousal

Need-for-arousal is a construct somewhat related to Zuckerman's sensation seeking (Zuckerman, 1994) in that it reflects the amount of novel ("collative") stimulation that an individual seeks out (see Berlyne, 1966; collative stimuli are novel, uncertain, complex, or surprising; see also Bischof, 1975). However, need-for-arousal is conceptualized as a motivational variable, serving as ideal-point value in an affect-based homeostatic system that regulates the arousal level in the organism. Accordingly, an individual with a high level of need-for-arousal is assumed to be more likely to both actively search for and better tolerate situations of high collative stimulation. Because risk-taking behavior typically leads to an increase in collative stimulation (particularly if the risk-taking behavior is accompanied by substantial affect, e.g., in bungee jumping), higher levels of need-for-arousal are expected to be associated with an increased risk-taking propensity. Need-for-arousal is assumed to be situationally as well as developmentally influenced. Ontogenetically, it is assumed to follow a developmental trajectory with relatively low values during childhood, an increase during adolescence and early adulthood, followed by a steady decline during adulthood (Bischof, 1975, 1985).

To capture more situation-unspecific trait-like aspects of need-for-arousal, we used an eight-item questionnaire about broad preferences regarding the level of novelty in general and the propensity to expose oneself to risky situations in everyday life (e.g., "I like a lot of variety," "I often position myself in an exciting/dangerous situation on purpose").[10] Responses on these and all other questionnaire items were made on a graphic rating scale ranging from 1 to 100. Scale endpoints were labeled *doesn't apply at all* and *applies very much*. Because need-for-arousal is a motivational affect-based variable, we hypothesized it would influence only affective but not deliberative risk taking; that is, we expected a significant correlation with risk taking only in the hot but not the cold CCT.

Executive Functions

Measures of executive functions were used as indicators of deliberative processes. Executive functions, such as planning, problem solving, and reasoning, have been associated with the deliberative cognitive neural network (e.g., Cohen, 2005; Steinberg, 2007). Deliberative decision making relies on executive functions, whereas decision-making tasks involving affective processes have been shown to be relatively independent of executive functions (e.g., Turnbull, Evans, Bunce, Carzolio, & O'Connor, 2005). Accordingly, we assumed that executive functioning would be a stronger predictor of CCT performance in the cold than in the hot CCT. We had no hypothesis about whether risk taking or information use would be more strongly influenced by executive functioning in the cold CCT.

We used the following four measures of executive functions: the Similarities Task, taken from the Wechsler Intelligence Scale for Children—3rd ed. (WISC–III; Wechsler, 1991), and the Key Search Task, the Zoo Map Test, and the Water Test, all from the Behavioral Assessment of Dysexecutive Syndrome for Children task battery (BADS–C; Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003). All tasks are suitable for adolescents and adults. The BADS–C tasks assess higher order executive functions such as planning, novel problem solving, inflexibility, and perseveration in tasks similar to the requirements of everyday life of children, adolescents, and adults. The Similarities Task assesses verbal reasoning, another aspect of executive functioning. These skills are usually assumed to be executed with substantial involvement of the dorsolateral region of the prefrontal cortex (see e.g., Cohen, 2005).

Working Memory Span

To test the alternative "learning-demands" explanation, we used the digit span forward and backward tests from the WISC–III (Wechsler, 1991). Forward digit span assesses mainly storage processes, whereas the backward digit span assesses capacity of both storage and manipulation of information, making it the more likely candidate for demonstrating developmental differences between adolescents and adults (Crone et al., 2006; Kwon et al., 2002). If differences in learning demands are responsible for age differences in hot CCT performance, we would expect to find negative correlations between working memory span and risk taking and/or information use for that task.

Hot–Cold Manipulation Check

In addition to examining hypothesized correlation patterns between the hot versus cold CCT and individual differences measures, we used a series of measures that directly assess whether the two CCT versions differentially involved affective versus deliberative processes. For *self-reported decision strategies*, participants rated their agreement on two items after completing the CCT. Affect-based strategy use was assessed with the item "I solved the task on a gut level," deliberative strategy use with the item "I tried to solve the task mathematically." We expected ratings for the affect-based strategy to be higher in the hot than in the cold condition and the reverse pattern for the deliberative strategy. *Emotional arousal* was assessed via self-report ("At times when I was deciding what to do, I felt some excitement") and via recording electrodermal activity (EDA). Magnitude of EDA-derived skin conductance response (SCR) is a widely used physiological measure of emotional arousal (Boucsein, 1992; Critchley, Elliott, Mathias, & Dolan, 2000). We compared SCR magnitude across the hot and cold CCT as well as during a baseline. We expected both self-reported and physiological emotional arousal to be higher in the hot than the cold CCT.

Overview of Experiments

Experiment 1 looked at risk taking and information use in the hot CCT in three age groups: younger adolescents, older adolescents, and adults. Experiment 2 investigated the same age groups using the cold CCT. In both experiments need-for-arousal was assessed for convergent evidence that affective processes more strongly influenced risk taking in the hot than the cold CCT. Experiment 3 involved two age groups, younger adolescents and adults. It served as replication of the results of Experiments 1 and 2 with respect to risk taking and information use. Executive

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[10] See supplemental materials for details.

functions were assessed to test for convergent validity of the assumed predominance of deliberative processes in the cold CCT. Self-reported decision strategies were used as a hot–cold manipulation check. Working memory span was included to investigate the alternative "learning-demands" explanation. Self-reported suspicion that the CCT was rigged was used to investigate the alternative "fixed-feedback" explanation. Experiment 4 served solely as a manipulation check for the differential involvement of affective processes in the hot versus the cold CCT. Accordingly, only one age group was investigated. Emotional arousal was physiologically assessed by SCR in the hot and the cold CCT. Table 1 provides a list of our hypotheses and alternative explanations, together with a guide to where they were tested.

Experiment 1

Method

Participants

Seventy-six participants ranged in age from 14 to 57 years and were divided into three roughly equal-sized age groups: 14–16 years (18 girls, 10 boys, $M = 15.3$ years, $SD = 0.27$), 17–19 years (10 girls, 12 boys, $M = 18.3$ years, $SD = 0.83$), and 20 years and older (16 women, 10 men, $M = 24.5$ years, $SD = 7.43$). Participants in the two youngest age groups were recruited from schools in the German-speaking region of Switzerland by contacting teachers and principals. Participants in the oldest age group were recruited from introductory classes at the University of Zurich, and by word of mouth to reach a more heterogeneous sample. Typical of the local population, participants came from primarily Caucasian middle- to upper-middle income families and were fluent in the Swiss–German language.

Procedure

Participants were tested in small groups of 1 to 5 either in a private room in their school or in a lab room at the University of Zurich and worked on the tasks alone on an individual computer. Participants first received general information about the study verbally. Instructions about the questionnaire and the computer card game, including practice trials, were then given in a standardized manner on the computer. As in all four experiments, respondents received a flat-rate payment of 5 Swiss Francs and could choose one small gift from a selection of different items (valued from approximately 2 to 3 Swiss Francs). Order of presentation—whether the card game or the questionnaire containing all individual differences measures was presented first—was counterbalanced across participants. Because there were no significant effects of presentation order on risk taking or information use, data were analyzed collapsed over the two order conditions: risk taking, $F(1, 66) = 0.22$, $p = .64$, $\eta^2 = .003$; information use, $F(1, 66) = 1.91$, $p = .17$, $\eta^2 = .03$.

Results

Risk Taking

Effects of age on risk taking. Effects of age on risk taking were examined with a univariate ANOVA with age group as the inde-

Table 1
Hypotheses, Alternative Explanations, and Results Across Experiments

Hypotheses (H)/Alternative explanations (AE)	Results
Age differences	
H: Adolescents take more risks than adults in the hot CCT	+ Exp. 1; + Exp. 3
H: Adolescents do not take more risks than adults in the cold CCT	+ Exp. 2; + Exp. 3
H: Adolescents show simplified information use in the hot CCT compared to adults	+ Exp. 1; + Exp. 3
H: Adolescents do not show simplified information use in the cold CCT compared to adults	+ Exp. 2; − Exp. 3
Manipulation check: Hot vs. cold CCT	
H: Decision making in the hot CCT involves greater emotional arousal compared to both decision making in the cold CCT and emotional arousal during baseline, as quantified by EDA	+ Exp. 4
H: Decision making in the hot CCT involves greater emotional arousal compared to decision making in the cold CCT, as quantified by self-report	+ Exp. 3
H: Participants in the hot CCT rely more strongly on affect-based decision strategies compared to in the cold CCT	+ Exp. 3
H: Participants in the cold CCT rely more strongly on deliberative decision strategies compared to in the hot CCT	+ Exp. 3
Predictors of risk taking and information use	
H: Need-for-arousal predicts risk taking in the hot CCT	+ Exp. 1
H: Need-for-arousal does not predict risk taking in the cold CCT	+ Exp. 2
H: Information use predicts risk taking in the hot CCT	+ Exp. 1; + Exp. 3
H: Information use does not predict risk taking in the cold CCT	+ Exp. 2; + Exp. 3
H: Executive functions predict risk taking and/or information use in the cold CCT	+ Exp. 3
H: Executive functions do not predict risk taking or information use in the hot CCT	+/− Exp. 3
Alternative explanations	
AE: Adolescents' smaller working memory span, compared to adults', explains adolescents' increased risk taking and/or simplified information use in the hot CCT	− Exp. 3
AE: Adolescents' ability to easier and/or faster detect the fixed feedback in the hot CCT, compared to adults', explains their increased risk taking	− Exp. 1; − Exp. 3

Note. + (−) indicates that results in the respective experiments were consistent (inconsistent) with the stated hypothesis/alternative explanation. +/− indicates mixed results. Exp. = experiment; CCT = Columbia Card Task; EDA = electrodermal activity.

pendent variable and average number of cards turned over as the dependent variable.[11] As predicted, we found a significant main effect for age group, with the two younger age groups taking greater risks than the adult age group, $F(2, 73) = 4.68$, $p < .05$, $\eta^2 = .11$[12] (see Figure 2, left panel, hot). Tukey's honestly significant difference (HSD) post-hoc tests indicated that the 17- to 19-year-olds followed riskier strategies than the adult group ($p < .01$), that the 14- to 16-year-olds did not significantly differ from the 17- to 19-year-olds ($p = .64$), and that the difference between the youngest and the adult age groups approached significance ($p = .06$).

Information Use

At the group level, complexity of participants' information use was analyzed with a 3 × 3 × 3 × 2 × 3 (Probability × Gain Amount × Loss Amount × Block × Age Group) ANOVA, in which the first four factors were within-subject and the last factor was between-subjects. Significant interactions of age group with all three card game factors (approaching significance for Gain Amount) indicated that information use differed between age groups: Age Group × Probability, $F(4, 146) = 5.65$, $p < .001$, $\eta^2 = .13$; Age Group × Gain, $F(4, 146) = 2.37$, $p = .06$, $\eta^2 = .06$; Age Group × Loss, $F(4, 146) = 8.55$, $p < .001$, $\eta^2 = .19$. To further compare age groups' information use, we analyzed each age group separately. As shown in Figure 3 and Table 2, the two younger age groups differed in information use from the adult age group: The adults took all three card game factors into account, with effect sizes ranging from .35 to .59. In contrast, the two younger age groups mainly centered on the factor probability, did not use the factor loss amount, and used the factor gain amount considerably less than the adult group.

Individual-subject level ANOVAs, reduced to the abovementioned summary measure (i.e., the count of the number of factors considered in the number of cards turned over), revealed information-use complexity increased with age, $F(2, 73) = 3.77$, $p < .05$, $\eta^2 = .09$, as shown in Figure 4 (left panel, hot). Tukey's HSD post-hoc tests indicated a significant difference in information-use complexity only between the youngest and the adult age groups ($p < .05$).

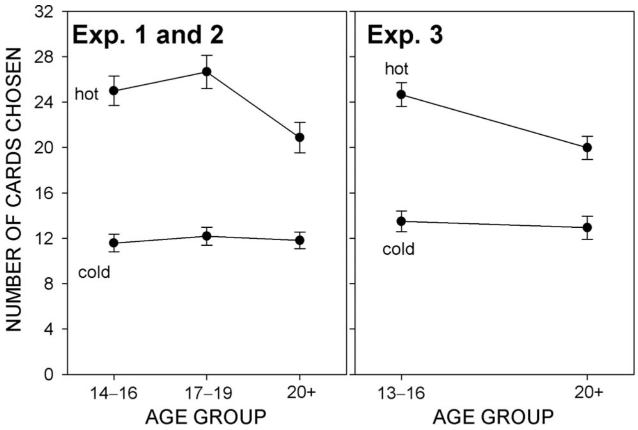

Figure 2. Risk-taking levels (number of cards chosen) as a function of age group in Experiment 1 (left panel, hot), Experiment 2 (left panel, cold), and Experiment 3 (right panel, hot and cold). Error bars denote ±1 *SE*.

Risk Taking, Information Use, and Need-for-Arousal

Risk taking was significantly negatively correlated with complexity of information use ($r = -.29$, $p < .05$), showing that individuals who used less of the relevant information took greater risks. Controlling for age did not lower the correlation substantially ($r = -.28$, $p < .05$). Need-for-arousal was significantly positively correlated with risk taking ($r = .24$, $p < .05$), indicating that motivational–affective factors influenced risk taking in the hot CCT. Controlling for age did not lower the correlation substantially ($r = .26$, $p < .05$). Age differences in risk taking were not an artifact caused by age differences in need-for-arousal, as the correlation between age and risk taking ($r = -.24$, $p < .05$) was not substantially altered by controlling for need-for-arousal ($r = -.26$, $p < .05$).

"Rigged-Feedback" Explanation

As mentioned above, a potentially problematic issue in Experiment 1 was the use of rigged feedback. Although only 1 participant mentioned that the feedback seemed rigged (his data were excluded), it is possible that more participants noticed the rigged feedback without mentioning it. To test whether our results were unduly influenced by participants who had potentially found out that they could not lose and therefore turned over more cards than they would have otherwise, we performed two tests. First, we repeated our main analyses, excluding participants who on average took a number of cards close to the maximum (29 or more, 28 or more, and 25 or more cards per trial). The results remained the same in all three cases, indicating that our findings were not caused by a small group of participants who always turned over close to the maximum number of cards.[13]

If participants had slowly discovered the rigged feedback, we would expect a learning effect in the form of an increase in chosen cards across trials. Because our card game consisted of two blocks of the same 27 trials, we compared the first and the second block of identical trials but found no significant effect of block, $F(1, 70) = 0.49$, $p = .49$, $\eta^2 = .007$. Although there was a significant Block × Age Group interaction, $F(2, 70) = 4.26$, $p < .05$, $\eta^2 = .11$, the effect did not follow the pattern expected from the alternative explanation. In the youngest age group, participants turned over slightly fewer cards in the second block compared to the first (Block 1 vs. Block 2, respectively, *M*s = 26.15 vs. 25.47). In the middle age group, the two blocks were virtually identical (*M*s = 26.51 vs. 26.43), and only in the adult group was there an increase in risk taking in the second block (*M* = 19.66 vs. 21.02). It therefore appears rather unlikely that increased risk taking in younger participants was caused by an increased likelihood of them discovering the rigged feedback during the first block of trials.

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[11] As gender effects were not the focus of our investigation, results with respect to gender are not included. The reported age differences hold true, irrespective of whether the factor gender is included in the analyses. For results regarding gender, please contact Bernd Figner.

[12] All reported effect sizes are partial eta-squares.

[13] See supplemental materials for details.

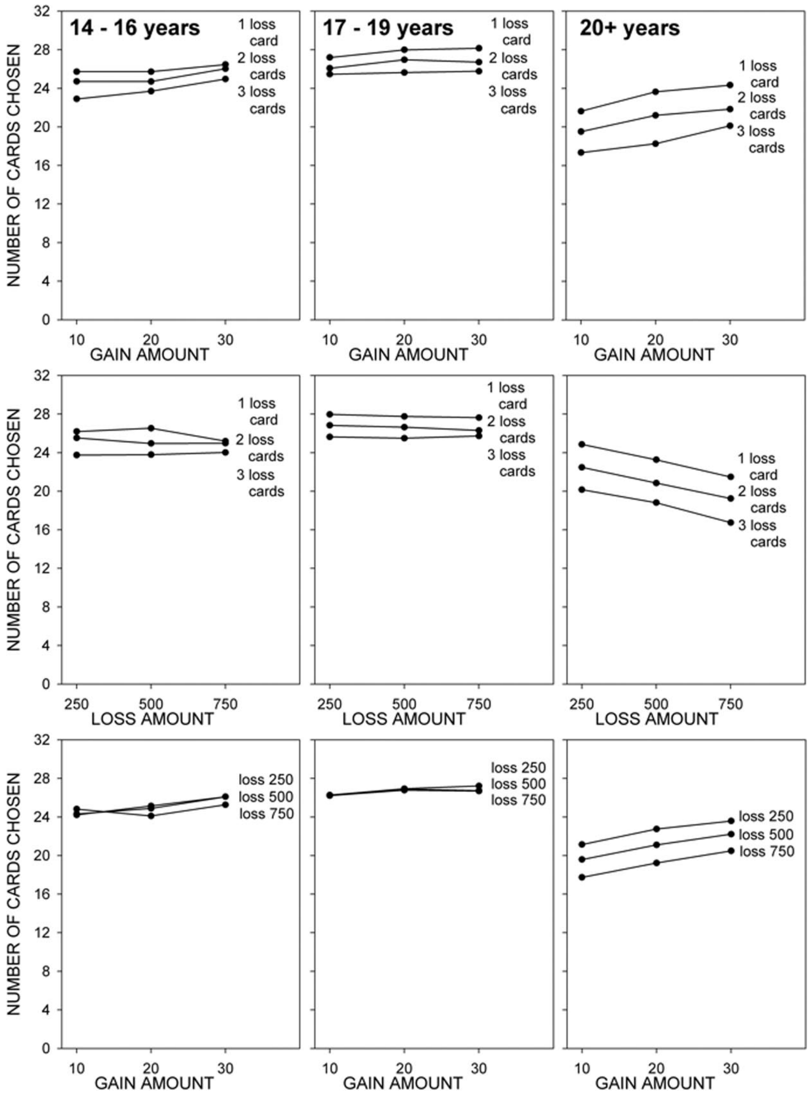

Figure 3. In Experiment 1, mean number of cards chosen as a function of the three factors, by age group. Each graph shows the integration of two factors collapsed over the third factor. Top row: gain amount and probability; middle row: loss amount and probability; bottom row: gain amount and loss amount. Left column: 14- to 16-year-olds; middle column: 17- to 19-year-olds; right column: 20-year-olds and older.

Discussion

As hypothesized, the results of Experiment 1 showed greater risk taking by the two adolescent age groups (14–16 and 17–19 years) than the adult group (20 years and older), consistent with patterns of risk taking in many domains of everyday life (e.g., Arnett, 1992). The positive correlation between need-for-arousal and risk taking suggested that affective processes influenced risk taking in the hot version of the card game.

Adults took more information into account than the two adolescent groups. Furthermore, risk taking was negatively correlated with information use, consistent with adolescents' everyday risk taking often being based on poor decision making (Steinberg, 2004).[14]

The results of Experiment 1 were consistent with traditional cognitive–developmental and dual-system explanations of adoles-

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[14] This is consistent with a dual-system explanation of adolescent risk taking: First, adolescents' strong affective impulses to take another card to receive the reward predispose them to take high levels of risk. Second, deliberative influences that might reduce risk-taking levels—for example, the probability of turning over a loss card worth −500 points is too high to make it a good decision when 27 cards are already turned over—are overridden by the affective system and cannot influence behavior. Accordingly, such a dynamic would lead to an overall negative correlation in the hot CCT between risk taking and information use. Participants whose decisions are more strongly influenced by deliberation would pay more attention to the varying levels of the probability, gain magnitude, and loss magnitude, which is reflected in increased information use and, in turn, would lead to decreased risk taking. The mechanisms involved in the cold CCT are assumed to differ and are outlined further below.

Table 2
Subsample Sizes, Mean Number of Cards Turned Over, and Information Use for the Three Age Groups in Experiment 1 (Hot) and Experiment 2 (Cold)

	Hot			Cold		
Measure and variable	14–16 years old	17–19 years old	≥20 years old	14–16 years old	17–19 years old	≥20 years old
Subsample size, *n*	28	22	26	28	26	30
Number of cards chosen						
M	24.99	26.66	20.87	11.58	12.19	11.81
SE	1.29	1.46	1.34	0.76	0.79	0.74
Probability (P)						
F	14.06***	32.61***	35.80***	51.55***	89.37***	47.06***
η^2	.34	.61	.59	.66	.78	.62
Gain amount (G)						
F	3.30*	2.62†	13.44***	13.56***	17.00***	13.02***
η^2	.11	.11	.35	.33	.41	.31
Loss amount (L)						
F	1.03	<1	16.55***	18.77***	19.26***	20.91***
η^2	.04	.02	.40	.41	.44	.42
P × G						
F	<1	<1	1.77	1.30	<1	2.64*
η^2	.03	.04	.07	.05	.01	.08
P × L						
F	1.45	<1	<1	2.40†	1.62	2.01†
η^2	.05	.03	.01	.08	.06	.07
G × L						
F	1.78	<1	<1	1.96	1.36	3.02*
η^2	.06	.01	.01	.07	.05	.09
P × G × L						
F	2.89**	2.28*	<1	1.64	2.46*	2.74**
η^2	.10	.10	.04	.06	.09	.09

$^{\dagger}p < .10$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

cent risk taking. The traditional cognitive explanation posits risk taking to be caused by immaturities of cognitive faculties (thus the negative correlation with information use). The dual-system explanation (and similarly the "reactive route" of fuzzy-trace theory; Rivers et al., 2008) posits that increased risk taking is caused when the affective system hijacks and overrides the deliberative control system. The positive correlation between risk taking and need-for-arousal supports the latter explanations. The results were not consistent with the "reasoned route" of fuzzy-trace theory, as we did not observe that processing less information was associated with less risk taking but rather found the opposite. However, task characteristics made it unlikely that adolescents would engage in the reasoned route in the first place. To further test between these alternative explanations, we need a control condition of the CCT that involves mainly deliberative processes. If in this condition we also find increased adolescent risk taking, *negatively* correlated with information use, a cognitive–developmental explanation would be favored. Finding increased adolescent risk taking, *positively* correlated with information use, would be consistent with fuzzy-trace theory's "reasoned route" explanation. Lastly, finding neither increased adolescent risk taking nor simplified information use would be consistent with a dual-system explanation.

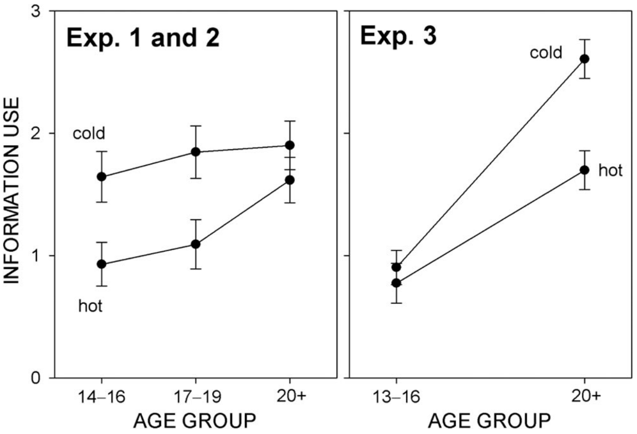

Figure 4. Complexity of information use by age group in Experiment 1 (left panel, hot), Experiment 2 (left panel, cold), and Experiment 3 (right panel, hot and cold). Error bars denote ±1 *SE*.

Experiment 2

The objective of Experiment 2 was to investigate risk taking and information use, as well as their association with need-for-arousal, under conditions of predominantly deliberative processes without substantial involvement of affective processes, comparing the same age groups as in Experiment 1.

Method

Participants

Eighty-four participants ranged in age from 14 to 45 years and were divided into the same age groups as in Experiment 1 (14–16 years: 17 girls, 10 boys, *M* = 14.9 years, *SD* = 0.88; 17–19 years: 14 girls, 12 boys, *M* = 18.2 years, *SD* = 0.88; 20 years and older: 16 women, 14 men, *M* = 23.6 years, *SD* = 5.69). Participants were drawn from the same populations as in Experiment 1 but had not participated in nor were familiar with Experiment 1.

Procedure

The procedures were the same as in Experiment 1 except that instructions for the card game were not given on the computer but in a standardized manner by the experimenter. Because the order of the tasks (CCT or questionnaire containing the individual differences measures first) did not have any significant effect in Experiment 1, we always presented the card game first.

Results

Risk Taking

Effects of age on risk taking. As expected, and in contrast to Experiment 1, we did not find a significant effect of age group, $F(2, 81) = 0.16$, $p = .86$, $\eta^2 = .004$. As can be seen in Figure 2 (left panel, cold), all age groups exhibited the same level of risk taking.

Information Use

In contrast to Experiment 1, we did not find any significant interactions of age group with the card game factors. To directly compare the information use of each age group with those in Experiment 1, we analyzed each age group separately. Not surprisingly, these analyses revealed no differences between age groups, as can be seen in Figure 5 and Table 2 (cold). In each age group, all three factors were taken into account. Complexity of information use, derived from participants' individual information use, showed no significant age effect, $F(2, 81) = 0.44$, $p = .65$, $\eta^2 = .01$ (see Figure 4, left panel, cold).

Risk Taking, Information Use, and Need-for-Arousal

In contrast to Experiment 1, risk taking and information use were not significantly correlated ($r = -.13$, $p = .25$; controlled for age, $r = -.15$, $p = .19$). As predicted, the correlation between risk taking and need-for-arousal was not significant and was close to zero ($r = -.03$, $p = .83$; controlled for age, $r = -.01$, $p = .90$).

Discussion

As hypothesized, there were no age effects in risk taking or information use in the cold CCT. This is consistent with the observation that cold tasks, like making hypothetical choices between lotteries without feedback, tend not to elicit increased risk taking in adolescents (e.g., Byrnes et al., 1999; Loewenstein et al., 2001; see also Steinberg, 2004, 2005). Further, we found no correlations between risk taking and information use or risk taking and need-for-arousal.[15] Together, these results contradict the traditional cognitive–developmental explanation that more general immaturities in adolescents' risky decision-making strategies are responsible for risk taking but are consistent with a dual-system explanation. If only cognitive processes are triggered, risk taking is under the guidance of the deliberative network. Because there are no affective impulses to be blocked, the resulting behavior, both with respect to risk-taking levels and information use, does not differ from adults'. Although the results of the first two experiments appear to be more consistent with a dual-system explanation than a purely cognitive–developmental explanation, we have not yet established that the two card game versions indeed differ in the involvement of affective versus deliberative processes. Experiments 3 and 4 served this purpose.

Experiment 3

Experiment 3 had five goals: (a) to replicate the main findings of Experiments 1 and 2; (b) to investigate differences in self-reported decision strategies (affect-based vs. deliberative) to test our assumption of the differential involvement of these two processes; (c) to test whether deliberative cognitive processes more strongly influenced decision making in the cold than the hot CCT, by including a series of tasks assessing different aspects of executive functioning; (d) to further test the alternative "rigged-feedback" explanation, by including an item asking participants whether they had the impression that the game was rigged; and (e) to investigate the alternative "learning-demands" explanation, by assessing working memory span. If adolescents' increased risk taking in the hot condition was due to limitations in working memory, we would expect a significant negative correlation between working memory span and risk taking, particularly in adolescents playing the hot CCT.

Method

Participants

Two age groups were used in Experiment 3: adolescents (13–16 years) and adults (20 years and older). There were 138 participants ranging from 13 to 38 years old who were randomly assigned to either the hot or the cold condition. The younger age group in the hot condition consisted of 13 girls and 18 boys (*M* = 14.4 years, *SD* = 0.75); in the cold condition there were 15 girls and 26 boys (*M* = 14.2 years, *SD* = 0.89). The older age group in the hot condition consisted of 16 women and 17 men (*M* = 24.5 years, *SD* = 4.37); in the cold condition there were 18 women and 15 men (*M* = 22.8 years, *SD* = 2.75). Participants were drawn from the same populations as in the other experiments and had not participated in nor were familiar with the previous experiments.

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[15] Risk taking in the cold CCT seemed to reflect mainly participants' beliefs about the optimal solution, with the information factors and their levels having little affective meaning. Informal observation and feedback suggests that participants' choices are based on rather affect-free calculus (which does not necessarily need to be explicit or correct). One participant might take into account all three factors and combine them in some way that suggests that it is good to take many cards, whereas another participant may also take all three factors into account, but in a way that suggests that it is optimal to take a small number of cards. Given that the analytic problem of the optimal number of cards in different trials is not trivial, the number of factors taken into account and the number of cards believed to be optimal can well be unrelated across participants, as reflected in the nonsignificant correlation.

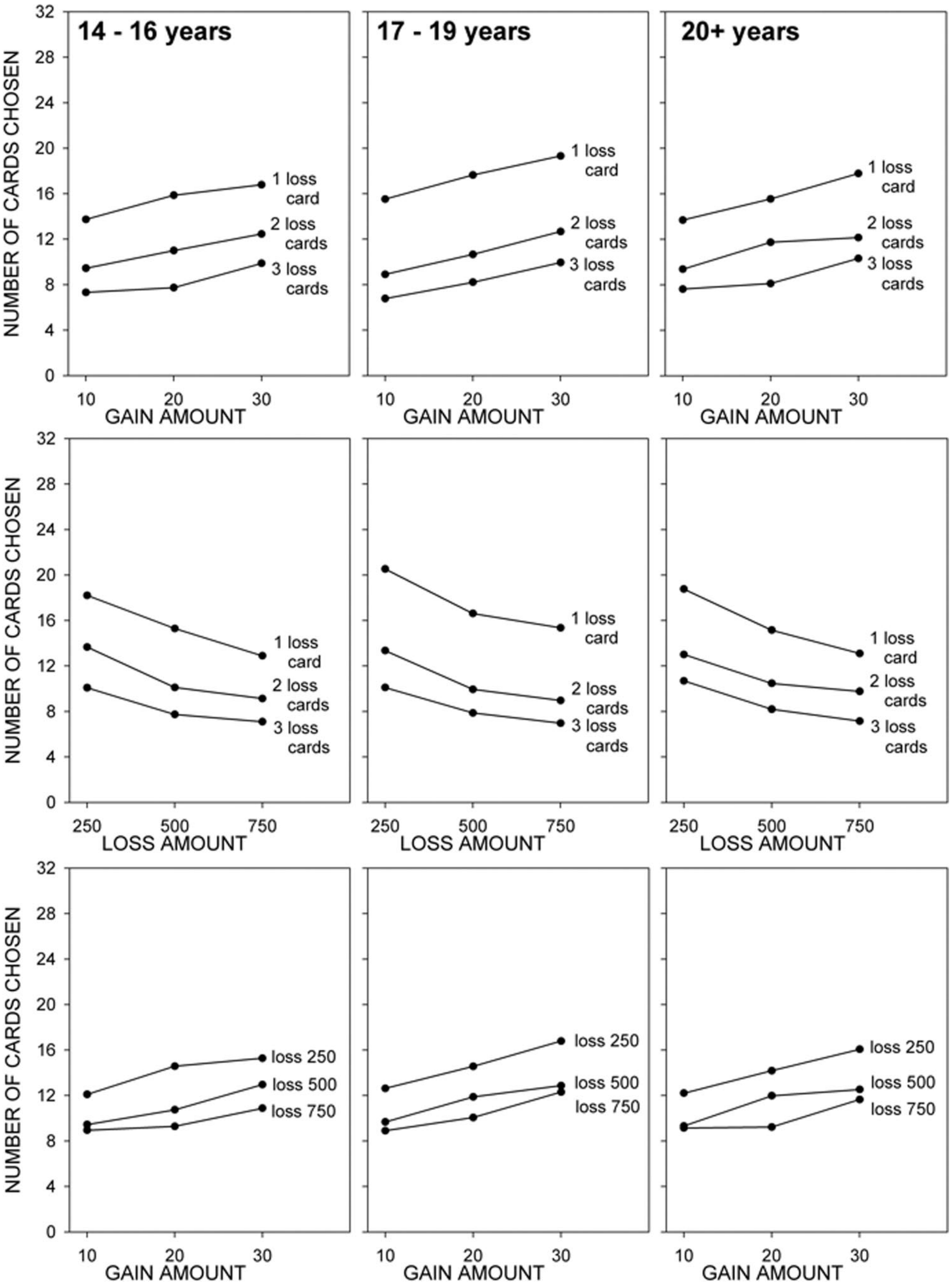

Figure 5. In Experiment 2, mean number of cards chosen dependent on the three independent factors and per age group. Each graph shows the integration of two factors collapsed over the respective third factor. Top row: gain amount and probability; middle row: loss amount and probability; bottom row: gain amount and loss amount. Left column: 14- to 16-year-olds; middle column: 17- to 19-year-olds; right column: 20-year-olds and older.

Procedure

Because the tests assessing executive functions had to be administered individually, all data were collected in single-participant sessions. The card game was always administered after the executive functions tests to avoid potential influence of hot or cold card game condition on test performance. Other than that, the procedures were the same as in the previous experiments.

Design and Stimuli

The hot CCT was the same as described in Experiment 1 except that instructions were given by the experimenter, as in Experiment

2. The cold CCT was the same as in Experiment 2 except that, to increase parallelism to the hot version, the 9 "loss trials" were added to the 54 experimental trials.[16] Executive functions were assessed with the Key Search Task, the Zoo Map Test, the Water Test (all from the BADS–C; Emslie et al., 2003), and the Similarities Task (from the WISC–III; Wechsler, 1991). Working memory span was assessed with the digit span forward (information storage) and backward test (information storage and manipulation) from the WISC–III.

Results

Risk Taking

Effects of age on risk taking. As shown in Figure 2 (right panel), in the hot condition adolescents turned over more cards than did adults, replicating the findings from Experiment 1, $F(1, 62) = 6.49$, $p < .05$, $\eta^2 = .10$. In the cold condition, we found no significant effect of age group, replicating the findings from Experiment 2, $F(1, 72) = 0.53$, $p = .47$, $\eta^2 < .007$.

"Rigged-feedback" explanation of hot CCT results. Participants' answer to the item "I have the impression the card game was rigged," given on a rating scale with values ranging from 1 to 100, did not differ by age group, $t(61) = 0.34$, $p = .73$, and ratings were below 50, indicating disagreement rather than agreement ($M = 38.37$, $SE = 4.40$). In separate analyses, we excluded participants who gave answers greater than 50, 30, 20, and 10, indicating different degrees of suspicion that the card game was rigged. Irrespective of the exclusion criterion, the age differences in risk taking remained the same, with adolescents turning over 22 to 23 cards and adults turning over 16 to 17 cards on average. We take this as evidence that the age differences in the hot CCT were not caused by adolescents noting more often than adults the difference between the stated and the true probability of encountering a loss card.

Information Use

The results on information use, which mostly replicated the results from Experiments 1 and 2, can be found in Table 3 and Figure 6. In the hot CCT, adolescents took into account only the factor probability, whereas adults took into account all three factors, indicating increasing complexity of information use with age in the hot CCT. In the cold CCT, the results from Experiment 2 were partly replicated: Adolescents took into account the factors probability and loss amount (but not the factor gain amount, as they did in Experiment 2), whereas adults took into account all three factors, as in Experiment 2. That is, in contrast to Experiment 2, we found a difference in information use between adolescents and adults. However, as in Experiment 2, adolescents' information use in the cold condition was again more complex than in the hot condition. Further, age differences were smaller in the cold than in the hot condition, replicating another central aspect of the previous results.

Complexity of information use, derived from the individual-subject level ANOVAs, was higher in the cold compared to the hot condition and in adults compared to adolescents, $F(1, 134) = 11.19$, $p < .05$, $\eta^2 = .08$; $F(1, 134) = 71.74$, $p < .001$, $\eta^2 = .35$, respectively. There was also a significant interaction of Condition × Age Group, $F(1, 134) = 6.34$, $p < .05$, $\eta^2 = .05$. As shown in Figure 4 (right panel), complexity of information use increased with age in both the hot and cold CCT. This unexpected result stands in contrast to Experiments 1 and 2 where we found age effects only in the hot but not the cold condition. Overall, complexity was lower in the youngest age groups of Experiment 3 than in both Experiments 1 and 2. One might suspect that this was due to the inclusion of 13-year-olds in the sample, which resulted in an overall younger adolescent group than in the other two experiments. However, within the adolescent age group, complexity of information use did not increase but rather decreased with age ($r = -.34$, $p < .05$). We suggest possible explanations in the *Discussion*.

Self-Reported Decision Strategies

Affect-based strategy use was assessed with the item "I solved the task on a gut level," and deliberative strategy use with the item "I tried to solve the task mathematically." Self-reported decision-related emotional arousal was assessed with the item "At times when I was deciding what to do, I felt some excitement." As predicted, we found greater affect-based strategy use and emotional arousal in the hot than in the cold CCT. Deliberative strategy use was greater in the cold than the hot CCT: gut level, $t(135) = 1.71$, $p < .05$; excitement, $t(134) = 1.88$, $p < .05$; mathematically, $t(135) = -2.85$, $p < .01$, all one-tailed (see Figure 7).

Risk Taking, Information Use, Executive Functioning, and Working Memory

Risk taking and information use. Replicating Experiments 1 and 2, the correlation between information-use complexity and risk taking was significantly negative only in the hot but not the cold condition ($r = -.56$, $p < .001$; $r = -.12$, $p = .31$, respectively). Controlling for age did not alter the correlations substantially (hot, $r = -.50$, $p < .001$; cold, $r = -.07$, $p = .62$).

Executive functioning, risk taking, and information use. Table 4 shows that the four measures of executive functioning assessed different aspects of executive functions, as the correlations between them were low and mostly nonsignificant (shown separately for participants in the hot and the cold conditions). As also shown in Table 4, executive functioning correlated with decision behavior more strongly in the cold than in the hot condition and correlated with information use more strongly than with risk taking: Out of the four measures of executive functioning, zero were significantly correlated with hot risk taking, one with hot information use, one with cold risk taking, and three with cold information use.

"Learning-demands" explanation: Working memory, risk taking, and information use. As expected, we found greater digit spans for adults than for adolescents only in the backward but not in the forward test. Adolescents' backward digit span was on average 5.13 ($SE = 0.22$) and adults' was 7.46 ($SE = 0.23$), $F(1, 140) = 52.167$, $p < .001$, $\eta^2 = .271$. In contrast, adolescents' forward digit span was on average 8.31 ($SE = 0.21$) and adults'

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[16] Because no feedback was provided until the end of the session in the cold version, the only effect of the 9 additional loss trials in the cold card game was to increase the number of trials from 54 to 63. In both CCT versions, only the 54 experimental trials were analyzed.

Table 3

Subsample Sizes, Mean Number of Cards Turned Over, and Information Use for the Two Age Groups in the Hot and Cold Conditions of Experiment 3

	Hot		Cold	
Measure and variable	13–16 years old	≥20 years old	13–16 years old	≥20 years old
Subsample size, *n*	31	34	41	32
Number of cards chosen				
M	24.47	19.91	13.77	13.02
SE	1.29	1.25	0.70	0.78
Probability (P)				
F	29.43^{***}	90.68^{***}	10.48^{***}	120.14^{***}
η^2	.50	.73	.21	.80
Gain amount (G)				
F	$2.96^{\dagger}$	19.85^{***}	$2.83^{\dagger}$	39.68^{***}
η^2	.09	.38	.07	.56
Loss amount (L)				
F	1.79	30.20^{***}	9.03^{***}	59.59^{***}
η^2	.06	.48	.18	.66
P × G				
F	1.38	3.63^{**}	1.33	4.14^{**}
η^2	.04	.10	.03	.12
P × L				
F	1.34	2.66^{*}	0.26	5.45^{***}
η^2	.04	.08	.006	.15
G × L				
F	0.78	0.96	4.76^{**}	5.39^{***}
η^2	.03	.03	.11	.15
P × G × L				
F	$1.96^{\dagger}$	0.62	1.16	6.19^{***}
η^2	.06	.02	.03	.17

$^{\dagger}p < .10$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

was 7.99 (*SE* = 0.22), $F(1, 140) = 1.097$, $p = .297$, $\eta^2 = .008$. Forward digit span was thereby ruled out as a potential explanation for age differences in risk taking and not used in further analyses.

In the cold condition, across both age groups, backward digit span was significantly positively correlated with information use but uncorrelated with risk taking (information use, $r = .31$, $p < .01$; risk taking, $r = -.01$, $p = .93$). In the hot condition, across both age groups, backward digit span was significantly positively correlated with information use and significantly negatively correlated with risk taking (information use, $r = .41$, $p < .01$; risk taking, $r = -.41$, $p < .01$). The alternative hypothesis that adolescents' risk taking was caused by overtaxing their working memory would predict that the association between risk taking and digit span should be stronger for adolescents than for adults. However, analyzing the correlations by age group revealed exactly the opposite result. The initial correlations over both age groups had been driven only by the adult subsample. Correlations in the adult subsample were the same as before (information use, $r = .43$, $p < .05$; risk taking, $r = -.44$, $p < .05$). In contrast, correlations in the adolescent subsample were both nonsignificant—close to zero for risk taking and even slightly negative for information use (information use, $r = -.22$, $p = .23$; risk taking, $r = -.01$, $p = .96$). This result cannot be attributed to a lack of variability in the measures in the adolescent subsample, as variability was virtually identical in both age groups. In summary, although there was some evidence that working memory span might influence performance in both card game versions, there was no evidence that adolescents' risk taking in the hot card game was caused by overtaxing their working memory capacity. On the contrary, the result that backward digit span correlates with adults' but not adolescents' risk taking in the hot CCT can be seen as further evidence that in adolescents the affective system is the main neural basis of decision making in the hot CCT, whereas that in adults deliberative processes are more involved: If it is true that the deliberative system gets overridden by the affective system in adolescents, we would expect that backward digit span would play little role in influencing their decision making, as the backward digit span test (explicitly storing and manipulating meaningless numerical information) is a deliberative process, usually located in the dorsolateral prefrontal cortex, which has been identified as one key structure of the deliberative system.

Discussion

Experiment 3 replicated the main findings of Experiments 1 and 2, showing that increased adolescent risk taking was specific to the hot CCT. Further, we replicated that the association between risk taking and simplified information use was specific to the hot condition, consistent with a dual-system explanation. Our assumption of different involvement of affective versus deliberative processes in the hot and cold CCT was supported by self-reports of affect-based versus deliberative decision strategies and decision-related emotional arousal. In addition, measures of executive functioning predicted decision behavior more strongly in the cold than the hot condition: More specifically, in the hot condition, both risk taking and information use were mainly uncorrelated with

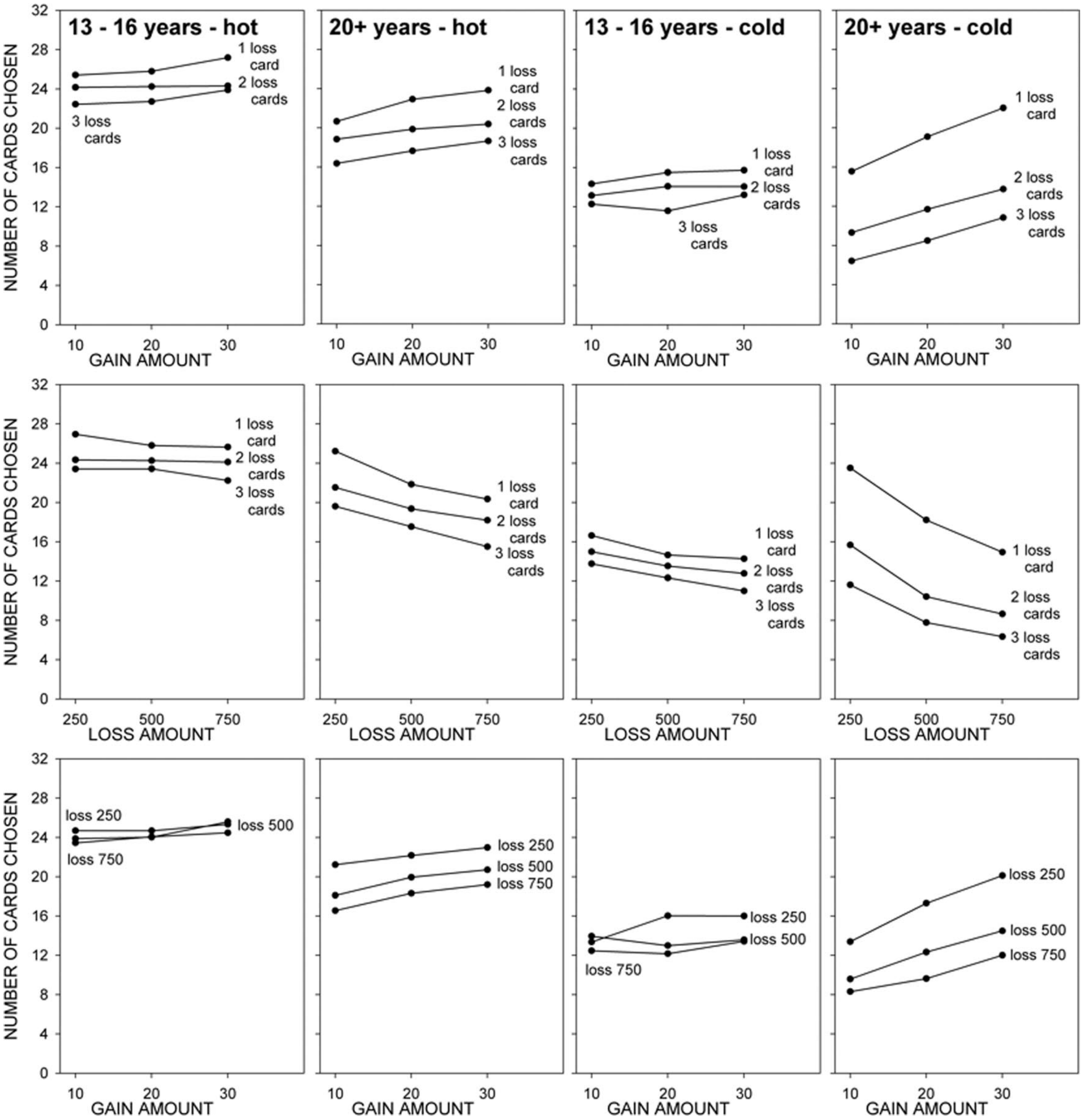

Figure 6. In Experiment 3, mean number of cards chosen dependent on the three factors probability, gain amount, and loss amount, depicted separately per card game condition (hot vs. cold) and per age group. Each graph shows the integration of two factors collapsed over the respective third factor. First column: adolescents, hot condition; second column: adults, hot condition; third column: adolescents, cold condition; fourth column: adults, cold condition. Within each column (from top to bottom panel): Gain Amount × Probability, Loss Amount × Probability, and Gain Amount × Loss Amount.

executive functioning, suggesting that executive functioning did not play an important role in the hot CCT. Different aspects of executive functions such as planning, reasoning, and problem solving influenced how much of the relevant information participants used in the cold CCT, consistent with the assumption that decisions here are based predominantly on deliberative processes. In contrast, risk taking in the cold CCT was only moderately influenced by executive functions, giving further evidence that risk taking and information-use complexity were independent aspects of decision making in the cold CCT. It appears that making “good” decisions (in the sense of taking into account all of the relevant information) does not necessarily lead to overall low risk-taking levels in the cold CCT (and indeed it should not, because in some trials it is good—in the sense of maximizing expected value—to take risks whereas in other trials it is good *not* to take risks). Taken together, the differential associations of executive functioning with the hot and the cold CCT are consistent with reports that decision-making tasks involving emotional processes are largely independent of executive functioning, whereas deliberate reasoning relies on executive functions (Turnbull et al., 2005).

The results of Experiment 3 argue against two alternative explanations for the age differences in risk taking in the hot CCT.

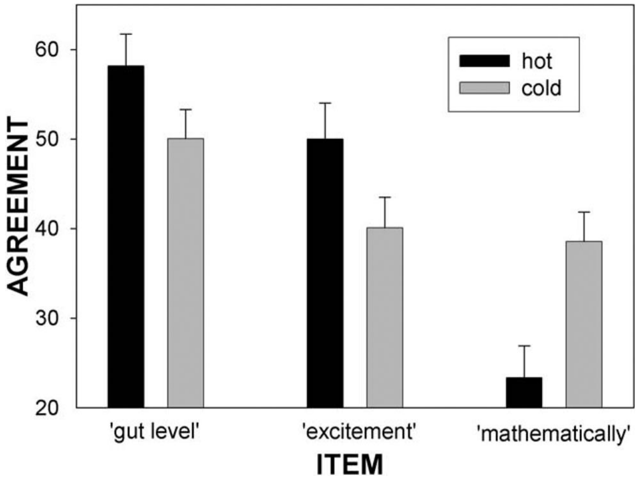

Figure 7. In Experiment 3, self-reported decision strategies by Columbia Card Task condition. Items "gut level" and "mathematically" assessed affect-based and deliberative strategy use, respectively. The item "excitement" assessed decision-related emotional arousal. Error bars denote ±1 *SE*.

The alternative "rigged-feedback" explanation was undermined because we found no age differences in suspicion that the hot CCT might have been rigged. Excluding participants on the basis of their suspicion also did not alter the observed age differences. The alternative "learning-demands" explanation was undermined because we found working memory capacity to be uncorrelated with risk taking and information use in the adolescent sample, making it rather unlikely that adolescent risk taking in the hot CCT was caused by limitations of their working memory.

An unexpected result of Experiment 3, different from the results of Experiment 2, was the age difference in information use in the cold CCT. This difference was smaller in the group analysis compared to the individual-level information-use measure, suggesting that "noisy" data at the individual level might have contributed to this result. If the young adolescents were somewhat inconsistent in their choices, the individual-level ANOVAs might have lacked power to detect their strategies. At the group level, aggregation across participants might have reduced the noise in the data and therefore resulted in smaller age differences in information use. Another possibility is that deliberative reasoning capabilities were not yet at a mature level in the adolescent age group. As we mentioned before, studies have shown that logical reasoning abilities are basically fully developed by age 16 (Casey et al., 2005; Keating, 2004; Kuhn, 2006). In Experiment 3, the adolescent age group consisted of 13- to 16-year-olds; accordingly, these logical reasoning abilities might have not yet been fully matured. This could have led to the relatively low levels of complexity of information use in the cold CCT. However, even under these circumstances adolescents' low levels of complexity of information use did not lead to increased risk taking in the cold CCT. This can seen as even stronger evidence that adolescent risk taking cannot be explained by more general cognitive deficits. To the contrary, it appears that in the cold CCT risk taking and information use are two independent aspects of decision making.

Experiment 4

Our purpose in Experiment 4 was to assess the differential involvement of affective processing in the hot versus the cold CCT by recording electrodermal activity (EDA) while respondents played one of the two versions of the card game. Because we assumed that the hot CCT triggered more affective information processing, we hypothesized the following results: (a) a higher level of emotional arousal while playing the hot compared to the cold CCT; (b) an increased level of emotional arousal while making decisions compared to baseline in the hot CCT; and (c) no increase in emotional arousal from baseline in the cold CCT.

Method

Participants

Because the sole purpose of Experiment 4 was to perform a hot–cold manipulation check, we did not investigate different age groups but had only a hot and a cold condition, with 10 participants in each group (respondents were aged 18–46; mean ages were 22.8 and 24.4 years in the hot and cold conditions, respectively; 8 women and 2 men in each condition). Participants were students and staff at Columbia University and were recruited via flyers, a posting on an internal Columbia University research list, and word-of-mouth.

Table 4
Partial Correlations of Risk-Taking Level, Complexity of Information Use, and the Four Executive Functioning Tasks for the Hot and Cold Conditions in Experiment 3

	Risk taking		Information use		Key Search Task		Zoo Map Test		Similarities Task		Water Test	
Measure	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
Risk taking	—	—	−.50***	−.07	−.13	−.18	−.07	−.21†	−.24†	−.04	−.04	−.24*
Information use			—	—	.03	.34**	.16	.29**	.28*	.51***	.12	.22†
Key Search Task					—	—	.20	.07	.30*	.17	.05	−.01
Zoo Map Test							—	—	.07	.15	.02	−.07
Similarities Task									—	—	.14	.04
Water Test											—	—

Note. Age was controlled for when calculating partial correlations.
† $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

Procedure

Participants were first given an explanation about the physiological measurement process and then prepared for the EDA measurement.[17] Next, participants received instructions about the card game as in the previous experiments. Participants then completed either the hot or the cold CCT. Participants were tested individually in the laboratory.

Custom-made MATLAB scripts were used to compute skin conductance response (SCR) magnitudes (standardized per second) from raw EDA data, indicative of emotional arousal (Boucsein, 1992). Each SCR data set was divided in two stages: a decision phase (from the start of the first trial to the end of the last trial; on average 9 min) and a baseline (from the start to the end of the questionnaire that followed the card game; on average 2 min).

Results

A repeated-measures ANOVA with stage (decision phase, baseline) as a within-subject factor, condition (hot, cold) as a between-subjects factor, and SCR magnitude (area under the curve, standardized per second) as a dependent variable indicated significant effects for stage, condition, and Stage × Condition, $F(1, 18) = 12.29$, $p < .01$, $\eta^2 = .41$; $F(1, 18) = 9.11$, $p < .01$, $\eta^2 = .34$; $F(1, 18) = 8.10$, $p < .05$, $\eta^2 = .31$, respectively.[18] Consistent with our hypotheses, two univariate ANOVAs comparing each stage across conditions revealed that the levels of emotional arousal differed between the hot and the cold conditions only during the decision phase (see Figure 8): decision phase, $F(1, 18) = 9.83$, $p < .01$, $\eta^2 = .35$; baseline, $F(1, 18) = 2.57$, $p = .13$, $\eta^2 = .13$; and the increase from baseline was significant only in the hot but not the cold CCT, $F(1, 9) = 11.22$, $p < .01$, $\eta^2 = .55$; $F(1, 9) = 1.07$, $p = .33$, $\eta^2 = .11$, respectively.

Discussion

The results of Experiment 4 further support the differential involvement of affective processes in the two versions of the CCT. As hypothesized, increase in emotional arousal was specific to the decision phase in the hot CCT. Emotional arousal differed between conditions only during the decision phase but not during the baseline, and the increase in emotional arousal from baseline was significant only in the hot but not the cold CCT.

General Discussion

We investigated the role of affective and deliberative processes in risk taking and underlying information use in younger and older adolescents (13–16 and 17–19 years) compared to adults (20 years and older). On the basis of the results of developmental patterns of everyday-life risk-taking behaviors and a dual-system framework, we predicted increased risk taking for adolescents in the hot, but not the cold, version of a new risky decision-making task, the Columbia Card Task (CCT). Dual-system models of decision making (Cohen, 2005; McClure et al., 2004) imply that adolescent risk taking is caused by the relative dominance of affective processes over deliberative processes in situations in which the affective system is sufficiently triggered (Casey et al., 2008; Steinberg, 2008). Under relatively affect-free conditions, in contrast, no age differences in risk taking between adolescents and adults were predicted.

Differential Involvement of Affective Versus Deliberative Processes in Hot and Cold CCT

Our two versions of the CCT were designed to trigger relatively stronger affective processes in the hot CCT and relatively stronger deliberative processes in the cold CCT. Presumably, for most participants, both kinds of decision processes were involved in both CCT versions. However, the hot CCT elicited higher emotional arousal, as indexed by EDA, compared to the cold CCT and to baseline. Manipulation checks and correlations between individual differences measures and the two versions of the CCT suggest that we succeeded in triggering substantially differential involvement of affective versus deliberative processes. Risk taking in the hot CCT, but not the cold, was positively correlated with the motivational–affective construct need-for-arousal, consistent with our hypothesis that risk taking in the hot CCT was based on affective processes. Information use in the cold CCT was predicted by several tasks assessing higher order executive functions such as planning, problem solving, and reasoning, whereas risk taking in the cold CCT was less influenced than information use. Executive functions are localized in prefrontal brain areas associated with the deliberative cognitive-control network, consistent with our assumption that the cold CCT version relied more on deliberative processes (e.g., Brand, Recknor, Grabenhorst, & Bechara, 2007; Turnbull et al., 2005). Self-reports about decision strategies (affect-based and deliberative) and emotional arousal when making decisions corroborated these indications of differential involvement of affective versus deliberative decision processes in the hot and cold CCT.

When comparing the average number of cards turned over in Experiments 1 and 2, it is obvious that far fewer cards were chosen in the cold condition. Comparing participants' performance directly between conditions is problematic because the hot and cold CCT versions differed on additional dimensions, not just the hot–cold dimension. It is likely that far more cards were turned over in the hot CCT due to the rigged feedback in that condition, but this would appear to be a main effect and not an explanation of the increased risk taking of adolescents in this condition. One could speculate that adolescents' risk taking might have been more strongly influenced by feedback (which was predominantly positive in the hot condition) than adults', consistent with Galvan et al.'s (2006, 2007) findings of increased reward sensitivity and its predictive power for everyday risk taking in adolescents. However, we found no evidence of differential learning effects in our data, and the pattern of age differences in risk taking in the hot CCT

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[17] See supplemental materials for details.

[18] Because, at least in the hot CCT, decision-related emotional arousal could also reflect feedback processing, we did the same analysis using only the first decision epoch in each CCT version (in the hot CCT, this was the time from starting the first trial to either clicking on the first card or taking no card at all; in the cold CCT it was the time from starting the first trial to choosing the number of cards in this trial). Accordingly, EDA was not influenced by feedback. The results were virtually identical: stage, $F(1, 18) = 16.66$, $p < .01$, $\eta^2 = .48$; condition, $F(1, 18) = 6.45$, $p < .05$, $\eta^2 = .26$; Stage × Condition, $F(1, 18) = 4.70$, $p < .05$, $\eta^2 = .21$.

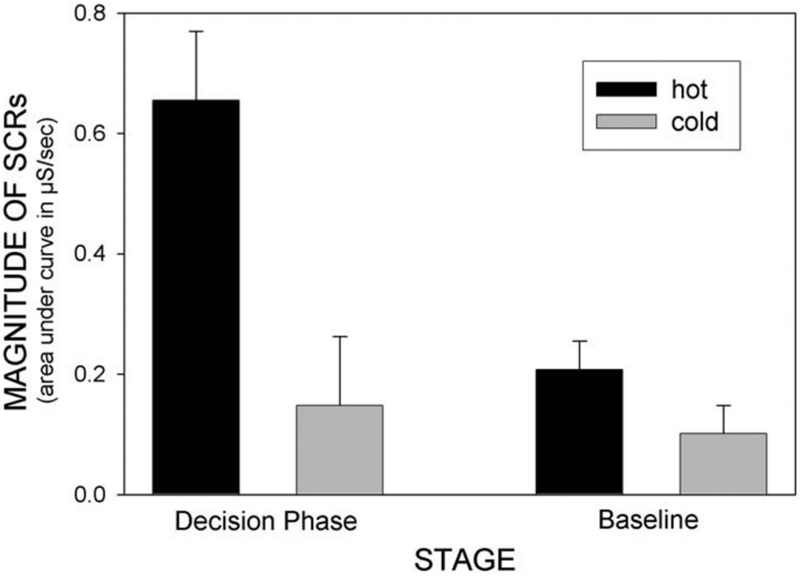

Figure 8. In Experiment 4, emotional arousal, assessed by skin conductance response (SCR) magnitude (standardized per second) as a function of condition and experimental stage. Emotional arousal differed significantly between hot and cold Columbia Card Task (CCT) during decision phase but not during baseline; increase from baseline was significant in the hot but not the cold CCT. Error bars denote ±1 *SE*.

held even when we restricted respondents to those who did not take large numbers of cards.

Age Differences

Risk taking. Consistent with predictions from dual-system models, we found increased risk taking in adolescents in the hot but not the cold CCT. Further, information use was associated with risk taking only in the hot but not the cold condition, with greater risk taking being associated with using less of the relevant information. These results contradict more traditional cognitive–developmental explanations of adolescent risk taking in the tradition of Piaget, which argue that adolescent risk taking is caused by immaturities in cognitive skills relevant for decision making (Baird & Fugelsang, 2004; Boyer, 2006; Reyna & Farley, 2006). In the traditional view, cognitive deficits are assumed to lead to suboptimal performance in processes such as identifying, representing, weighting, or integrating risk-relevant information. This in turn can lead to increased risk taking, for example, when potential losses or the probability of their occurrence are not considered appropriately. However, on the basis of such an explanation, increased adolescent risk taking would have been expected in both affect-charged and affect-free conditions. In addition, simplified information use would have been expected to predict risk taking in both conditions. Contrary to these predictions, no age differences were observed in risk taking in the cold CCT, nor did information-use complexity predict risk taking in the cold CCT. This dissociation of hot and cold CCT findings is consistent with a dual-system explanation. The results were also partly consistent with fuzzy-trace theory: The "reactive route" (e.g., Rivers et al., 2008) of risk taking predicts, similarly to the dual-system account, that a lack of inhibition in adolescents can lead to increased risk taking in situations of heightened emotional arousal. Cold CCT results are less clearly reconciled with fuzzy-trace theory, as this theory predicts increased reliance on verbatim-based calculus in adolescents than in adults and a positive correlation of information use and risk taking. We did not observe evidence for either prediction. However, we have to note that testing fuzzy-trace theory was not a main objective of the article, as the article was concerned primarily with testing traditional cognitive–developmental and dual-system accounts of adolescent risk taking. Furthermore, the specific predictions of fuzzy-trace theory depend critically on task characteristics, and therefore our results have to be interpreted with caution with respect to fuzzy-trace theory.

Testing of alternative explanations. The two versions of the CCT differed not only in the relative involvement of affective versus deliberative processes. First, because the hot CCT was a dynamic decision-making task but the cold CCT was a static task, one could argue that the hot version was more taxing on working memory than the cold CCT. However, we found that working memory did not correlate with adolescents' risk taking or information use in the hot CCT. This makes it rather unlikely that adolescents' increased risk taking in the hot CCT, compared to adults', was caused by adolescents' smaller working memory spans. Second, in order to maximize assessment of *voluntary* stopping in the CCT trials (as opposed to involuntary stopping by turning over a loss card), we fixed the feedback in the hot CCT. This increased comparability to the cold CCT, because stopping in both CCT versions was basically always voluntary (except for the "loss trials" that were not included in analyses). Consequentially, the stated probability distribution differed from the experienced one in the hot CCT. We found no evidence, however, for the hypothesis that adolescents might have been better at discovering this discrepancy, thus explaining their greater risk taking and simplified information use in the hot CCT. Participants' judgments showed that they did not view the hot CCT as rigged, on average, with no greater suspicion among adolescents than adults. Excluding participants with higher than minimal levels of suspicion did not alter the observed age differences in CCT performance nor did excluding participants with the highest levels of risk taking (i.e., those most likely to have discovered the discrepancy). Lastly, a comparison of risk taking during the two identical blocks of trials during the hot CCT showed no evidence that adolescents discovered the discrepancy during playing the game; that is, they did not take more cards in the second compared to the first block.

Information use. Age differences in information use were apparent in the hot CCT. Adults took into account all three factors, whereas adolescents appeared to take into account only the factor probability. The factor gain amount had a comparatively small effect and the factor loss amount had virtually no effect on adolescents' decisions in the hot CCT. This finding is consistent with Huizenga, Crone, and Jansen (2007), who found that adolescents are more sensitive to the frequency than the magnitude of reward and punishment. In the hot CCT, risk taking was negatively correlated with information use. This is consistent with the observation that in everyday life, adolescent risk taking is often based on poor or even "absent" decision making (Reyna & Farley, 2006; Steinberg, 2004). Information-use complexity in the cold CCT was the same across age groups in Experiment 2, but not in Experiment 3, where information-use complexity increased with age. Although the reasons for this are not entirely clear (see *Discussion* of Experiment 3), it is important to note that even under these circumstances, information-use complexity did not predict risk taking in the cold CCT, undermining traditional cognitive–developmental explanations of adolescent risk taking.

Overall, risk taking differed less across conditions in adults than in adolescents, consistent with the assumption that adults' decision making in our study was more balanced with respect to affective and deliberative processes across conditions. This difference between adolescents' affect-based versus deliberative decision making matches the gap between adolescents' reasoning competence and actual performance that has been reported elsewhere (Crone & van der Molen, 2004; Hooper, Luciana, Conklin, & Yarger, 2004; Reyna & Farley, 2006).

Comparison of CCT to Other Risky Decision-Making Tasks

The basic idea behind the CCT (especially its hot version) is that the riskiness of acting increases dynamically with each additional action taken. Slovic (1966) was the first to use a dynamic risk-taking task to investigate children's risk-taking propensity in an experimental study. The same task was more recently shown to predict children's risky behavior in a naturalistic traffic situation (Hoffrage, Weber, Hertwig, & Chase, 2003). Other tasks have used the same basic idea of dynamic increases in riskiness over time, such as a task used to investigate risk taking in psychopaths (Siegel, 1978), the Balloon Analogue Risk Task (BART; Lejuez et al., 2002), and its variant, the Angling Risk Task (Pleskac, 2008). Although the BART and the CCT share several characteristics, there are also some important differences: In contrast to the BART, in the CCT probabilities do not have to be learned but are explicitly stated. The CCT varies not only probability but also gain and loss magnitudes, and it unconfounds probability and magnitude of a loss. Moreover, in the BART, even adolescents typically do not take enough risks (i.e., they are below the optimal number of puffs), whereas in our task, adolescents (specifically in the hot CCT) were typically above the optimal level of risk taking. Further, in contrast to the CCT, the BART has (at least so far) never shown the typical developmental trajectory of an adolescent peak in risk taking. Nevertheless, several studies have shown the validity of the BART by predicting real-world risk taking in adolescents, healthy adults, and users of licit and illicit substances (e.g., Lejuez, Aklin, Jones, et al., 2003; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Lejuez, Simmons, Aklin, Daughters, & Dvir, 2004). Our measure of need-for-arousal included items asking about everyday risk-taking behaviors, and accordingly, the positive correlation of need-for-arousal and risk taking in the hot CCT could—with appropriate caution—be interpreted as preliminary evidence for the ecological validity of the hot CCT. However, clearly more work is needed, particularly with respect to risk taking in the cold CCT. It would be interesting to compare it with other "cold" tasks, such as choices between hypothetical lotteries without feedback and/or measures of deliberative everyday risk taking of a more static nature.

Other decision-making tasks operationalize risk-taking propensity as the number of risky choices in a series of binary choices between a relatively safe option and a more variable, risky option. Among these tasks are the Cambridge Gambling Task (CGT; Rogers et al., 1999), the Cups Task (Levin & Hart, 2003), the Game of Dice Task (GDT; e.g., Brand et al., 2005), and the risky decision-making task used by Reyna and Ellis (1994; Reyna, 1996). In both the CGT and the GDT, the advantageousness of choices (i.e., choosing the option with the higher expected value) is confounded with risk taking: The riskier option is characterized not only by a higher maximal payoff and a lower minimal payoff compared to the less risky option but also by a lower expected value compared to the less risky option. Accordingly, choosing the less risky option can be driven either by risk avoidance or by choosing the option with the higher expected value. Similarly, disadvantageous choices can be driven by greater risk seeking, neglect of the involved probabilities, or increased reward sensitivity. A newer version of the Cups Task (see Levin, Weller, Pederson, & Harshman, 2007) disentangled advantageousness of choice and risk seeking by incorporating different types of trials into the task, some trials in which the two choice options have the same expected value, some in which the risky option has a higher expected value, and some in which the safe option has a higher expected value. Reyna and Ellis avoided confounding risk and reward magnitude in their task by using a full factorial design that actually crossed these two dimensions, similarly to our CCT. In addition, this study was the first to document developmental differences in risk taking under well-controlled laboratory conditions. However, as the safe and the risky options had the same expected value, it is accordingly not possible to test advantageousness of choice with this task.

The most widely used decision-making task is the Iowa Gambling Task (IGT; e.g., Bechara et al., 1994). Findings with the IGT have led to the development of the somatic marker hypothesis (SMH; Bechara & Damasio, 2005), and the task has been widely used in different subject populations, including children (e.g., Kerr & Zelazo, 2004), adolescents (e.g., Hooper et al., 2004), and adults with or without brain lesions or mental disorders (e.g., Goudriaan, Oosterlaan, de Beurs, & van den Brink, 2005; Stout, Rock, Campbell, Busemeyer, & Finn, 2005). However, both the task and the SMH have been substantially criticized and challenged (for a recent review, see Dunn, Dalgleish, & Lawrence, 2006). For example, Brand, Labudda, and Markowitsch (2006) noted that the IGT confounded decisions under ambiguity and under risk, gradually switching from the former to the latter during an individual's testing session. Others have directed their criticisms more toward the underlying SMH. For example, Maia and McClelland (2004, 2005) were able to show that participants have explicit knowledge about the task contingencies much earlier than previously reported, questioning the necessity of somatic markers in making good decisions.

Compared to these risky decision-making tasks, the CCT has two advantages. First, it assesses not only risk taking but also complexity of information use. With the CCT, we are able to assess at the individual-subject level which of three important risk-relevant factors (probability, gain amount, and loss amount) have influenced a participant's choices. Second, the two versions of the CCT allow an investigation of risky decision making under two different conditions, one in which the decisions are made based mainly on deliberative cognitive processes and one in which affective processes are substantially involved. The two CCT versions were designed to mimic two typical everyday-life decision situations: making a decision in a calm and "cool" mode (such as sitting at a desk and choosing between Insurance A or B) or making a more affect-charged decision (such as deciding whether or not to have additional drinks during an evening of bar hopping with friends). Future studies should compare the two versions of the CCT with some of the abovementioned tasks, as well as measures of different aspects of everyday risk-taking behavior in a within-subject design, to investigate commonalities and differences and differential predictive power of these methodological approaches.

Summary

The current article, to our knowledge, is the first to investigate dual-system explanations of adolescent risk taking by comparing participants' behavior in two versions of the same risky decision-making task that differ in the involvement of affective and deliberative processes. Considering the results of our four experiments in combination, we think that our findings are best (and well) predicted by a dual-system model of adolescent risk taking. Alternative explanations fare less well. Particularly, more traditional cognitive–developmental theories would not predict increased risk taking associated with simplified information use to be specific to the hot CCT. With respect to fuzzy-trace theory (Reyna & Brainerd, 1995), we see the evidence as mixed: Results with the hot CCT are consistent with fuzzy trace's "reactive route" of risk taking (Rivers et al., 2008). Results with the cold CCT appear to be less consistent with fuzzy trace's "reasoned route," as we observed neither an indication of overuse of deliberative strategies in adolescents' cold risky decision making nor an association between more deliberative strategies and increased risk taking in the cold CCT. However, the present study was not designed with the main objective of testing fuzzy-trace theory. It is very likely that—at least—two different mechanisms can lead to increased risk taking in adolescents. First, as observed in our study, risk taking occurs when the impulse from the affective system overrides deliberative impulses to avoid risk. Second, relying too much on deliberation can lead to increased risk taking in adolescents in situations in which adults would never even consider the pros and cons but instinctively would avoid a risk because of a strong fear response (e.g., when choosing whether to play Russian roulette).

There is still a lack of controlled studies looking into the mechanism underlying developmental differences in risky decision making. One promising approach would be to further investigate spontaneously occurring individual differences, for example in people's reliance on affective versus deliberative strategies, and how these individual differences are associated with differences in risk taking and information use. Also, future studies should focus more directly on the interplay and competition between neural systems in risky choice. This could be done, for example, by investigating the role of inhibitory control on risky choices in different conditions and age groups. Even more direct evidence about the interplay of different neural systems would come from an fMRI examination of brain activity during risky decisions in different age groups in hot and cold conditions. Such studies are currently underway in our laboratory, and we hope that they will shed additional light on the processes involved in adolescent risk taking and the developmental transitions from childhood to adolescence and adulthood.

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