Gamblers at any Chance?

On the Influence of Task Context and Individual Differences in Adolescent Risky Decision-Making

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Contents

Summary

Models on adolescent development assume that hypersensitivity to rewarding or socioemotionally arousing situations encounter a protracted development of cognitive control, accounting for imprudent decisions and maladaptive outcomes in adolescence (for a review, see Shulman et al., 2016). Thereby, various methods and study designs are used to study adolescent development. The present thesis aimed at investigating the influence of contextual moderators and individual differences in cognitive and socioemotional functioning on adolescents’ reactions in brain and behavior, specifically, during risky decision-making.

The thesis is built upon two publications and a manuscript reporting on the influence of different kinds of incentives on age-related differences in reward-processing and the influence of task context as well as individual differences in cognitive and socioemotional functioning on risky decision-making in adolescence. In *Paper I,* previous studies investigating developmental differences in goal-directed behavior, learning, and choice behavior in adolescence are reviewed and compared based on the type of incentives used. The review reveals, that there is no adolescent-specific reactivity to positive and negative incentives in most tasks. Only when highly salient cues are at stake adolescents engage in heightened activity in reward-related brain regions while on the behavioral level most adolescent-specific effects concern risky choices in arousing task settings.

As such, *Paper II* aims at comparing developmental trajectories in choice behavior between task contexts that are designed to be differentially socioemotionally arousing and appropriate to study risky choices also in a young sample ranging from pre to late adolescence. The findings reveal divergent developmental trajectories between the task contexts, with middle adolescents engaging in more risks under uncertainty than when risks are known. Other comparisons, however, do not reflect adolescent-specific effects, such as heightened risks in prospect to rewards than losses as the assumed hypersensitivity to positive

incentives in adolescence would suggest. Adolescents rather become increasingly risk-averse with age when gambling to minimize losses, suggesting more deliberate decisions. Individual differences in fluid intelligence account for the developmental changes in risky choices, while venturesome adolescents are more tolerant of engaging in risks with known probabilities for losses above age. Under time pressure, high impulsive and empathic adolescents are more likely to engage in risky choices when negative outcomes are less predictable.

Finally, *Manuscript I* provides evidence against the hypothesis that adolescents are not only more sensitive to positive rewards but also to social influences in risky decision-making, while the review of *Paper I* also reveals peer presence to predict more risky choices in adolescence than younger and older ages. The findings posit that adolescents are not riskier when under peer observation but the social condition moderates age differences in learning. All adolescents show adaptive risky choices, i.e. learn over the task and decrease risk following negative consequences. Middle to late adolescents generally perform better, irrespective of the peer observation condition, while younger ages show less adaption to previous experiences than older ages, specifically when observed. Individuals that report low resistance to peer influences are the only ones more likely to heighten risk-taking when observed.

In sum, the present thesis contributes to the understanding of when adolescents engage in motivated behavior, what are the characteristics that trigger them to engage in risks, and who are the adolescents that are willing to take these risks. Thereby, adolescents prove to be adaptive decision-makers in most situations and are more willing to explore unknown risks but not without deliberation. Some individuals might still be more inclined to act without thinking but a reduced reliance on cognitive control during motivated behavior does not seem to be an as universal developmental trend as some model perspectives would assume.

Zusammenfassung

Modelle bezüglich der Entwicklung im Jugendalter gehen von einer Hypersensitiviät gegenüber Belohnungen oder sozialemotional erregenden Situationen in dieser Zeit aus. Gegeben der sich nur graduell im Jugendalter entwickelnden kognitiven Kontrolle sollen Jugendliche deswegen zu mehr maladaptivem und unüberlegtem Verhalten tendieren (für eine Übersicht, siehe Shulman et al., 2016). Dabei werden sehr unterschiedliche Methoden und Studiendesigns genutzt, um die Entwicklung von Jugendlichen zu untersuchen. Die vorliegende Dissertation zielte darauf ab, den Einfluss von Kontextmoderatoren und individuellen Unterschieden in kognitiver und sozioemotionaler Funktionalität auf die altersbedingte Erregbarkeit von Gehirnaktivität und motiviertem Verhalten, insbesondere Risikoverhalten, zu untersuchen.

Die Arbeit basiert auf zwei Veröffentlichungen und einem Manuskript, die über den Einfluss verschiedener Arten von Anreizen auf altersbedingte Unterschiede in der Belohnungsverarbeitung, und den Einfluss des Aufgabenkontexts, sowie von individuellen Unterschieden in der kognitiven und sozioemotionalen Funktionsweise, auf riskante Entscheidungen im Jugendalter berichten. In *Paper I* werden Ergebnisse früherer Studien, die Entwicklungsunterschiede in Bezug auf zielgerichtetes Verhalten, Lernen und Entscheidungsverhalten im Jugendalter untersuchen, anhand der Art der verwendeten Anreize rezensiert und verglichen. Das Review zeigt, dass es bei den meisten Aufgaben keine jugendspezifische Reaktion auf positive und negative Anreize gibt. Nur wenn es sich um besonders saliente Hinweisreize handelt, üben Jugendliche eine erhöhte belohnungsbezogene Aktivität in betreffenden Hirnarealen aus, während auf der Verhaltensebene hauptsächlich Befunde zu Risikoentscheidungsverhalten jugendspezifische Effekte in aufregenden Situationen zeigen.

Daher zielt *Paper II* darauf ab, Entwicklungsverläufe im Auswahlverhalten zwischen Aufgabenkontexten zu vergleichen, die so konzipiert sind, dass sie unterschiedliche sozioemotionale Erregungen hervorrufen und geeignet sind, riskante Entscheidungen auch in einer jungen Stichprobe von Prä- bis später Adoleszenz zu untersuchen. Die Ergebnisse zeigen unterschiedliche Entwicklungsverläufe zwischen den Aufgabenkontexten, wobei mittlere Jugendliche unter Unsicherheit mehr Risiken eingehen als bei bekannten Risiken. Andere Vergleiche spiegeln jedoch keine jugendspezifischen Effekte wider, wie z. B. ein erhöhtes Risiko in Reaktion auf Belohnungen als Verluste, wie die von Entwicklungsmodellen angenommene Überempfindlichkeit gegenüber positiven Anreizen im Jugendalter nahelegen würde. Jugendliche zeigen sich mit zunehmendem Alter eher risikoscheu im Versuch Verluste zu minimieren was insgesamt auf überlegtere Entscheidungen hindeutet. Individuelle Unterschiede in der fluiden Intelligenz erklären dabei die entwicklungsbedingten Veränderungen in Entscheidungen unter bekannten Risiken, während wagemutige Adoleszente toleranter in Entscheidungen für Optionen mit bekannten negativen Konsequenzen sind. Unter Zeitdruck treffen hoch impulsive und einfühlsame Jugendliche eher riskante Entscheidungen, in Aufgaben in denen negative Ergebnisse weniger vorhersehbar sind.

Schließlich liefert *Manuskript I* Hinweise gegen die Hypothese, dass Jugendliche nicht nur empfindlicher auf positive Belohnungen, sondern auch auf soziale Einflüsse in riskanten Entscheidungen reagieren. Auch *Paper I* zeigte dabei, dass die Anwesenheit Gleichaltriger mehr Risikoentscheidungen in Jugendlichen veranlasst als in jüngeren oder älteren Altersgruppen. Die Ergebnisse zeigen, dass Jugendliche nicht risikoreicher reagieren wenn sie von einem Peer beobachtet werden, jedoch moderiert die Beobachtung durch einen Peer Altersunterschiede im Lernen. Alle Jugendlichen zeigen adaptive riskante Entscheidungen, d.h. lernen über die Aufgabe hinweg und verringern das Risiko nach negativen

Konsequenzen ihrer Entscheidungen. Jugendliche in mittleren und späten Entwicklungsstadien schneiden im Allgemeinen besser ab, unabhängig davon ob sie beobachtet werden oder nicht, während jüngere ihr Verhalten weniger an vorangegangene Erfahrungen anpassen als ältere wenn sie beobachtet werden. Adoleszente, die eine geringe Resistenz gegen Peer-Einflüsse berichten, sind die Einzigen, die das Risiko eher erhöhen, wenn sie beobachtet werden.

Zusammenfassend trägt die vorliegende Arbeit dazu bei, zu verstehen, wann Jugendliche sich auf motiviertes Verhalten einlassen, welche Merkmale sie zu Risiken veranlassen und wer die Jugendlichen sind, die bereit sind, diese Risiken einzugehen. Dabei erweisen sich Jugendliche in den meisten Situationen als anpassungsfähige Entscheidungsträger und sind eher bereit, unbekannte Risiken zu explorieren, jedoch nicht ohne dabei Nachzudenken. Eine Subgruppe Adoleszenter ist möglicherweise immer noch eher geneigt, ohne nachzudenken zu handeln, aber eine geringere Allokation kognitiver Kontrolle während motivierten Verhaltens scheint kein so universeller Entwicklungstrend zu sein, wie man es gegeben einiger Modellperspektiven annehmen würde.

List of Publications

This dissertation is based on two articles that were published as ‘original’ articles in international peer-reviewed journals and one unpublished manuscript. I am a collaborating author of Paper I and the first author of Paper II and Manuscript I. Other authors that contributed to the work are listed below. The published articles are presented in section ‘*II Original Research Articles’* and summarized in Part I of the dissertation under section *‘3. Overview of publications’*. Single paragraphs of the introduction and discussion include content similar to the published articles. In Part II of the dissertation, the unpublished manuscript is fully reported.

Paper I

Kray, J., Schmitt, H., Lorenz, C., & Ferdinand, N. K. (2018). The Influence of Different Kinds of Incentives on Decision-Making and Cognitive Control in Adolescent Development: A Review of Behavioral and Neuroscientific Studies. *Frontiers in Psychology, 9*(May), 0–21. https://doi.org/10.3389/fpsyg.2018.00768

The final publication is available at www.frontiersin.org.

Paper II

Lorenz, C., & Kray, J. (2019). Are Mid-Adolescents Prone to Risky Decisions? The Influence of Task Setting and Individual Differences in Temperament. *Frontiers in Psychology, 10*(July), 1–16. https://doi.org/10.3389/fpsyg.2019.01497

The final publication is available at www.frontiersin.org

Manuscript I

Lorenz, C., & Kray, J. (2020). *Developmental Differences in Adjustment to Risk Uncertainty Under Peer Observation During Adolescence.* Unpublished article.

List of Figures

PART I

PART II

List of Tables

PART II

List of Abbreviations

BART	Balloon Analogue Risk Task
BAS	Behavioral Approach System
EEG	Electroencephalography
e.g.	For example
ERP	Event-Related Potential
i.e.	That Is
RPI	Resistance to Peer Influence Scale
THT	Treasure Hunting Task

I. A Period of Heightened Risks and Chances

“By definition, a transition period such as adolescence is disequilibrating and disrupting and thus replete with opportunities that are both dangerous and growth-enhancing” (Baumrind, 1987, p. 98, as cited in Spear, 2000).

Historically, adolescence is a controversial topic, both in its meaning for society and psychological development. Already ancient Greek philosophers, as well as more recent scholars, emphasized the notion of imprudent behavior in adolescence under the influence of ‘raging hormones’. Nonetheless, adolescence is a relatively new term. In post-industrial urban societies, laws governing age and employment were increasingly prosecuted to protect children from child labor. With longer times dedicated to occupational training following childhood, Hall (1904) dedicated himself to the investigation of this period of life and paved the way for the adaption of the term adolescence, also in developmental research. Until today, the offset of adolescence is linked to rituals and age limits that indicate full maturity, like the age of consent in Western societies (age 18-21 years). Yet, the onset of adolescence is associated with the beginning of pubertal maturation.

However, while the timing of adolescence and puberty certainly overlap, the terms are not to be treated synonymously. First, puberty is considered a restricted phase that is biologically founded and ends with sexual maturation. In contrast, adolescence is most commonly defined as a gradual transition through a series of events that include but are not restricted to sexual maturity or any other specific moment of attainment (B. J. Casey, Jones, & Hare, 2008; Spear, 2000). Second, the start of puberty hardly differs between individuals and gender (1-2 years earlier in girls than boys) and occurs at an ever-earlier age in contemporary societies (between 9 – 12 years of age). Conversely, adolescence is rather seen as a transition period that induces multiple developmental tasks, like becoming independent from parents, establishing interpersonal relationships, and dealing with emotional as well as physical changes. That is, amongst other reasons, why there is no consistent definition of adolescence in terms of the age range.

Thus, adolescent development usually implies multiple transitions in biological, cognitive, and social functioning that prepare adolescents for their adult roles but can also lead to maladaptation. However, while the number of negatives outcomes in adolescence, e.g., due to risky behavior, certainly speaks in favor of this time being a period of ‘storm and stress’ (Hall, 1904), engagement in such behaviors might only be a side effect of broader changes. That is, impulsive or imprudent behavior during adolescence may only be an expression of features that promote the attainment of necessary skills for independence, like to seek for and engage in new and exciting situations, behaviors and sensations (E. A. Crone & Dahl, 2012; Spear, 2000). This speaks in favor of an evolutionary strategy to ensure emotional separation from parents and an approach towards sexual partners and peers, especially as adolescent-specific behavior can be observed in a variety of species (for reviews, see Laube & Van Den Bos, 2016; Spear, 2000, 2011). Taken together, developmental changes in adolescence imply both, risks and chances towards a meaningful adaption to adult roles.

The present thesis relates to this, as *Part I* of the thesis gives an overview of theoretical models and experimental accounts on adolescents’ motivated behavior, specifically on risk-taking. These accounts serve as a basis for studies that investigated changes in motivated behavior and risky decision-making in adolescence (*Paper I* and *Paper II*). *Part II* further depicts findings concerning the influence of social context on a risky decision-making task (*Manuscript I*). Finally, the thesis ends with a general discussion about how the studies eventually contributed to insights into the circumstances of adolescent's motivated behavior.

PART I:

Theoretical and Experimental Accounts on Adolescent's Motivated Behavior and Heightened Tendencies for Risk

1. Introduction

In the last decade, it became evident that adolescence is a transitional period that implies chances, i.e., opportunities for learning, but also risks. As such, many risk behaviors occur within this period and sometimes pave the way for maladaptive developmental trajectories throughout the lifespan. Several model perspectives suggest changes in motivated behavior to be the key to understand adolescent development, also based on insights into changes in adolescent brain maturation and functioning. Though there is evidence for adolescence being a period of ‘storm and stress’, findings do not always draw the picture of the ever imprudent adolescent. This resulted in researchers asking the questions when adolescents engage in heightened risk-taking, what are the reasons, and who is willing to take them during this period.

The present thesis addresses these questions by investigating adolescent motivated behavior, foremost risky decision-making under various contexts, and characteristics of the risk-taker. The first study serves as a literature review about age-related differences in motivated behaviors and their neural and neuronal underpinnings across adolescent development. In the second study, various game-like decision-making tasks were implemented to compare their developmental trajectories from pre to late-adolescence and their susceptibility to individual differences. Eventually, the findings of the thesis contribute to a fuller picture of the change in adolescent risk behavior by challenging the view of the imprudent adolescent through the investigation of a) whether there is indeed a heightened motivation to approach exciting situations during adolescence, b) under which circumstances adolescents are motivated to engage in risky choices and c) individual dispositions that moderate heightened risky decision-making during adolescence.

2. Theoretical and Empirical Foundations

The following sections serve as a review on theoretical and empirical foundations of adolescent development in cognitive and socioemotional functioning. Beginning with a description of models on adolescent development, the second section outlines the most relevant theories and empirical findings on risk-taking behavior during adolescence. In particular, evidence concerning motivational influences on risky decision-making is provided. More specifically, the following sections will capitalize on findings concerning risky decision-making in various motivational contexts and the influence of individual differences in cognitive control and socioemotional functioning in predicting risky choices, as this is the main focus of the thesis. Accordingly, the second section closes with an outline of the research objectives of the present thesis. Finally, the third section serves as a summary of the published *Paper I* and *Paper II.*

2.1. Model Assumptions on Adolescent Development

It is only in the last decade that the period of adolescence received ample scientific interest. With the advancement of neuroscientific approaches to study structural and functional brain maturation, research got insights into the extensive changes that take place in the adolescent brain. Both human and animal models revealed that higher-order brain regions show pruning during adolescence. That is, the grey matter becomes thinner in the process of synaptic refinement, which is the reorganization of synapses and connections without significant change in their number or strength and thus, more efficient. Other connections are formed specifically in adolescence, as the innervation of cortical and subcortical brain regions with dopaminergic cells (for a recent review, see Dahl, Allen, Wilbrecht, & Suleiman, 2018). The findings that revealed adolescent brains to differ from children's or adults' inspired several new frameworks and models that try to explain adolescent-specific behaviors, such as the drive to look out for novel and exciting situations and risk-taking, as well as any neurodevelopmental changes associated with these behaviors.

In an attempt to summarize and conceptualize findings on adolescent brain maturation and behavior, multiple research groups suggested a dual-systems perspective on adolescent development according to recent neuroscientific findings (e.g., Casey, 2015; Casey et al., 2008; Crone & Dahl, 2012; Luciana & Collins, 2012; Luna & Wright, 2015; Shulman et al., 2016; Somerville & Casey, 2010; Somerville, Jones, & Casey, 2010; Steinberg, 2008, 2010; for critical comments, see Pfeifer & Allen, 2012, 2016; Strang, Chein, & Steinberg, 2013; van den Bos & Eppinger, 2016). The focus lies thereby on brain regions that are known for their role in cognitive control and socio-emotional functioning. More specifically, the two brain systems were observed to mature with different paces. That is, the socio-emotional system, consisting of the striatum, medial, and prefrontal cortices, matures earlier than the cognitive control system, which includes the lateral prefrontal, lateral parietal, and anterior cingulate cortices.

Recently, there is an increase in studies that find pubertal hormones to have an important role in the initiation of neuronal changes in adolescence (for a recent review, see Dahl et al., 2018). More specifically, increased fluctuations of gonadal hormones, like testosterone, are associated with changes in emotional and motivational functioning during adolescence (Laube & Van Den Bos, 2016). However, some but not all changes in the adolescent brain and behavior might be explainable by hormonal changes during puberty (Spear, 2000; Steinberg, 2008). The following sections will review findings within and between age groups across the adolescent period, childhood, and adulthood, also as most developmental studies focused on age-related changes so far.

The discussed models differ in their assumptions about the specific development of the two brain systems and thus, in their assumptions about potential maturational imbalances between processing systems. Such model assumptions are of specific interest in this thesis, as studies are about the influence of motivational contexts on adolescent performance in cognitive control, learning, and foremost risky decision-making. Furthermore, studies incorporated various indicators of the socioemotional and cognitive domain, like approach tendency, impulsivity, and general intelligence to predict risk-taking behavior. As such, the following sections will review findings on functional and structural brain maturation concerning a) socioemotional and b) cognitive control functioning and c) the significance of their interaction in explaining adolescent behavior.

2.1.1. Socioemotional Development

The brain system that is associated with the processing of socioemotional cues and situations in adults shows a peak in maturation during adolescence. Specifically, adolescent brains change in the suspension of dopaminergic cells in brain regions that have a critical role in affective and motivational regulation. That is, small aggregates of dopaminergic cells multiply and begin to function as a dopaminergic system that consists of key nodes, like the amygdala, nucleus accumbens, orbitofrontal cortex, medial prefrontal cortex, and superior temporal sulcus (Nelson, Leibenluft, McClure, & Pine, 2005). These structures are implicated in the processing of social and emotional stimuli, judgments, and reasoning (for a review, see Blakemore & Mills, 2014; Ruff & Fehr, 2014; Telzer, 2016). Thereby, subcortical brain regions, such as the ventral striatum, seem to process both social and non-social incentives (Nelson, Jarcho, & Guyer, 2016; Ruff & Fehr, 2014). That is, dopamine expression in these regions peaks during adolescence and likely affects the course of socioemotional development (see Telzer, 2016, for a review). Accordingly, some dual systems models assume that the socioemotional system follows an inverted-U-shaped developmental course (see *Figure 1a*). That is responsivity to rewards increases in early adolescence and declines in early adulthood (Luna & Wright, 2015; Steinberg, 2008). In contrast, the socioemotional system indeed shows a peak in maturation in mid-adolescence, but that maturation reaches a plateau at this time that keeps socioemotional responsivity constant until adulthood, according to the perspective of Casey and colleagues (2008, see *Figure 1c*).

It has been suggested that socioemotional development influences motivated behavior in adolescence. In developmental research, motivational regulation has mostly been investigated in the sense of reinforcement learning theory. In sum, reinforcement learning theory posits that behaviors that have previously been associated with positive outcomes or affect, to reoccur more likely than behaviors that resulted in negative outcomes or emotions. Interchangeably, one would more likely approach situations in the prospect of positive reinforcers or rewards, but avoid situations that promise negative reinforcers or punishments. Indeed, several meta-analyses and reviews show that, beneath accelerated maturation of reward-related brain regions, structures like the dorsal and ventral striatum are specifically sensitive to incentives in adolescence (e.g., Galvan, 2010; Goddings et al., 2014; Pfeifer & Allen, 2012; Silverman, Jedd, & Luciana, 2015; Spear, 2011). That is, accumulating evidence speaks in favor of greater responses to positive incentives in adolescents than in younger or older age groups (e.g., Braams, van Duijvenvoorde, Peper, & Crone, 2015; Chein et al., 2011; Christakou, Brammer, & Rubia, 2011; Galvan, Hare, Voss, Glover, & Casey, 2007; Geier, Terwilliger, Teslovich, Velanova, & Luna, 2010; Padmanabhan, Geier, Ordaz, Teslovich, & Luna, 2011; Schreuders et al., 2018; Smith, Halari, Giampetro, Brammer, & Rubia, 2011; Somerville, Fani, McClure-Tone, McCluretone, & McClure-Tone, 2011; Van Leijenhorst, Gunther Moor, et al., 2010; Van Leijenhorst, Zanolie, et al., 2010), according to the assumptions of neurodevelopmental models.

Thereby, it has been posited that it is due to this reward-sensitivity that adolescents show heightened approach behavior in various situations. In this sense, socioemotional development has been associated with characteristics and behaviors that can specifically be observed during adolescence, like sensation seeking, which refers to an adolescent's tendency to engage in novel and exciting situations, despite potential risks (e.g., Steinberg, 2008; Zuckerman, 2007). While some studies found reward-related activity in brain regions, like the nucleus accumbens, also to be age-invariant across this period (e.g., Hawes et al., 2017; Luking, Luby, & Barch, 2014; van Duijvenvoorde et al., 2014), reward-related brain activity is linked to psychological outcomes and behavioral findings, like sensation seeking (Hawes et al., 2017) and real-life risk-taking (Braams et al., 2015; Galvan et al., 2007), also in animal studies (Spear, 2000; Steinberg, 2008).

Previously, most research has focused on approach behavior, e.g., to potential positive incentives, but the motivation to avoid negative outcomes or emotions has mostly been neglected. In contrast, Ernst (2014) proposed that the growing ability to regulate motivational and emotional drives stands in conflict with extensive development in not one but two systems that are associated with the processing of social and non-social emotional cues. Also given findings that did not show the adolescent's striatum to be more active than adults in negative contexts, the so-called Triadic Model further reflects a third node based on the function of the amygdala. Respectively, beneath findings on neurodevelopment in key nodes for reward-related processing (e.g., striatum) during adolescence, the amygdala, and associated structures, like hippocampus and insula, would play a significant role in processing aversive stimuli (see *Figure 1b*). Accordingly, adolescents showed greater activation in these structures than adults in negatively valanced contexts, e.g., in response to fearful facial expressions (Guyer et al., 2008). However, the amygdala and striatum have a shared role in processing emotionally salient cues, and it remains unclear whether such a classification into approach (striatum-centered) and avoidance systems (amygdala-centered) does only seem appropriate given the disproportion in studies that investigated avoidance-tendencies (Ernst, 2014).

Nevertheless, researchers assume that neurobiological maturation triggers adolescents to show increased sensitivity to socioemotional contexts that amplify the engagement in novel and exciting situations despite their risks during this period. Inconsistencies in hypotheses drawn on socioemotional development during adolescence partly emerge from differing views on whether and to which degree cognitive control development interferes with changes in motivated behavior. In the following section, we will review findings concerning the maturation of cognitive control regions and their associations with adolescent-specific behavior.

2.1.2. The Development of Cognitive Control

Originally, interest in research on the neuronal substrates of cognitive control emerged from patients with frontal lobe damage. Some famous case studies demonstrated patients with severe problems to function in everyday life as they malfunctioned in the control and regulation of their behavior. On the contrary, cognitive control refers to the ability to align one's thoughts and actions to short- and long-term goals and intentions (Miyake et al., 2000). According to the impact of frontal lobe damage on self-regulation in adults, cognitive control abilities are closely tied to maturation of the prefrontal cortex in developmental research. And, similar to conclusions drawn on adults with frontal lobe damage, researchers assumed that adolescents engage in imprudent decisions and risk-taking because their cognitive control system is still immature.

Indeed, higher-order brain regions, like lateral prefrontal, lateral parietal, and anterior cingulate cortices, and associated cognitive control abilities develop gradually from childhood ways into young adulthood. As such, children slowly improve in cognitive control functioning and adolescents gradually encompass transitions that are markers of robust self-control. For example, adolescents improve in the suppression of irrelevant or concurrent information, which is a cornerstone in cognitive development and induces a change from impulsive behavior or acting without thinking, to goal-directed behavior (Somerville et al., 2017). Moreover, adolescents grow in the ability to keep distant goals in mind and to delay gratification, that is, they show more patience in various behaviors. Accordingly, impulsive action (e.g., acting without thinking) and choice (e.g., delay gratification) decline with increasing ability to exert cognitive control across adolescence (Romer, Duckworth, Sznitman, & Park, 2010; Romer, Reyna, & Satterthwaite, 2017).

Concerning the aforementioned dual systems perspectives that posited divergent developmental trajectories between brain regions associated with cognitive control and socioemotional functioning, Steinberg (2008), as well as Casey and colleagues (2008), proposed a slowly developing cognitive control system that continues to mature through late adolescence. In contrast, given the adult-like performance at least in non-affective contexts, Luna and Wright (2015), as well as Luciana and Collins (2012), proposed that cognitive abilities reach adult-like levels already in mid-adolescence. Thereby, cognitive control serves only as an overarching term for mental operations in these models that enable to represent current goals, allocate one’s attention to important features of the environment, and to implement behavior to achieve these goals in various contexts (Botvinick & Braver, 2015; Miyake et al., 2000). That is, cognitive control incorporates a variety of sub-processes, such as inhibition, working memory, and cognitive flexibility that may differ in their roles for development from child- to adulthood (Steinbeis & Crone, 2016).

In sum, children and adolescents increasingly overcome habits by exerting cognitive control over environmental signals, show rather proactive than reactive control, and gradually more self-direction in these behaviors (Munakata, Snyder, & Chatham, 2012). Thereby, neurodevelopmental models not only differ in their expectations about the developmental course of brain regions associated with cognitive control abilities but also in assumptions about their role for adolescent approach behavior, e.g., in reaction to appetitive cues. The following section will introduce model perspectives and findings on the interaction between control and motivated behavior in adolescence.

2.1.3. On the Interplay Between Motivation and Control

As the previous chapters elaborated, adolescents undergo immersive neurodevelopmental changes, both in terms of structure and functioning of cortical and subcortical brain structures. Insights into brain maturation during adolescence led various research groups to suggest heuristics that might also explain how these changes account for increases in motivated behavior, like sensation-seeking and risk-taking. Dual systems theory addressed the divergent age trends found in developmental pathways of these structures across adolescence and promoted a dichotomic view on adolescent behavior. Accordingly, immature cognitive control, as well as heightened socioemotional responsivity would independently account for age-related differences in risk and rationality across adolescence in some versions of dual systems models (Shulman et al., 2016; Smith, 2013; Steinberg, 2008). Thereby, socioemotional functioning, like changes in sensation seeking, is rather related to the peak in hormonal changes during puberty than cognitive control functions that rise gradually with age and experience according to this view (Steinberg, 2008; Luna & Wright, 2015).

In contrast to the rather strict separation of the two systems as highlighted above, other research groups suggested that the maturation of prefrontal control regions and their increasing functional connectivity, like with reward-related regions, account for a decline in imprudent behavior with age (Casey et al., 2008; Luciana & Collins, 2012). That is, adolescents reflect less when engaging in behavior due to an imbalance between the maturation of control regions and brain regions responsible for socio-emotional processing. Children and adults, on the other hand, do not show such a maturational imbalance, as they either did not yet encompass the peak of socioemotional maturation or already grew abilities to control affective tendencies, respectively.

Thus, recent revisions of imbalance models stress out the importance to move away from system-based approaches but investigate how various systems grow in inner and interconnectivity instead (Casey, 2015). It has been posited that there are hierarchical dependencies in the development of different brain circuitries, that is, developmental changes in some brain circuits (e.g., connections within reward-related brain regions) are needed for others (e.g., top-down cortical control connections) to develop during adolescence. As such, reward-related brain regions have regularly been observed to be activated under activation in cognitive control regions, as the lateral prefrontal and parietal cortex (Crone, 2009; Luna, Padmanabhan, & Hearn, 2010), and other regions, like the temporal-parietal junction, or the medial prefrontal cortex that have been associated with perspective-taking, mentalizing, and social behaviors (Blakemore, 2010; Blakemore & Mills, 2014). This suggests that motivated behavior is rather driven by interconnected networks between cortical and subcortical regions in adolescence (see *Figure 2A*; Casey, 2015).

Accordingly, there is accumulating evidence in cognitive neuroscience suggesting that incentive processing occurs in consecutive stages that all are associated with varying sub-systems dedicated to infer about the meaning of behavioral outcomes in the brain (for a review, see Ruff & Fehr, 2014). Some dopaminergic brain structures mainly code the anticipation of rewards (ventral tegmental area; substantia nigra), while individuals learn through discrepancies between anticipation and actual outcome via dopaminergic neurons that encode and send prediction errors in subcortical (e.g., amygdala, ventral and dorsal striatum) and cortical (e.g., anterior cingulate cortex, orbitofrontal cortex, anterior insula,

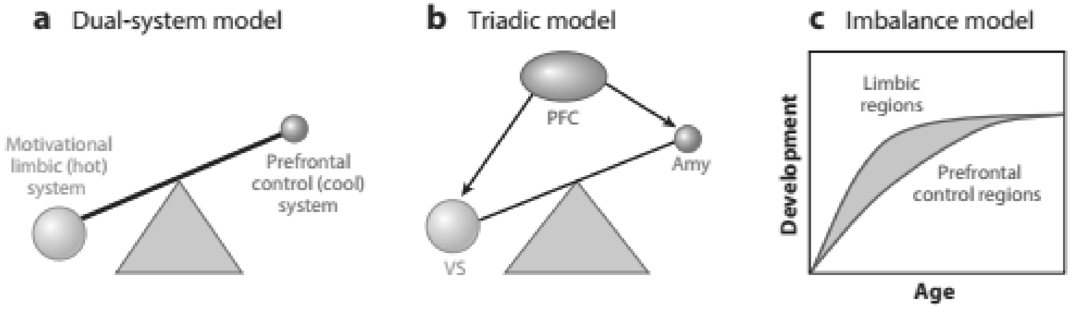

Figure 1. Theoretical models on the neurobiological development during adolescence according to three prominent representatives, (a) Dual-systems model, (b) Triardic model and (c) Imbalance model. Abbreviations: Amy =amygdala, PFC = prefrontal cortex, VS = ventral striatum. Adapted from Casey, 2015.

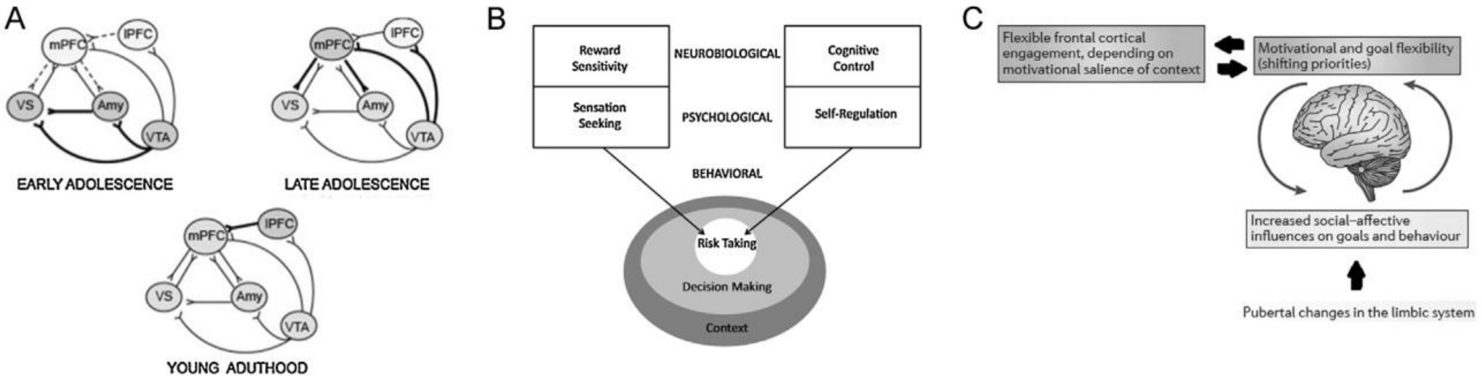

Figure 2. Recent developmental models that posit more nuanced views on adolescent maturation in brain and behavior as proposed by (A) Casey, 2015, (B) Shulman et al., 2016, and (C) Crone and Dahl, 2012. Adapted from van Duijvenvoorde, Peters, Braams, & Crone, 2016.

ventromedial prefrontal cortex) dopaminoreceptive regions to update anticipated values and adjust behavior (Ruff & Fehr, 2014; Telzer 2016). Given the dramatic changes that occur in the adolescent dopaminergic brain systems (for a review, see Telzer, 2016; Ruff & Fehr, 2014), developmental differences in incentive processing may concern different stages, i.e. incentive anticipation or reception, and associated brain structures with varying degrees.

Beneath differing views on the associations between maturation in socioemotional and cognitive control systems (see *Figure 1*), all models suggested that neurodevelopmental change accounts for motivated behavior that promotes tendencies to approach situations that are novel or promise potential for positive incentives during adolescence. However, few studies take different stages during goal-directed and choice behavior into account, or compare the reaction to varying types and amounts of incentives between multiple age groups, when investigating how adolescents process incentives. In a meta-analytic study, adolescents and adults showed activation in similar brain systems when anticipating (e.g., ventromedial prefrontal cortices) receiving, or consuming incentives (e.g., orbitofrontal cortex, anterior cingulate cortex), but sometimes to varying degrees (for a review, see Silverman et al., 2015). During anticipation, adolescents showed larger activation of the insula, amygdala, and putamen, while the amygdala was more active in adolescents than adults during receipt of incentives, indicating a higher sensitivity to salient stimuli during adolescence than adulthood.

Thereby, interpretation of neuroimaging data often underlies reverse inference, which means inferring about cognitive states or behavior by brain activity patterns solely. As such, there is little consent about measures of motivation and control, as well as the interaction between brain and behavior during adolescence. In an attempt to integrate findings on neural maturation, brain activity patterns, and behavior into a common conceptual framework, some research groups defined different measurement levels (neurobiological, psychological, behavioral) and associated constructs that are thought to represent socioemotional functioning and cognitive control in adolescence (Smith 2013; Shulman et al., 2016, see *Figure 2B*).

Thus, who shows when and why an imbalance between socioemotional and cognitive control functioning during adolescence may also highly dependent on the context at hand (Smith, 2013; Shulman et al., 2016, see *Figure 2B*). For example, heightened risk-taking in adolescence has particularly been shown when rewards were encountered immediately after taking a decision (Defoe et al., 2015; but see also Figner & Weber, 2011) when experiencing unknown situations (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016; Tymula et al., 2012; van den Bos & Hertwig, 2017) and in the presence of peers (Chein et al., 2011; Shulman et al., 2016). As such, Crone and Dahl (2012) suggested that the highly flexible recruitment of cognitive control in arousing situations may be triggered by pubertal influences on the limbic system during adolescence but overall serves goal-directed behavior (see *Figure 2C*). Following, while changes in motivation and control during adolescence have mostly been associated with engagement in risks, heightened neural reward-sensitivity and approach behavior in youth and can also imply positive developmental trajectories, e.g. in learning or social behavior (Crone & Dahl, 2012; Peters & Crone, 2017; Telzer, 2016).

In sum, motivated behavior in adolescence is still discussed in terms of a dichotomy between imprudent behavior on the one hand, and adult-like cognitive abilities on the other hand. A view that did not change much from a more historical point of view on adolescent development that can already be derived from the research tradition of Hall (1904). However, increased approach behavior to a variety of potentially rewarding cues may ultimately lead to the exploration of new environments and social roles and as such, to adolescents that make valuable experiences for a successful transition into adulthood (Crone & Dahl, 2012).

Intermediate Summary and Implications for the Present Study

Adolescent-specific behaviors, like a heightened tendency to approach novel and exciting situations despite their risks, have always been the driving force to understand how adolescents change. Neurodevelopmental models summarize heuristics concerning different developmental pathways in brain maturation and transfer prominent changes in neural activation patterns on adolescent behavior. Unanimously, these models suggest that imbalances between the maturation of brain regions that are linked to the processing of socioemotional cues, and regions that are responsible for controlled reactions to these, account for adolescent-specific behaviors, like risk-taking.

More recently, developmental models also integrate findings on positive trajectories during adolescence and suggest that some of the very same brain activity patterns and behaviors that have previously been regarded as maladaptive, can be linked to adaptive outcomes in adolescence, like increased learning and flexibility in the use of cognitive control abilities. Especially, as adolescents are constantly confronted with the need to adjust behavior in reaction to changing and unknown environments in the transition from being children to become independent adults. Furthermore, adolescents require experiences to grow in the ability to maneuver through various and complex settings in the everyday life, why increased approach behavior and risk-tolerance may not always be a sign of maladaptive outcomes but of normal adolescent development. In sum, hormonal and neurodevelopmental changes during this time have both been regarded as hindering when negative developmental trajectories increase the risk for the adolescent's physical and mental health or growth-enhancing.

Therefore, in recent years, various abilities were tested and an even greater number of methods used to investigate motivated behavior in the sense of developmental models in the adolescent literature. As such, conflicting findings concerning a peak in motivated behavior in youth may be due to the variability in study designs used to investigate the interplay between motivation and control. More specifically, *Paper I* had the working hypothesis that different types of incentives could account for conflicting findings on age-related differences in cognitive control, decision-making, and learning during adolescence. In contrast to model assumptions, there were mainly no peaks in motivated behavior during adolescence when reviewing behavioral and neuroscientific findings in the adolescent developmental literature on this behalf. However, most studies relied on a restricted adolescent sample in terms of an age range, or a comparison with another adult or child group at the utmost. In a similar sense, most studies applied a single task context to infer the influence of motivation on adolescent behavior.

As such, *Paper II* aimed at comparing developmental trajectories between risky decision-making tasks within a sample of a broad age range from pre to late adolescence. These game-like tasks are some of the most investigated experimental risk-taking tasks in the adolescent literature and differ in characteristics that are thought to heighten risk-taking in adolescents to various degrees. Furthermore, individual differences have often been disregarded in studies but are known to account for variance in risk tendencies. Therefore, *Paper II* also included predictions on the influence of individual differences in temperament in risky decision-making above differences in age, gender, and general intelligence. More specifically, it was assumed that task contexts differ in their socioemotional arousability and might depict specific states that are differentially susceptible to individual differences in cognitive abilities and temperamental dispositions in youth.

Furthermore, the review of *Paper I* showed that the motivated behavior with the greatest age variance across adolescence would be risky decision-making in social contexts. However, the conclusion that specifically adolescents show heightened risk-taking under social influences was mostly drawn from one task setting, that is, simulated driving. Additionally, only a few studies tested age differences in the peer effect, why it remains unclear whether such effects, e.g., of peer presence, are generalizable to other risk contexts and whether they are adolescent-specific. As such, the study of *Manuscript I* addresses this question by introducing a virtual peer to observe adolescents while conducting the Balloon Analogue Risk Task (BART, Lejuez et al., 2002). The BART is a dynamic risky decision-making task in which adolescents can only experience risk probabilities. As previously suggested, the study had the advantage of testing developmental differences in social influences on risky choices in a broad age range from pre to late adolescence. Furthermore, the dynamic nature of the task allowed to test moderators on such influences, like the integration of previous risk experiences during the task, but the study also considered gender and individual resistance to peer influences as potential moderators on the level of the individual.

The previous chapters elaborated some of the most prominent methods to measure and findings on age-related differences in adolescent brain maturation, functionality, and behavior that partly overlapped with paragraphs and conclusions of the published review (*Paper I*). As this thesis primarily focussed on risky decision-making during adolescence in subsequent studies (*Paper II* and *Manuscript I*), the following review of empirical findings will further capitalize on age-related differences in risk-taking behavior. In sum, the next section will describe measures of and findings on risk-taking and discuss the strengths and limitations of models that have been posited concerning developmental differences in risky decision-making during adolescence.

2.2. Adolescent Risk Behaviors

The previous section presented common views on adolescent development that presume most adolescent-specific behaviors to be due to the divergent pace in changes in brain maturation and functionality of socioemotional and control regions during this period. One of the most discussed topics in the literature about adolescent development is risk-taking behaviors that have mostly been associated with negative health outcomes. In analogy to the previous sections about adolescent development, more nuanced views on adolescent's tendency for risk imply that individuals encompass both challenges and opportunities that may lead to maladaptive and/or adaptive functioning.

On the one hand, despite increasing physical strength and reasoning, mortality rates rise to 200% during adolescence (Dahl, 2004). More specifically, such mortality rates are mostly due to self-induced causes, as reflected by the number of, e.g., accidents and drug abuse. Even though risk behaviors, like binge drinking and tobacco use, are decreasing among adolescents over the last years, such risk-behaviors are still more common in adolescents than other age groups in the Western part of the world (e.g., Steinberg, 2015). Accordingly, advisories to improve adolescent health worldwide encourage the consideration of an adolescent-specific tendency for risk, especially regarding its predictivity for such behavior later in life (Dick & Ferguson, 2015).

On the other hand, risk-taking has also been suggested to reflect normal adolescent development, at least when it does not overcome a certain degree of exploration and experimentation. For example, the experimentation with culturally accepted risk behaviors, like alcohol and tobacco consumption, can be viewed as normative. That is, engaging in behaviors that are seen as adult-like in particular cultures may be a sign of adaptive functions to become independent. However, exploration of risk-behaviors can have long-term effects on individuals' health trajectories and imply a costly trade-off between learning and experiencing how to deal with risky situations and negative consequences, like addiction and delinquency. Nonetheless, greater cognitive control and flexibility in reasoning and information processing highlight that most adolescents transition from child- to adulthood without greater consequences for physical or mental health (Crone & Dahl, 2012). As such, adolescent-specific tendencies for exploration and risk may be seen as opportunities as well, instead of vulnerability only.

Measures of Risk-Taking Behavior. Thereby, risk-taking behavior has been defined and measured in various ways. Previously, most studies referred to risk-taking when individuals stated that they did engage in risks with a certain probability for negative health outcomes (e.g., “Have you ever jumped off a cliff to dive into the water?”; “How often have you done so?”) or that they would engage in a hypothetical risk situation in self-reports. (e.g., “Would you jump off a cliff to dive into the water?”). Furthermore, some questionnaires infer about other influences on risky decisions, like social pressure (e.g., “If your friends would jump off a cliff, would you do the same?”). Accordingly, questionnaires about risk-behaviors were mostly used to predict the consequences of such tendencies in developmental research, i.e., negative health outcomes or trajectories. In sum, important insights about morbidity and mortality could be drawn from questionnaires about real-life and hypothetical risk decisions during adolescence. However, statements in questionnaires might not have real consequences in terms of actual behavior and are susceptible to distortions caused by social desirability and self-portrayal.

Thus, a variety of experimental measures emerged that allowed to investigate actual behavior in the risky situation itself, that is, in abstract tasks. Risky decision-making task reflects behavioral measures that elicit revealed preferences in somehow incentivized risk situations. In most tasks, participants decide between options that differ in the probability of positive and negative outcomes. In the tradition of the decision-making literature, risk-taking is thereby defined as the tendency to preferentially engage in or decide for options for which positive and negative outcomes are variable and/or unknown (e.g., gain a high amount or nothing), instead of playing safe and not risking anything (e.g., gain a static low amount; Figner & Weber, 2011).

While the abstract nature of experimental tasks raised concerns about the ecological validity of such measures, several more naturalistic game-like tasks emerged, specifically in the adolescent literature. In these tasks, decisions for or against risk are differentially incentivized, and/or contextual factors aim at raising emotional arousal to resemble more naturalistic risk settings in everyday life. Though a variety of designs have been used to investigate risky decision-making during adolescence, in terms of participants, methods, and experimental settings (Defoe et al., 2015), the meaning of experimental measures in explaining real-life risk behaviors remains a topic that is currently discussed (e.g., Frey, Pedroni, Mata, Rieskamp, & Hertwig, 2017).

In the laboratory as in real life, the context of risky decision-making differs in characteristics and induced arousal, which is of great interest to study motivational influences on adolescents' tendencies for risk and rationality. This is also of significance for the present thesis, as studies reviewed (*Paper* I) and are about developmental differences in some of the most investigated experimental risk-taking tasks in the adolescent literature (*Paper II* and *Manuscript I*). While some analogies can be drawn from previous chapters about models on adolescent development, the following section will focus on assumptions that are specifically about the development of risk-taking. As such, after a) reviewing model assumptions on development in risk-taking, the following chapters will capitalize on experimental findings and the influence of b) developmental stage, c) task context, and d) individual differences in socioemotional functioning on risky decision-making.

2.2.1. Model Assumptions on Development in Risk-Taking

The development of risk-taking behavior during adolescence has extensively been investigated during the recent decade. As described in the previous chapter, this can partly be explained by the rapid rise in insights into brain development and functioning during this period. More specifically, some findings on the association between brain maturation or activity patterns and risk-taking contributed to model assumptions but also shaped more nuanced views on adolescent development recently (Shulman et al., 2016; Telzer, 2016). In a nutshell, neurodevelopmental models highlight imbalances in biological factors that contribute to the understanding of the adolescents' tendencies for approach, sensation-seeking, and risk-taking.

Previously, adolescents have also been suggested to show an imbalance between their biological and social maturation. That is, they reach full reproductive capacity, i.e., biological maturation, earlier than they engage in the social roles of adulthood. This may lead to rebellious behavior against parents or societal norms, i.e. risk-taking, as adolescents perceive a lower social status without the opportunity to engage in more adult activities (Moffitt, 1993). Therefore, beneath biological factors, tendencies for risk would highly depend on psychological and cultural factors during adolescence as well. Relatedly, meta-theories try to explain changes in real-life risk behavior during adolescence by considering several streams of influence. In the Theory of Triadic Influence (Flay, Snyder, & Petraitis, 2009), (1) intrapersonal/individual, (2) social/normative, and (3) cultural/environmental factors influence initiation and development of risk-behavior during this period. As such, not only individual biological and psychological development but perceived norms and culture contribute to risk-taking behavior. The influences of these domains on risk behavior are highly intercorrelated in adolescence, thus, risk-taking tendencies would only be fully understood when taking all of them into account.

Thereby, hypotheses on age differences in decision-making during adolescence are often extrapolated from the aforementioned heuristics that reconcile a variety of behaviors, or real-life risk-taking, and in sum, suggest heightened risky decisions in adolescence. Recently, a review on dual systems theory emphasizes that risk-taking may not ubiquitously peak in adolescence but highly depend on decision-making processes, i.e., the integration of contextual information, as well as psychological factors and individual differences in risk-susceptibility (see *Figure 2B*; Shulman et al., 2016). In sum, the accumulated findings and theories suggest that individual and environmental factors influence confidence and motivation in engaging in risk-behaviors, and these may be ultimately predictable by underlying decision-making processes (Flay et al., 2009; Shulman et al., 2016).

Thus, fuzzy-trace theory (Reyna & Rivers, 2008; Reyna, Wilhelms, McCormick, & Weldon, 2015) specifically infers about choice behavior and predictions for development in such behavior were derived from its assumptions. More specifically, the fuzzy-trace suggests that decisions may rely on concrete memory for described (verbatim) information but abstract memory for its meaning (gist). Concerning the development of decision-making processes, it can be deduced that with increasing cognitive abilities adolescents gain strength in the ability to remember precise information (verbatim) but also gist-based intuition is fostered during decision-making across adolescence (Reyna et al., 2015; see also, Defoe et al., 2015; Defoe, Dubas, & Romer, 2019; Romer et al., 2017). That is, adolescents become more categorical and secure in what ‘feels’ like the right choice, i.e. represent risk as some versus none or less versus more, which contributes to more risk aversion with age. Nonetheless, adolescents are in the middle of the developmental process of relying increasingly on gist but still more on verbatim-based choices than adults. Verbatim-based choices imply more rational trade-offs between risks and rewards and use of concrete information that is associated with risk-taking (Reyna et al., 2015). According to the assumptions of the fuzzy-trace theory, children would show more risks than adolescents and further, adolescents more risks than adults, which would be the most risk-averse (see also, Defoe et al., 2015, 2019; Romer et al., 2017).

In a similar intent, the lifespan wisdom model (Romer et al., 2017) suggests a more nuanced view on risk-taking, that is, the theory posits various forms of risky decision-making. As such, adolescents engage in less gist-based decision-making due to the lack of experience with risk situations and lower cognitive control abilities compared to adults, why risk-taking declines monotonically. Romer and colleagues (2017) posit that exaggerated engagement in risk during adolescence, as proposed by imbalance models, may only be a sign of a subset of individuals that are risk-indifferent and show heightened risk tendencies rather irrespective of context and cognitive maturation. Normally developing adolescents in turn, show a peak in sensation seeking that also results in more risk-taking but is a rather adaptive form of exploration behavior. Adaptive exploration means a gain in experience with risks and their potentially negative consequences that increases learning and wisdom development during adolescence.

To summarize, several factors may contribute to the understanding of the adolescents' decision for risk, as they might moderate heterogeneity in age differences found in previous studies. On the one hand, there are cognitive and affective, or motivational task characteristics that may account for differences in hypothesized developmental pathways of risky decision-making. On the other hand, heightened risk-taking in youth may not be true for all adolescents, but individuals with certain temperamental dispositions, like impulsivity and reduced control, as some theories posit. The following paragraphs will summarize findings on (a) age and gender differences in risky decisions, as well as (b) the influence of contextual factors and (c) individual differences in temperament on developmental trends in risky decision-making across adolescence, as such indicators were investigated in the present study.

2.2.2. The Influence of Developmental Stage on Risky Decision-Making

Whether, why, and to which degree adolescents engage in risks seems to be a matter of the individual developmental stage. This assumption has been reflected in various models and theories that suggest general risk tendencies and influences differ between adolescents and adults, but also between pre (until age 11), early (aged 11-13 years), mid (aged 14-16 years) and late adolescents (aged 17-21 years; Defoe et al., 2019). Moreover, developmental trajectories differ between boys and girls given differential pubertal, societal, and cultural influences between genders. As such, male adolescents are overrepresented in statistics concerning maladaptive or delinquent behavior (for a meta-analysis, see Byrnes, Miller, & Schafer, 1999) and many risk behaviors show a peak during mid-adolescence (Flay et al., 2009; Steinberg, 2015) .

Thereby, an extensive meta-analytic study compared findings on experimental decision-making in various risk settings to infer about developmental trends and moderators in such behavior (Defoe et al., 2015, for a summary, see Defoe et al., 2019). Indeed, adolescents showed more risk-taking compared to adults across task settings, but engage in equal levels of risk as children do. Moreover, early adolescents showed higher propensities of risk than mid-adolescents. These findings are in sum against predictions of neurodevelopmental imbalance models that suggest a peak in risky decision-making in adolescence, not a constant decline. Thus, fuzzy-trace theory posits a monotonical decline in risky choice in line with the overall findings of the meta-analysis. Based on changes from quantitative (e.g., better take the chance to lose nothing but a high amount) to more qualitative representations of choice options (e.g., better lose a small amount for sure than a lot for some probability) during adolescence, individuals become more risk-averse . However, most studies investigated risky decision-making in one adolescent age group, or compared adolescent groups with another younger or older sample only. Moreover, most studies did not compare effects between the gender, why conclusions on developmental trends in risky decision-making may be inconclusive.

Additionally, findings of younger adolescents engaging in more risks than late adolescents do not reflect developmental trends in real-life risk behavior that increase with age across adolescence. Thereby, inconsistencies between observations in the real world and the laboratory may derive from the influence of previous risk exposure. Older adolescents have more opportunities to explore and experience risk situations due to higher independence in everyday life. The authors conclude that younger adolescents would probably engage in more risk-taking than older adolescents in the real world, just like in the laboratory, when they would have similar freedom in choosing or creating their environments (Defoe et al., 2019). In contrast, risk exposure is the same for all developmental stages when investigating risky decision-making in the laboratory that may partly explain the contradicting findings between risk measures. However, the meta-analysis combined the effects in the mid- and late adolescent groups, why it is still not clear whether early adolescents would engage in more risky decisions than both older age groups or mid- or late-adolescents only, in the laboratory.

While many models do not make explicit predictions about gender differences in the development of risk-taking, evolutionary theory suggests heightened risk-taking in adolescence to be a prominently male phenomenon given a greater need for independence and social status. That is, male adolescents would be more likely to engage in risks than females, especially in the presence of male counterparts (Wilson & Daly, 1985). Accordingly, risk-taking behavior has been shown to occur more likely in males (for a review, see Byrnes et al., 1999) and male adolescents described themselves as more sensation-seeking than females (Cross, Copping, & Campbell, 2011). This has mainly been explained in terms of a male drive to show social success and to engage in a competition (Wilson & Daly, 1985), for which risk-taking may signal that one is tough or strong to enhance one’s reputation or status in the group (Ellis et al., 2012). As such, males described themselves as less resistant to peer influence (Paus et al., 2008; Steinberg & Monahan, 2007; Sumter, Bokhorst, Steinberg, & Westenberg, 2009) and showed more risky decisions in the presence of peers, while females did not in a recent study (Defoe, Dubas, Dalmaijer, & van Aken, 2019).

In sum, it has been suggested that males are more inclined to explore and engage in novel and exciting, but also risky situations than females. Nevertheless, gender differences in the developmental trajectory of risk-taking have mostly been neglected in the adolescent literature, especially in experimental assessments, and findings have been mixed (Defoe et al., 2015, 2019). Therefore, it also remains unclear whether males would generally engage in more risks than females, or whether this may be a domain-specific effect (e.g., in social situations only). To infer about both developmental trends in risky decision-making and potential differences between the genders herein, the literature requires studies that compare a wide age range or investigate the longitudinal change in risky decision-making across adolescence.

2.2.3. The Influence of Task Context on Age Differences in Risky Decision-Making

Beneath difficulties in comparing findings based on the various age groups used and neglected gender differences when investigating adolescents' tendencies for risk, contradicting findings concerning heightened risky choices during adolescence may further derive from the diverse risky decision-making tasks implemented in studies. Accordingly, meta-analytic findings suggest that the risk context has a great influence on developmental trends in risky decision-making, but only a few studies directly compared specific task characteristics (Defoe et al., 2015). As the studies of *Paper II* and *Manuscript I* aimed at investigating the influence of different task contexts on the prediction of development in risky choices, the following section will further review differences in experimental risk assessments and their meaning for the heterogeneity in age-related effects in adolescent's risky decision-making.

As such, it is common knowledge that the way riskiness is framed in a given situation drives when and to which degree individuals might engage in risk-taking behavior in the decision-making literature. Thereby, a prominent question in developmental research is *when,* i.e., under what circumstances adolescents are triggered to engage in risk-taking. In analogy to the dichotomic view on adolescent maturation, it has been suggested that adolescents only show heightened risk tendencies in affectively arousing or 'hot' contexts, but would be quite prudent decision-makers in described, that is 'cold' contexts (Figner & Weber, 2011). Accordingly, dual-systems theories suggest that in arousing situations, approach tendencies overcome cognitive control abilities, irrespective of potential negative outcomes when engaging in risky behavior. Yet, motivation has been differentially conceptualized in various research fields. In psychology, it is usually referred to as motivation when investigating how goal-directed behavior or performance can be altered based on external and internal cues or states. As such, changing objective properties of risky choices, i.e., potential gains, losses, and their probabilities, allows for a better insight into the premises of adolescent's risky decisions and contributes to the question of *when* adolescents engage in heightened risk-taking.

Consequently, risk-taking is a multifaceted phenomenon with various factors that have been suggested to be highly influential on how adolescents act in and perceive a certain risk-situation, potentially also dependent on the individual developmental stage. Accordingly, another important question is *what* drives adolescents to engage in risks, i.e., what are the underlying mechanisms that may account for differing risk levels with age. To better understand the mechanisms of risky decision-making, experimental designs allows one to decompose different components of risk-taking. However, formal decision models were mostly applied to infer about potential mechanisms underlying risky decision-making in adults. Yet, developmental models would benefit from such methodological tools to better understand mechanisms in psychological and neural processes and specify theoretical frameworks that are often rather heuristic (e.g., Pfeifer & Allen, 2016; van den Bos & Eppinger, 2016; van Duijvenvoorde, Blankenstein, Crone, & Figner, 2016)

Prominent versions of formal models are expectation models that suggest individuals calculate a subjective value of each available choice option by integrating all information about outcome magnitudes and probabilities. As such, individuals prefer choice options with the highest subjective value. The expected value models point out that objective attributes of risk situations (e.g., probabilities, gain and loss amounts) are translated into subjective representations that may deviate from their objective counterparts (e.g., Kahneman & Tversky, 1979). For example, in a version of the prominent Prospect Theory (Tversky & Kahneman, 1992) formulates a value function that suggests loss-aversion (i.e., losses loom larger than gains) and a probability weighting function that posits adults to overweight small probabilities but underweight large probabilities during risky decision-making. These formal frameworks revolutionized the view on human decision-making as they uncovered some of the mechanisms that are common in adult’s risky decisions and highlight the subjective perspectives humans have when considering to engage in risks.

Besides, also the reinforcement learning model and the fuzzy-trace theory were applied to investigate risky decision-making in the laboratory. These accounts have been discussed in terms of their value for predictions about developmental changes in behavior across adolescence in previous sections of the present thesis (see *chapter 2.2.1* and *chapter 2.3.1*, respectively). In sum, fuzzy-trace theory, reinforcement learning, as well as formal models on risky decision-making, suggest differing tendencies of approach or avoidance of risky choices with different outcome magnitudes, valence, and probabilities. Thereby, experimental task settings differ in whether and how such tendencies can be attributed to certain task characteristics and as such, in the testability of formal decision frameworks in the adolescent developmental literature. Some of the most discussed influences of task context on age differences in risky decision-making are (a) the type of choice that adolescents are confronted with and (b) the valence and type of incentives that are provided in specific task settings, which will be discussed in the following sections.

Type of Choice: Risk and Ambiguity. As the previous section elaborated, it has been suggested that experimental risk-taking tasks fail to represent real-life risk situations. That is, individuals can infer about risk probabilities and outcomes of choice options in most decision-making tasks, as information is described. On the contrary, real-life risks occur under ambiguity, i.e. decision-making when choice outcomes are only attributable to previous experiences. This process is associated with emotion-based learning and thus, choices under ambiguity are more affectively arousing than choices under risk (Defoe et al., 2015; Figner & Weber, 2011; Rosenbaum, Venkatraman, Steinberg, & Chein, 2018). Settings with choices under ambiguity heighten the ecological nature of decision-making tasks but also the adolescent's engagement in risk-behavior, according to developmental models. In contrast, adults have been found to show a reversed pattern and engage in fewer risks in uncertain conditions, known as the description-experience gap (Hertwig, Barron, Weber, & Erev, 2004). This difference in risky decision-making between adolescents and adults has been attributed to the adolescent's higher tendency to underweight rare risk outcomes in choices under ambiguity but overweight them in described situations (Hertwig et al., 2004). Thereby, risky decision-making tasks are sometimes completely described, like various forms of gamble tasks, wheel-of-fortune tasks, and the Cups Task, or experience-based like the Iowa Gambling Task, Chicken or Stoplight Task, and the Balloon Analogue Risk Task.

Furthermore, some tasks are constructed to include a described, as well as an uncertain variant, like in the hot and cold variants of the Columbia Card Task.

For example, some gambling tasks present participants with a choice between two wheels of fortune. Thereby, the size of the areas dedicated to specific outcomes implies the chances of a wheel to stop at these areas, and thus, the probability to which either of the two wheels might result in positive or negative outcomes. Under risk, information about the value and valence of probable outcomes enable individuals to calculate the expected value of each decision option, or wheel of fortune, respectively (see *Figure 3A*; .75 x 20€ + .25 x 0€ = 15€ vs. 5€). In contrast to real-life risks when probabilities and potential negative consequences are unknown, participants can infer about the advantages and disadvantages of engaging in risk in described decision-making.

In more naturalistic settings, researchers can increase ambiguity in decisions for risk, for instance, by decreasing the level of information that is apparent during task conduction. That is, part of the wheels would be covered for which participants cannot fully assess the probabilities and values of potential outcomes in ambiguous conditions of the foregoing example (see *Figure 3B* and *Figure 3C*). In contrast, risks and underlying probabilities are fully unknown for each trial in tasks under uncertainty. Furthermore, underlying probabilities are uncertain at the beginning of the task, but participants can learn about outcomes by sampling choice options in experience-based task settings (see *Figure 3D*). Thereby, some researchers exchanged static choice options, i.e., choices that are self-contained in terms of probabilities and outcomes with dynamic choices, i.e., trials in which consecutive choices for the risky option increase the outcome value but also the probability for negative outcomes (e.g., BART, Lejuez et al., 2002). Such decision situations are thought to be more similar to real-life risk behaviors, like alcohol consumption, where each drink increases hedonic value but also risks for physical health. While static choice options depict decisions to engage in risks or not, dynamic settings rather refer to decisions about when to stop engaging in risks. That is, researchers manipulated ambiguity during decision-making in various ways and suggested differential developmental patterns in risky decision-making between task contexts.

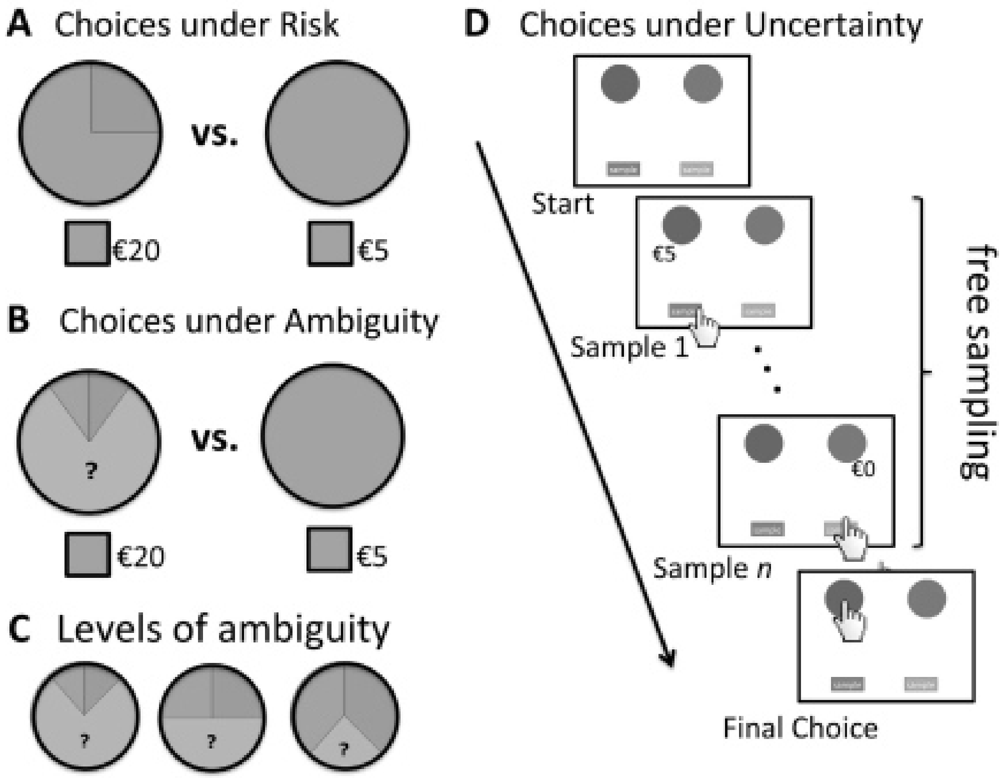

Figure 3. Example of a wheel-of-fortune task, a gambling task that includes decisions for gamble (left wheel) or safe choice (right wheel) under (A) risk or (B & C) varying levels of ambiguity. The choices under (C) uncertainty give no information about possible outcomes and their probabilities at all, which can only be estimated with experience. From van den Bos & Hertwig, 2017.

In a meta-analytic approach, risky decisions showed a developmental decrease in tasks in which outcomes attributable to different choice options are explicitly described (Defoe et al., 2015). Especially, when tasks contrast safe options that imply a certain gain of a small amount against more risky options with equivalent or varying expected values (see *Figure 3A*), there is a monotonic decline in risk-taking from childhood over adolescence to adulthood. However, the same decline is apparent in choices under risk without a sure option being provided, at least when it was controlled for differences in intelligence to exclude distortion of findings given differing task complexity between settings (Defoe et al., 2015). A recent review further emphasizes that only a few studies that compared age groups or investigated developmental trajectories in description-based decision-making found age differences in risky choice (Rosenbaum et al., 2018). The findings were inconsistent across task contexts and between studies using similar tasks, suggesting that only the riskiest trials or those with the highest possible reward likely elicit more risky choices in youth.

In contrast, experience-based tasks were more likely to show age-related differences, with adolescents showing higher risky decisions than adults, suggesting that uncertainty in taking risks is indeed more associated with real-life risk decisions and more affectively arousing. However, differences in experience-based settings, like expected values and probabilities, might further interfere with developmental differences, as well as further differences in affective task manipulations between studies (see Rosenbaum et al., 2018, for a review). Thereby, few studies directly compared task settings that differ in ambiguity levels, or compared reactions to varying task settings between developmental stages, which may contribute to the conflicting findings on adolescents' tendency for heightened risk decisions.

In one developmental study, attitudes to known risks indeed decreased with age from pre to late-adolescence (e.g., aged 8-22 years; van den Bos & Hertwig, 2017), while other findings also suggested no age differences herein (aged 10-25 years; Blankenstein et al., 2016). However, findings posited adolescents to be specifically ambiguity tolerant (Blankenstein et al., 2016; aged 12-17 years, Tymula et al., 2012; van den Bos & Hertwig, 2017) and differential effects of ambiguity on risk-taking across the lifespan (aged 12-50 years, Tymula, Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013). In a recent neuroscientific study, adolescents engaged in similar levels of risky decisions between risky and ambiguous settings but the study did also not test age differences herein (aged 11-24 years). Yet, risky choice under risk and ambiguity revealed distinct neural mechanisms between risk initiation and outcome processing stages and these processes were differentially associated with individual differences in task behavior and self-report (Blankenstein, Schreuders, Peper, Crone, & van Duijvenvoorde, 2018). Altogether, findings on differences between known and ambiguous or uncertain risk choices demonstrate the importance to consider various risk-taking measures and moderators to understand adolescent risk-taking.

Accordingly, choices under risk are thought to be associated with development in cognitive functioning, like numeracy (Levin, Bossard, Gaeth, & Yan, 2014), and thus, to represent risky decision-making in a rather ‘cold’ context (Defoe et al., 2015; Figner & Weber, 2011). Adolescents seem to improve abilities to infer about risks and take more prudent decisions with age, at least when all information is described. Therefore, providing information about risk probabilities and dangers would decrease adolescents' risk-taking. Thus, the role of cognitive abilities on risky decision-making is assumed to be smaller than could be hypothesized based on the protracted development of cognitive abilities across adolescence (e.g., Rosenbaum et al., 2018; van den Bos & Hertwig, 2017). Relatedly, intervention strategies attempt to clarify potential risky behaviors but are rather unfruitful in actually decreasing such behaviors in youth (e.g., Drug Abuse Resistance Education (DARE) program, West & O’Neal, 2004). Consequently, adolescents' approach tendencies to novel and exciting situations may still encourage them to ‘leap before they look’ (van den Bos & Hertwig, 2017).

As such, ambiguity tolerance was associated with motivational (novelty seeking) but not cognitive functioning (intelligence, working memory, numeracy) in an exploratory analysis (van den Bos & Hertwig, 2017). Accordingly, findings showed ambiguity tolerance also to be positively associated with real-life risk-taking (Blankenstein et al., 2016; van den Bos & Hertwig, 2017), suggesting that exploration of unknown risks is a ‘hot’ decision-making context and may contribute to the understanding of adolescent-specific risk tendencies. However, risky decision-making under ambiguity has been attributed to sensation-seeking tendencies in youth that may not be devoid of cognitive control (Romer et al., 2017). Accordingly, ambiguity-tolerance would be a sign of adolescents being even more adaptive in their behavior than adults, i.e., from an economical point of view, as adults have repeatedly been shown to be risk-averse and thus, to dare but also gain less than adolescents in uncertain decision situations (Crone & Dahl, 2012; Romer et al., 2017).

Type of Outcome: Incentive Valence. Thereby, tendencies to approach or avoid certain risk-situations have been suggested to highly depend on what is at stake for the risk-taker. This is of importance for the present thesis in which studies had the goal to compare the influence of different types of positive and negative incentives on developmental trends in motivated behavior in general (*Paper I*), and risky decision-making in particular (*Paper II*). The following section will describe how outcomes of risky decisions are manipulated in terms of their type, value, and valence in previous research and how such variation may account for differences in developmental findings on adolescent risky decision-making.

As such, one of the most studied motivational influences on goal-directed and choice behavior in developmental research, but also in cognitive research and neuroscience more generally, is the influence of incentives. Thereby, incentives come in various forms and can differ in valence and type. In a first attempt, valence defines whether an incentive is evaluated as positive or negative, e.g., whether one takes risks for or against potential gains or losses. The gains and losses can further vary in their amount, that is, in positive or negative values. As such, studies vary in whether they used gain-, loss-, or mixed gambles, that is, whether adolescents engaged in risky decisions to maximize gains or minimize losses or both simultaneously, which may moderate age differences in risky decision-making across adolescence.

According to previous assumptions in the decision-making literature, like the influential Prospect Theory (Kahneman and Tversky, 1979; see section *2.2.1. Model Assumptions on Development in Risk-Taking*), decision-making differs depending on risky choice framing, e.g., whether positive (gains) or negative incentives (losses) can be expected. This assumption holds for adults, as they have been shown to take more risks to prevent losses than to maximize gains in many decision contexts (for a review, see Barberis, 2013). In contrast, adolescents are thought to be specifically prone to take risks when positive incentives are provided, following the logic of reward-sensitivity in youth. Adolescents would engage in more risks under gains than losses or mixed gambles, compared to both children and adults, as predicted by neurodevelopmental models. However, developmental models do not have specific predictions about the effect of negative incentives on loss and mixed gambles. Only the aforementioned fuzzy-trace theory (see section *2.2.1. Model Assumptions on Development in Risk-Taking*) posits that with the increase in gist-based decision making during adolescence, risky decisions would decrease for mixed and loss compared to gain gambles with age. This leads to contrasting predictions concerning the effect of gains and losses on developmental trajectories of risky decision-making.

Based on neuroimaging data, some brain structures were specifically active in response to positive incentives when gambling during adolescence, but reduced responses were found in studies that investigated loss events (see Silverman et al., 2015, for a review). Meta-analytic results suggested adolescents show larger activation of the nucleus accumbens, prefrontal cingulate cortex, and lateral occipital cortex to positive versus negative incentives. This suggests links between the processing of positive incentives with motor interfaces and self-referential cognitive activity that facilitates an approach to incentive-based stimuli. However, study results also showed adolescents to reduce activation in the amygdala, orbitofrontal cortex, and anterior cingulate cortex in reaction to negative incentives. Blunted sensitivity to negative feedback, i.e., threats or losses, has thereby been associated with adolescent risk-taking during which negative consequences might not be adequately weighted by adolescents (Silverman et al., 2015). However, while the meta-analysis did only test overall differences in brain activity patterns between adolescents and adults during incentive processing, this comparison was not reported concerning valence sensitivity, why age differences in neuronal valence sensitivity remain unclear.

In studies testing age differences in valence sensitivity, some structures were specifically active in response to positive incentives when gambling, with children and adolescents showing higher activation in these structures compared to older ages (e.g., in the anticipation stage, ventral striatum and orbitofrontal cortex, Chein et al., 2011; in the receipt stage, anterior insula and striatum, van Leijenhorst, Zanolie, et al., 2010), in accordance to presumed reward-sensitivity in youth. Studies that did apply mixed gambles showed that adolescents also engage in more (e.g., in the receipt stage, nucleus accumbens, Ernst et al., 2005; orbitofrontal cortex, van Leijenhorst, Crone, & Bunge, 2006) or less activity in response to gain omission or loss trials than adults (e.g., in the receipt stage, orbitofrontal cortex, van Leijenhorst et al., 2010; amygdala, Ernst et al., 2005). Furthermore, findings show higher activity in response to gains than losses in some brain structures (e.g., in the receipt stage, striatum and orbitofrontal cortex, May et al., 2004; prefrontal cortex and ventral striatum, van Duijvenvoorde et al., 2014), or higher activity for losses than gains in others (e.g., in the receipt stage, ventrolateral prefrontal cortex, van Leijenhorst et al., 2006) without age differences being found.

Additionally, some studies applied electroencephalography (EEG) measures, or more specifically, event-related potentials (ERP's), to investigate how adolescents differ in their neural reaction to the receipt of positive and negative incentives. The feedback-related negativity (FRN) is an ERP that depicts an individual's reaction to both positive and negative feedback. However, the FRN is usually more pronounced following negative than positive feedback, as it is thought to represent signals for a behavioral adjustment (e.g., Luck, 2014). In gambling tasks, the FRN also shows to be predominantly higher for negative than positive feedback (e.g., Crowley et al., 2013; Gonzalez-Gadea et al., 2016; Grose-Fifer, Migliaccio, & Zottoli, 2014; Santesso, Dzyundzyak, & Segalowitz, 2011) with small age differences in amplitude and latency but irrespective of valence domain (e.g., Crowley et al., 2013). Only male adolescents (13-17 years) showed a smaller FRN ratio between low gains versus low losses than adults (23-35 years) in one study (Grose-Fifer et al., 2014), indicating a lower valence sensitivity in receiving choice outcomes in adolescent males

In sum, neuroscientific findings show, if at all, only small age differences in reaction to positive and negative incentives during risky decision-making. Thereby, studies mainly focused on the receipt stage in the processing of positive incentives that implies difficulties in concluding neuronal valence sensitivity in youth. Furthermore, only a few neuroscientific findings on the valence-sensitivity show an association with actual choice behavior (e.g., Chein et al., 2011), with one study showing adolescents to report more positive feelings in gain trials than adults on incentive delivery (Ernst et al., 2005). In the following, there are differing views on how developmental differences in risky decision-making vary with outcome valence, that is, the meaning of risk-taking in terms of behavioral adjustment, i.e., to approach positive but avoid negative outcomes. However, a meta-analysis revealed that heterogeneity in risky decision-making between children, adolescents, and adults could not be accounted for by task settings that differed in gain versus mixed gambles (Defoe et al., 2015). Thereby, most hypotheses concerning adolescent risky behavior were based on reward-sensitivity and approach behavior in youth, that is, on assumptions of neurodevelopmental imbalance models. Consequently, most studies focused on the influence of incentives with differing values in the gain domain, or implemented mixed gambles at the utmost, why no age group comparisons concerning loss gambles were possible in the meta-analysis (Defoe et al., 2015).

As such, there are only a few studies that directly compared task settings in the gain and loss domain and even fewer studies that compared such influences on risky decision-making between multiple age groups. Across age, adolescents showed overall risk aversion in the gain but risk-seeking patterns in the loss domain (Barkley-Levenson, Van Leijenhorst, & Galván, 2013; Reyna et al., 2011; Tymula et al., 2013; van den Bos & Hertwig, 2017, but see Galván & McGlennen, 2012; Levin et al., 2014), indicating that adolescents are as loss-averse as adults in described risk situations, according to formal models (value function, Kahnemann & Tversky, 1992). When taking developmental differences into account, one study used the Cups task, a risky decision-making task in which participants choose between arrays of cups for which outcomes are either the same or include a gamble in which outcomes vary (Levin et al., 2014). In this study, parents showed more decisions for the risky array of cups when outcomes were framed in terms of losses than gains, a choice pattern that was not observed in their children (aged 8-17 years). However, adolescents showed a peak in risky choices under gains and a decline in risky choices under losses with age in a wheel-of-fortune task used in a recent study (van den Bos & Hertwig, 2017), a finding that in sum is in favor of imbalance perspectives on adolescent development. That is, the effect of incentive valence on developmental trajectories in risky decision.making showed conflicting results, also on the behavioral level.

By that means, the effects of incentive valence may show conflicting results as valence effects further interact with provided outcome magnitudes (high or low variability, high or low values, Kahnmann & Tversky, 1992) and probabilities (ambiguity or known risk). As such, loss aversion is often found in described but usually not in experience-based task settings when tested in adults (for a review, see Wulff, Mergenthaler-Canseco, & Hertwig, 2018). As such, comparing task settings that differ in provided information about outcome magnitude and probability would be one way to investigate the moderating effects of probability weighting on the influence of incentive valence across adolescence. In sum, insights into developmental differences between gain, loss, or mixed choices in risky decision-making are scarce, especially in the loss domain for experimental settings (Defoe et al., 2015). Furthermore, the findings highlight the importance to consider various reference points in the prediction of risky decision-making in adolescence and to investigate how neural responses (brain activity patterns and ERP's) in distinct processing stages relate to actual behavior in youth.

Type of Outcome: Incentive Type. Age differences in risky decision -making may not only depend on whether incentives are presented in terms of gains or losses, but also on the type of incentives used. Therefore, the review that is part of this thesis (*Paper I*) had the hypothesis that diverse reactions to different kinds of incentives would partly account for inconsistencies in findings concerning a peak in motivated behavior during adolescence. On the one hand, some incentives are innate as their value and significance root in primary needs, like eating and drinking. Secondary incentives, on the other hand, hardly depend on individual needs, and their value and significance are experienced or learned, as it is the case for monetary, cognitive, and social incentives. Based on the assumption that specifically social incentives are salient during adolescence and thus, that adolescents would approach social situations more likely than younger or older ages, *Manuscript I* investigated the effect of peer observation on risky choices from pre to late adolescence. As such, the influence of incentives on adolescent brain and behavior may vary with their valence, value, and type dependent on previous (life) experience.

However, to our knowledge, no study considered comparisons between various types of incentives when investigating adolescents' tendencies for risky decisions. As such, it remains unclear, for instance, whether children and young adolescents would prefer primary over secondary incentives and vice versa, whether older adolescents and adults would prefer secondary over primary incentives, and following would approach some incentives to a higher extent than others. By that means, accumulating evidence speaks in favor of brain structures showing overlapping roles in the processing of different types of incentives, like non-social and social ones (for a review, see Ruff & Fehr, 2014). In sum, heightened risky decisions in adolescence may be domain-specific, also concerning what type of outcomes adolescents chose during task conduction. This may be the case as primary and varying types of secondary incentives might differentially elicit socioemotional arousal in youth.

As already summarized in previous sections, positive and negative incentives showed varying influences on adolescents' brain and behavior, and only a few studies found age-differences in valence effects during risky decision-making. In contrast, a meta-analysis found generally higher reward activity in reward-related brain regions, like the ventral striatum, in adolescents compared to children and adults (Silverman et al., 2015). To date, most studies in the decision-making literature focused on monetary incentives, that are implemented choice options with varying amounts of money or coins, that can be gained or lost with varying probabilities. However, there are no studies that tested the effects of primary incentives, for instance., of sweets, on adolescent risky decisions. One study suggests children (aged 7-11 years) report more overall positive feelings when gambling for sweets and different activity patterns in reaction to losing them compared to adults (aged 22-26 years, Luking et al., 2014), but they did not include an adolescent sample. Hence, it remains unclear whether primary incentives would trigger adolescents to more or less risky decisions than children or adults, while reactions to primary incentives seem to be age-invariant so far.

In a similar vein, it is common practice in the developmental literature of childhood to replace monetary by cognitive incentives, i.e., points, as children might have only a little experience with monetary values. Especially, as the effects of monetary incentives would be distorted when comparing children's reactions to these with more mature age groups that already have gained experiences with money and consequently might have a different perspective on monetary values. This may similarly the case in comparisons between adolescents, younger and older age groups. In one study, especially early adolescents (aged 9-12 years), but also young adults (aged 18-26 years) made better predictions under low-risk than high-risk trials when gambling for points (van Leijenhorst et al., 2006). This finding was accompanied by stronger recruitment of cortical structures for high-risk compared to low-risk trials in both age groups, but stronger recruitment of anterior cingulate cortex in young adolescents. Thereby, losing points resulted in stronger activation in the ventrolateral prefrontal and orbitofrontal cortex, while activation in the latter was stronger for young adolescents and in sum, suggests loss aversion in gambles for points. To summarize, adolescents and adults seem to process cognitive incentives similarly, and both age groups took the riskiness of the situation into account when gambling for points.

Finally, researchers highlighted the fact that adolescence is a sensitive period for social development as adolescents undergo dramatic changes in brain regions that are known for their role in mentalizing, that is, thinking about the beliefs and states of others, as well as in regions that are active in the processing of social cues (for a review, see Blakemore & Mills, 2014; van Hoorn, Shablack, Lindquist, & Telzer, 2019). Beyond changes in structural and functional brain maturation, adolescents undergo a social reorientation that signifies individuals to move away from family structures and increasingly spend time with their peers (Brown & Larson, 2009). Accordingly, adolescents are preoccupied with their peers' views and to adjust to the (cultural) norms of their peer group, also expressed through similar taste in music and clothing style. Moreover, most decisions for risk-taking occur in the presence of peers during adolescence (Gardner & Steinberg, 2005), and social cues or incentives may be of particular interest in understanding heightened risky decision making during adolescence (Defoe et al., 2019; Shulman et al., 2016)

As such, adolescent-specific tendencies for risky decisions may not be limited to situations that are associated with incentives in terms of specific values, like certain amounts of sweets, money, or points. A variety of socioemotional contexts have been shown to have a high impact on, e.g., adolescent decision-making (e.g., Steinberg, 2008; Chein et al., 2011; Shulman et al., 2016; Smith et al., 2013). For example, adolescents showed a specific tendency for risky decisions when they previously experienced a social exclusion situation (Peake, Dishion, Stormshak, Moore, & Pfeifer, 2013) and under peer presence in a traffic situation (Chein et al., 2011). Specifically, the latter finding revealed that only adolescents showed higher activity in the striatum and more risky decisions when peers were present than both children and adults. This further emphasized the notion that adolescents are both specifically sensitive to social and non-social incentives with a shared role of the striatum in these developmental processes (Ruff & Fehr, 2014; Silverman et al., 2015). Interestingly, heightened activity in reward-related brain regions in social situations was also shown during decision-making that was not related to risk-taking (Smith, Steinberg, Strang, & Chein, 2015), indicating that heightened social sensitivity exists independent from the riskiness of a situation in adolescence. Thus, there is a need to incorporate social influences and responses from brain regions involved in social information processing into models of adolescent decision-making. Accordingly, a recent meta-analytic study indicates that the dorsomedial prefrontal cortex, inferior frontal gyrus/insula, and ventral striatum are consistently associated with adolescent decision-making in social contexts (van Hoorn et al., 2019), but activity within these regions was modulated by the type of social context and social actors involved.

Recently, there is increasing interest in understanding the influence of peers on risk-taking, also in the laboratory. Up to now, studies differ in the manipulation of peer influence as sometimes peers are present in the laboratory (e.g., Gardner & Steinberg, 2005), remotely present (e.g., Chein et al., 2011), or virtual (e.g., Smith, Chein, & Steinberg, 2014). Furthermore, following a social norm perspective, studies investigated the effects of peer advice or pressure, by introducing risk-seeking or risk-averse peer behavior (e.g., Simons-Morton et al., 2014) and/or feedback (e.g., Shepherd, Lane, Tapscott, & Gentile, 2011). In sum, social situations have repeatedly been shown to heighten adolescents' tendencies for risky choices in simulated driving (e.g., Cascio et al., 2015; Chein et al., 2011; Gardner & Steinberg, 2005; Peake et al., 2013; Shepherd et al., 2011; Simons-Morton et al., 2014; but see Kretsch & Harden, 2014), while the mere presence of peers sometimes did not and adolescents only engaged in more risks when actively encouraged by peers to do so (e.g., Bingham et al., 2016; Centifanti, Modecki, MacLellan, & Gowling, 2014).

Studies on adolescent risky decision-making, amongst other findings on cognitive control and learning tasks, indicated that social situations can also lead to more cautious and deliberate decisions (Cascio et al., 2015; Kessler, Hewig, Weichold, Silbereisen, & Miltner, 2017; Shepherd et al., 2011; Somerville et al., 2019; Telzer, Ichien, & Qu, 2015; van Hoorn, McCormick, & Telzer, 2018) and accelerate learning and performance (for a review, see Telzer, 2016). Thereby, peer influences may further be dependent on other factors, like the aforementioned differences in the type of risk and outcomes. Peer presence sometimes did increase risky choices in gambling tasks (e.g., Smith et al., 2014; Van Hoorn, Crone, & Van Leijenhorst, 2017) but sometimes showed mixed results (e.g., Haddad, Harrison, Norman, & Lau, 2014; Lloyd & Döring, 2019; Somerville et al., 2019) or even the reverse effect (Kessler et al., 2017). One recent study further suggests that peer effects in simulated driving apply to male adolescents only (Defoe et al., 2019a), while most studies did not report gender differences (Defoe et al., 2015) and some studies tested risky decision-making only in males (e.g., Kessler et al., 2017; Lloyd & Döring, 2019; Simons-Morton et al., 2014), possibly to avoid age-related findings to be distorted by different developmental trajectories between the gender.

2.2.4. Relations Between Individual Differences and Risky Choice

The previous sections elaborated that heightened risky decision-making might not be ubiquitously true in adolescence as some developmental models would suggest. In contrast, age differences in risk propensity depend on task contexts in adolescence, such as settings with different types of risk, incentives, and social situations. Thereby, it is crucial not only to question *when* adolescents engage in risks and *what* triggers them to do so but also to investigate *who* is willing to engage in heightened risky decisions and *why*. Therefore, the following section will review some of these individual differences in socioemotional functioning that have commonly been suggested to influence risk tendencies in youth and which were also investigated in the studies of *Paper II* and *Manuscript I*.

Accordingly, personality-tied concepts, like previous experiences with risk and the resulting individual differences in risk-attitudes, as well as individual differences in temperament (e.g., impulsivity), arousability (e.g., approach behavior/sensation seeking) and cognition (e.g., intelligence) have been considered to differentially predict risk-taking in adolescence. Here, it is referred to as temperament when speaking about dispositions that, in contrast to personality, reflect innate characteristics and influence behavior already early in life. However, temperament and at least some personality measures share an endogenous nature and relatedly, an intrinsic maturation (for a review, see McCrae et al., 2000). Consequently, a clear dissociation between temperament and personality is not reliable. Furthermore, empirical research yielded conflicting results on the interplay between personality traits, or temperamental dispositions, and decision-making, thereby increasing the gap between studies on behavioral and personality outcomes (for a review, see Appelt, Milch, Handgraaf, & Weber, 2011; Mohammed & Schwall, 2009). Thus, developmental researchers were especially discouraged to conclude about the interaction between risk-related traits and risky choices in experimental settings (e.g., Lauriola, Panno, Levin, & Lejuez, 2014).

Thereby, weak associations between experimental decision-making and, e.g., self-reported risk preferences or propensity measures of actual risky activities, might be tied to the variety of task settings used and consequently, the differences in task characteristics might mask the potential effects of individual differences in task behavior (Mohammad & Schwall, 2009; Figner & Weber, 2011). Especially, as researchers have been focusing on a variety of experimental settings, as well as an unsystematic set of personality measures (Appelt et al., 2011). With a psychometric approach, Frey and colleagues (2017) found weak correlations between self-reported risk preferences and task behavior, and concluded behavioral tasks were not suited to infer about general risk preference. However, experimental tasks with different choice architectures, like choices under risk or ambiguity, would be well suited to investigate how risk contexts, i.e., specific states, interact with individual differences in personality or temperamental dispositions (Frey et al., 2017).

As such, adolescents show a specific tendency to approach exciting (sensation- or novelty-seeking) and potentially rewarding (approach behavior) situations, which has also been associated with heightened activity in reward-related brain regions, like the nucleus accumbens (Braams et al., 2015; Hawes et al., 2017; Urošević, Collins, Muetzel, Lim, &

Luciana, 2008), and real-life risks (e.g., Galvan et al., 2007; Reyna et al., 2011). However, sensation-seeking and related constructs may predict risky choices only in specific situations. That is, relations between self-reported sensation-seeking were reported for choices in experience-based settings (e.g., in the Balloon Analogue Risk Task, Lauriola et al., 2014) and under ambiguity, and uncertainty, but not risk (van den Bos & Hertwig, 2017). However, predictions by sensation-seeking tendencies and approach behavior might differ between individuals and developmental stages (e.g., Duell et al., 2016) and might not only reflect socioemotional functioning but also development in cognitive control (Romer et al., 2017; Zuckerman, 2007), that is, adaptive risk-exploration tendencies.

Thereby, approach and sensation-seeking diminish for more impulsive temperaments, which reflect decisions about immediate urges without considering potential consequences. Impulsivity has previously been considered to include various facets of acting without thinking (Eysenck & Eysenck, 1978). Some individuals might describe their behavior as imprudent (i.e., acting without thinking) because of their impulsive temperament, while others describe themselves as venturesome, as they would engage in risky behaviors only when riskiness and potential consequences are known (e.g., bungee jumping). As such, some but not all impulsive tendencies might be reflected in more risky choices and their predictions in risk-taking behavior may be domain-specific. Thereby, impulsivity and associated constructs also show a peak in adolescence but are inversely correlated with control abilities, like working memory, suggesting that impulsive adolescents are more likely to maintain negative consequences of risky behavior (Romer et al., 2017). That is, as sensation seeking and approach behavior decline but cognitive control abilities increase until early adulthood, risk-taking during this period seem less due to imbalance than to individual differences in disposition to impulsivity that emerge before adolescence and predict heightened negative consequences of risk-behavior stable across development (Bjork & Pardini, 2015; Iacono, Malone, & McGue, 2008; Khurana, Romer, Betancourt, & Hurt, 2018; Moffitt et al., 2011).

Finally, there is an increasing interest in understanding how social development attributes to risky behaviors (Blakemore & Mills, 2014). Given that some of the most salient incentives in adolescence are from the social domain (Crone & Dahl, 2012), like peer presence or feedback, socioemotional engagement might promote empathetic responses and following the development of social functioning (e.g., Allemand, Steiger, & Fend, 2015). Especially, as resistance to social influences has been shown to still be developing during adolescence (Paus et al., 2008; Steinberg & Monahan, 2007; Sumter et al., 2009). In return, individual levels of, e.g., empathy or resistance to peer influence, may predict adolescents' tendency to decide for risks in specific situations. Accordingly, adjustment of risky choices to social influences was associated with individual susceptibility or resistance to such influences in previous studies (e.g., Chein et al., 2011; Kessler et al., 2017; Peake et al., 2013). Furthermore, self-reported resistance to peer influence was associated with differences in neural responses to risky decisions when alone or peers were present, suggesting that there is also a biological mechanism for social influence and functioning on risk-taking (Chein et al., 2011).

In sum, risky decision-making is domain-specific during adolescence, so might be predictions of individual differences on risk-behavior. Accordingly, the empirical studies that are part of this thesis aimed at partly filling the gap between person and behavior by considering also individual differences in cognitive and socioemotional functioning to predict risky choices in a broad age range and various task contexts during adolescence.

Intermediate Summary and Implications for the Present Study

In a nutshell, choices in risky decision-making emerge in various forms that all may be influential to the subjective representation of risk in a given situation. While developmental models suggest an adolescent-specific tendency for risk-taking, heuristics, as well as formal models on decision-making, imply that such developmental trajectories differ with types of choices and outcomes. However, risky decision-making in general and few task characteristics showed to be age-variant across adolescence. As such, adolescents become more risk-averse in described risk situations, when all information about risks and outcomes are given, but more tolerant to the unknown (ambiguity and uncertainty) with more explorative behavior than both, children and adults in experimental decision-making. While there are no clear findings suggesting adolescents to specifically approach positive incentives or avoid negative ones more or less with age, reward-sensitivity, as well as social sensitivity alters brain activity patterns during adolescence.

Thereby, high emotional and especially, social situations have been shown to alter risky decision-making in adolescents that are thought to best represent risk-behavior in an adolescent’s everyday-life. That is, experimental decision-making tasks manipulate perceived risk through varying task contexts and objective risk characteristics and thus, have proven useful to investigate *when* adolescents engage in risk-taking and *what* ultimately drive risky choices during this period. It is for these advantages that experimental decision-making tasks are thought to trigger specific states that might further be useful to understand *who* engages in risky choices during adolescence, like individuals that describe their behavior as seeking for exciting or rewarding situations, impulsive, or sensitive to social circumstances. Concluding, research on various types of risky decision-making might further account for the variance in the interaction between the when, what, and who of risk-taking during adolescence.

However, there are some caveats in these conclusions. First, there are few direct comparisons between specific task characteristics across or within the adolescent period that would allow for conclusions about (individual) differences in developmental trajectories of risky decision-making dependent on such characteristics. Second, some findings and model perspectives on adolescent-specific responses are reduced to the neuronal level, often without adolescents showing different behavioral responses than other age groups. Finally, most findings are from one adolescent sample or from comparisons with a younger and/or older age group, which are not sufficient to infer about developmental trajectories, i.e., the effect of the developmental stage, or individual differences on risky decision-making.

However, developmental research in adolescence needs studies that investigate such effects in wide age ranges across adolescence and/or in longitudinal studies to better understand how adolescent tendencies for risk change, also dependent on specific contextual factors, like in the presence of peers. The following paragraph will summarize the previously reported theories and model perspectives, as well as the strengths and limitations of studies testing these hypotheses and based on that, will give an overview of the research objectives of the actual study.

Summary and Research Objectives

Overall, neurodevelopmental models allowed for simple and intuitive access to formulate hypotheses concerning developmental changes during adolescence. However, despite the growing number of studies that investigated adolescent-specific behaviors, not all behaviors can be explained by heightened socioemotional sensitivity during this period (Casey, 2015; Crone & Dahl, 2012; Defoe et al., 2015; Spear, 2011). For example, adolescents also show less or no differences in responsivity to appetitive, emotional, and aversive cues compared to other age groups (e.g., Casey, 2015; Spear, 2011). Thus, despite its intuitive description of developmental processes during adolescence, dual-systems heuristics might not be sufficient to depict complex associations in adolescents brain maturation and associated changes in motivated behavior (e.g., Casey, 2015; Casey, Galván, & Somerville, 2016; Pfeifer & Allen, 2012; van den Bos & Hertwig, 2017)).

Paper I

Given the inconsistent findings in the literature concerning the suggested peak in reward sensitivity and resulting motivated behavior in youth, the review of *Paper I* had the working hypothesis that different types of incentives might have divergent influences on goal-directed behavior, like on performance in cognitive control and learning tasks, as well as choice behavior between children, adolescents, and adults. By reviewing the findings on this behalf *Paper I* helped to better integrate the model assumptions and hypotheses of our study that investigated motivated behavior with various methods into the actual adolescent literature.

In a word, the review (*Paper* I) included and separated between studies that investigated the influence of primary, monetary, and /or social incentives on cognitive control abilities, learning, or choice behavior, with behavioral, EEG, and MRI methods, in the anticipation and feedback phase of incentive processing. To infer about differential age trends depending on the aforementioned moderators and methods, studies were only included when they investigated a broad age range or included at least two age groups across adolescence.

As such, the review (*Paper I*) offers important insights into a) common and divergent functions of different kinds of incentives in different stages of motivated behavior, b) potential age-differences herein, and c) whether different kinds of incentives are processed in similar brain regions across ages.

However, comparisons between studies on motivated behavior in youth come with certain limitations. First, findings on adolescent development are mostly about cross-sectional studies that either investigate one age group in the adolescent period or compare them with another adult group or a group of children (see also Casey, 2015; Casey et al., 2016; Defoe et al., 2015). However, most models on adolescent development imply linear, as well as nonlinear developmental trends, and often explain adolescent behavior in terms of interactions between such divergent age trends. Furthermore, many studies investigate, e.g., reactions to socioemotional cues or cognitive control abilities only, and cannot conclude possible interactions between underlying processes. In sum, most study designs did not enable to test the interaction between the two systems directly and might foster conflicting findings on adolescent development.

Second, conflicting findings concerning adolescent-specific behaviors might further derive from the vast variability in measures used. Not only do measures on neuronal and behavioral levels often differ in their predictions about adolescent-specific effects, but findings also differ based on investigated processing stages and task settings used. Finally, many findings were not reflected in terms of potential individual differences in socioemotional and control functioning that might account for diverse reactions in motivated behavior. In sum, only a few studies simultaneously compared various age groups or developmental stages, task contexts, and individual differences in their predictions about adolescent-specific behavior.

Beyond difficulties in comparing various study designs, the findings of the review of *Paper I* suggested that there are only a few indices for an adolescent-specific peak in motivated behavior. These were mostly about the effects of highly salient incentives, or about specific task settings during adolescence, like risky decision-making, for which heightened risk tendencies during adolescence have specifically been found under risk uncertainty and social influences. Consequently, studies of *Paper II* and *Manuscript I* focused on the development of risky decision-making from pre to late adolescence. Given the previously mentioned caveats in studies testing developmental differences in motivated behavior in youth, studies of the present thesis simultaneously incorporated various contexts, also a social one, and individual differences in the prediction of risky choice in a broad age range across adolescence.

That is, empirical studies of the actual thesis (*Paper II* and *Manuscript* I) are based upon a longitudinal study to investigate normal adolescent development in motivation and cognitive abilities over two years. Participants were invited across a wide age range from pre to late adolescence (range 9-18 years). While this thesis focuses on data from the first wave, thus on cross-sectional effects of age only, the study allowed to test age trends in the full range from pre to late adolescence, a period when the most prominent developmental changes occur during adolescence. The study tested cognitive abilities, decision-making, as well as socioemotional functioning, with a great variety in measures and domains.

Paper II

Previously, hypotheses on adolescent risk-taking have primarily been drawn on behalf of neurodevelopmental models in adolescence that suggest mid-adolescents to be specifically prone to engage in risk (e.g., Steinberg, 2008). Based on the insight that risky decision-making is a multifaceted construct and that not all types of risk-taking might be heightened during adolescence (e.g., Defoe et al., 2015), the study of *Paper II* included four well-known experimental decision-making task contexts that differ in risk versus ambiguity, gain versus loss domain, static versus dynamic risk and time pressure versus no time pressure. As such, linear and non-linear developmental trajectories were compared between game-like task contexts in a broad age sample ranging from pre to late adolescence.

It has been suggested that task settings differ in how they trigger socioemotional arousal during adolescence and as such, might explain when adolescents engage in heightened risky choices and what characteristics urge them to do so. Furthermore, not all adolescents might be prone to take more risky choices and not in all task contexts. To infer the question *who* engages *when* in risky decision-making, the study considered individual differences in age, gender, and intelligence, as well as individual differences in temperamental dispositions, like impulsivity, approach behavior, and empathy, to predict risky choices across adolescence. Thereby, predictions might differ between task contexts that have previously been shown to reflect more or less independent risk situations, i.e., trigger diverse states depending on task characteristics.

That is, the study of *Paper II* is built upon suggestions that adolescents may not ubiquitously engage in heightened risky decision making and gives insight into a) whether task contexts reflect similar or divergent risky choice behavior and as such, b) whether choice behavior in these tasks shows divergent developmental trajectories across adolescence. Furthermore, the study gives insight into c) whether individual differences in temperamental dispositions account for risk propensities in experimental risk-taking above individual differences in age, gender, and intelligence, potentially differentially between task settings.

Manuscript I

Part II of the thesis will give an overview of social influences and specifically, about peer influences on risky decision-making in adolescence. Recently, researchers highlight the importance to include changes in social functioning and associated social sensitivity into models on adolescent development (e.g., Blakemore & Mills, 2014). In terms of risk-taking, most real-life risks occur in the peer group (e.g., Steinberg, 2015) and peers have been shown to heighten risky decision-making and associated brain activity patterns in reward-related brain regions, specifically in adolescence (e.g., Chein et al., 2011). Thereby, heightened risky decisions have mostly been shown in one task setting, i.e., simulated driving. However, results are conflicting, showing sometimes more or less risk-taking under peer presence when altering task context and type of peer influence or pressure (see also Defoe et al., 2019), suggesting adolescents to flexibly adjust choice behavior to social situations. Accordingly, social influences have already been shown to have positive outcomes in youth (see Telzer, 2016 for a review), beneath findings of negative consequences, like accelerated risk-taking.

Thereby, few studies looked at developmental differences in peer influences on risky choices throughout the adolescent phase. Furthermore, the mechanism or the dynamics behind choice behavior under peer influence remain unclear (e.g., Braams, Davidow, & Somerville, 2019; Ciranka & van den Bos, 2019). Finally, it has been suggested that social sensitivity in choice behavior might underly individual differences during adolescence. Consequently, not all adolescents would engage in more risky choices when under peer influence, as this might be a specifically male phenomenon (e.g., Defoe et al., 2019a; Wilson & Daly, 1985), or a characteristic of adolescents that are specifically low resistant to peer influence, as it is the case for younger compared to older adolescents (e.g., Steinberg & Monahan, 2007).

As such, one of the risky decision-making tasks implemented in our study was manipulated in such a way that adolescents believed they would be observed by a same-age same-sex peer via webcam during task conduction in the study of *Manuscript I*. That is, participants conducted the task once alone and once under virtual peer observation. Thereby, the Balloon-Analogue Risk Task (BART, Lejuez et al., 2002) is a dynamic and experience-based decision-making task that allows one to infer about choice behavior when each decision for risk heightens the chance to gain more but also the unknown probability to lose all previous achievements. Following, the study of *Manuscript I* give insights into a) how adolescents might adjust their risky choices to peer observation and b) potential age differences from pre to late adolescence herein. The manuscript further informs about potential moderating effects on age trajectories of the peer observation effect that are c) reactivity to previous outcomes (gain or gain omission) or general learning from previous trials and d) individual differences in gender and resistance to peer influences.

Altogether, the thesis aims at giving insight into the question of whether adolescents indeed engage in motivated behavior, irrespective of potential negative consequences, and show reduced performance. In contrast, the thesis also reflects adolescent behavior concerning the question of whether it represents a flexible adjustment to the situation at hand that might also be adaptive, given the ever-changing environment and few experiences in youth. In the view of adolescence being a period of risks and chances, risky decision-making is a suitable approach to sum up these research objectives by inferring about whether adolescents are gamblers at any chance. Thus, the studies of the present thesis derive about the influence of task context and individual differences in cognitive control and socioemotional functioning in predicting adolescent tendency for risky choices in a multitude of settings and about potential age-related differences in a broad age range from pre to late adolescence herein.

3. Overview of Publications

Paper I

Kray, J., Schmitt, H., Lorenz, C., & Ferdinand, N. K. (2018). The Influence of Different Kinds of Incentives on Decision-Making and Cognitive Control in Adolescent Development: A Review of Behavioral and Neuroscientific Studies. *Frontiers in Psychology, 9* (May).

This review reports differences in behavioral, ERP, and MRI findings on the influence of different kinds of incentives (primary, cognitive, monetary, and social) on cognitive control and decision-making performance between children, adolescents, and adults.

Theoretical background. Based on the assumption of dual-systems models that adolescents show a peak in the maturation and activity of reward-related brain regions, like dorsal and ventral striatum (for a review, see Silverman et al., 2015), researchers assumed adolescents to be specifically sensitive to incentives (e.g., Casey et al., 2008; Luna & Wright, 2015; Shulman et al., 2016; Steinberg, 2008). Thereby, models also differ in their assumptions about developmental trajectories of cognitive control regions, and there are differing views on whether and how the cognitive control and reward-related systems interact during motivated behavior (for a review, see Shulman et al., 2016). Accordingly, studies show controversial findings on whether incentives enhance or hamper cognitive control and decision-making performance in adolescents.

Inconsistencies in the literature concerning a peak in reward-sensitivity during adolescence could be due to several reasons. First, studies vary in the investigated age groups, including only a narrow age range within the adolescent period, or only including two age groups from adolescence, childhood, or adulthood to examine age differences. Second, quite various tasks and paradigms were used to investigate the influence of incentives on adolescent behavior. Third, different methods were used to infer the impact of incentives on adolescents' brains and behavior, ranging from self-report and, behavioral data, to neuroscientific methods. Neuroscientific methods have the advantage to enable researchers to investigate the influence of incentives during different processing stages, such as incentive anticipation, response selection, and evaluation.

In terms of reinforcement learning, positive incentives are thought to heighten the probability of the respective behavior in the future. Finally, the possibility that incentives of different domains and amounts may also have a differing impact on age-related differences in cognitive control, performance, decision-making, and learning has been neglected so far. In contrast to primary incentives that are innate, like food, or sweet liquids, the value of secondary incentives, like money, points, or social feedback, is learned. As such, differences in incentive types but also in their amount, magnitude, and the probability of occurrence may further inform about age-related differences in processing and on the impact of incentives on goal-directed behavior.

Inclusion criteria and hypotheses. Given the inconsistencies in findings of age-differences in the influence of incentives on adolescent goal-directed behavior and the variability in study designs used to infer about such influences, this review aimed at investigating whether inconsistent findings could be due to divergent influences of different kinds of incentives used in studies about adolescent development. Thereby, studies were only included when they investigated cognitive control performance, learning, and/or decision-making under the prospect of primary or secondary incentives. Further, studies had to compare motivated behavior between at least two age groups within adolescence or between an adolescent group and a group of children and/or adults to be considered in the review.

Comparisons between studies were separated for findings concerning the impact of primary, cognitive, monetary, and social incentives and for each incentive type between behavioral data and neuroscientific (fMRI and EEG) findings for different processing stages, if able. As such, sensitivity to incentives may change from childhood to adulthood but possibly only for specific types of incentives and/or only during specific processing stages, such as during the anticipation/preparation, the decision/response selection, and during the feedback/evaluation phase. Moreover, children may rather be motivated by primary incentives, while the value and impact of (some) secondary incentives may indeed show a peak during adolescence given the greater experience with such incentives.

Main results and conclusion. In sum, most findings do not suggest age-related differences in the influence of different kinds of incentives on cognitive control performance, learning, and decision-making. This stands in contrast to neurodevelopmental models that suggest higher cognitive control-related activity in adults but higher reward-related activity in adolescents. However, with rather high monetary incentives, unknown decision options, and in social contexts, adolescent behavior differed from children and adults. In general, the adolescent literature needs studies that directly compare different task contexts, incentives, and multiple age groups throughout adolescence to further infer about adolescent-specific behavior. Thereby, it is also important to determine the role of different processing stages and individual differences in the subjective value of incentives to understand under which circumstances adolescents show an imbalance between reward and control.

Paper II

Lorenz, C., & Kray, J. (2019). Are Mid-Adolescents Prone to Risky Decisions? The Influence of Task Setting and Individual Differences in Temperament. *Frontiers in Psychology, 10*(July), 1–16. https://doi.org/10.3389/fpsyg.2019.01497

The study investigates the role of task context and individual differences in temperament on developmental trajectories in risky choices from early over mid to late adolescence.

Theoretical background. While the maturational imbalance between socioemotional sensitivity and cognitive control is assumed to be greatest in mid-adolescence, findings on an adolescent-specific tendency to engage in risky decisions are controversial. That is, several task contexts emerged to investigate risky decision-making in the laboratory, and adolescents did not ubiquitously engage in more risks than children and adolescents in all types of risky decision-making (Defoe et al., 2015), suggesting that heightened risk tendencies in youth are domain-specific.

Formal models on decision-making differentiate between certain characteristics of risk settings that trigger more or less risky choices. Thereby, adolescents would engage in more risky decisions under (socio)emotional arousal, that is, in so-called ‘hot’ contexts but would be quite deliberate decision-makers in described, ‘cold’ task contexts (Figner & Weber, 2011). However, several factors are thought to heighten socioemotional arousal during decision-making, like ambiguity in risk probabilities and outcomes, the prospect of rewards, like gains in money or points, but also social situations, time pressure, and dynamic changes in risk probabilities. Such moderating factors may contribute to the understanding of the often conflicting findings on adolescent-specific tendencies for risk.

Furthermore, not only when adolescents engage in more risky decisions and what causes them to react in a risky manner, but also the question of who is willing to engage in risky choices is important to conclude about the generalizability of heightened risk-tendencies in youth (e.g., Casey et al., 2008). Thereby, some individual differences are associated with risk propensities in the laboratory, like gender, social, and cognitive functioning, as well as temperamental dispositions for imprudent behavior (e.g. approach to rewards, impulsivity), but to varying degrees. More specifically, who engages in heightened risky decisions during adolescence may also highly depend on the task contexts used (Lauriola et al., 2014), which depict specific states under which some individuals might be more prone to take risks than others.

Hypotheses. The study investigated developmental trajectories in risky decision-making from pre to late adolescence (age range 9-18 years) and potential differences herein depending on four well-known task contexts in the adolescent literature (Treasure Hunting Task in a gain and a loss domain [THT Gain and THT Loss, see Cups Task [Levin, Weller, Pederson, & Harshman, 2007]; Balloon Analogue Risk Task [BART. Lejuez et al., 2002] and Stoplight task [e.g., Chein et al., 2011]). According to previous findings that showed accelerated tolerance for unknown risk situations but decreased risky decisions in described settings during adolescence (e.g., van den Bos & Hertwig, 2017), developmental trajectories were expected to differ between risky decision-making tasks for which risk probabilities and outcomes are known (THT Gain and THT Loss) or uncertain (BART and Stoplight task). Furthermore, given a hypothesized reward-sensitivity during adolescence (e.g., Steinberg, 2008), choices under known risk were predicted to be heightened in the gain compared to the loss domain from pre to late adolescence (THT Gain and THT Loss). Accordingly, task contexts in which risk probabilities and outcomes can only be experienced by sampling trials often also differ in the type of outcome (e.g., gain or gain omission of monetary outcomes, BART; gain or loss of time, Stoplight task) and risk probabilities that can either be static for each choice (Stoplight task) or dependent on previous choices i.e., can be dynamic (BART). As such, the study was based on the questions, whether risky decision-making is associated with task contexts, or whether risky decision-making depicts quite different processes between divergent task contexts during adolescence.

Furthermore, risky choices are influenced by individual differences during adolescence (e.g., Lauriola et al., 2014), suggesting not all individuals to increase risky choices in all situations during this time. Previously, it has been posited that above individual differences in age, gender, and cognitive functioning, some temperamental dispositions, such as behavioral approach to rewards, impulsivity (e.g., acting without thinking, venturesomeness) and social engagement (e.g., empathy) cause heightened risky decisions during adolescence (e.g., Steinberg, 2008) or are characteristics of adolescents that are specifically susceptible to imprudent behavior above development during this time, respectively (Romer et al., 2017). Thereby, it remains unclear whether different types of risky decision-making are similarly susceptible to the aforementioned individual differences during adolescence.

Main results and conclusion. The tendencies in choice behavior were overall quite similar to findings in the decision-making literature that are mostly about risky choices in adulthood. First, concerning differences between description- and experience-based risky decision-making, individuals engaged in more risky choices under known risk (THT Gain and THT Loss) than under uncertainty (BART and Stoplight task), which is in line with the finding that adults are typically more risk-averse under unknown than known risks (Hertwig et al., 2004). Second, adolescents overall engaged in more risky decisions to prevent losses (THT Loss) than to maximize gains (THT Gain), which is in line with Prospect Theory that suggests higher risk-aversion in the loss than the gain domain of risky decision making (framing effect, Tversky & Kahnemann, 1992).

However, mid adolescents showed less differentiation between description- and experience-based contexts, suggesting an age-specific tolerance for the unknown during risk-taking. Accordingly, previous studies that directly compared choice behavior under risk and uncertainty revealed similar ambiguity tolerance in adolescents (aged 10-25 years; Blankenstein et al., 2016; aged 12-17 years, Tymula et al., 2012; aged 8-22 years; van den Bos & Hertwig, 2017). In contrast to the hypothesized reward-sensitivity in youth, findings revealed no age differences in valence sensitivity in choice under risk, and task contexts in which adolescents aimed at maximizing monetary gains (THT Gain and BART) were not susceptible to any of the considered individual differences, like approach behavior, or impulsivity, in this study. This stands in contrast to some findings that show risky choices in the gain domain to be most pronounced in adolescence (Reyna et al., 2011; van den Bos & Hertwig, 2017) or at least increasing during this time (Levin et al., 2014). The differences in findings might be attributable to varying magnitudes that could be gained during task conduction for which values were significantly higher (e.g., Reyna et al., 2011), or more variable (e.g., van den Bos & Hertwig, 2017), than in this study, suggesting reversed framing effects in the prospect of specifically salient incentives during adolescence.

Thus, risky choices to decrease known losses (THT Loss) became less with age and general intelligence, while individuals with higher venturesomeness were more likely to engage in such risks. Moreover, decisions to engage in risks to prevent a loss in time (Stoplight task) were most pronounced in mid-adolescence and high impulsive, as well as empathetic adolescents, were predicted to engage in more risks in such task context. These findings suggest that rather loss-aversion than approaching positive incentives underlies individual differences in temperamental dispositions above age and gender differences, as well as cognitive functioning in youth.

In sum, the results of *Paper II* revealed several important insights. First, the four task settings showed differential developmental patterns from late childhood to late adolescence. Second, the task settings were only moderately associated with each other, suggesting that diverse task contexts depict unique decision-making processes. Finally, only some of the investigated task settings were susceptible to individual differences in temperament and intelligence (THT Loss and Stoplight task). The findings highlight that task contexts, varying risks, and outcome characteristics would trigger diverse states that are variable in their prediction of risky choice during adolescence.

II Original Research Articles

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REVIEW
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The Influence of Different Kinds of Incentives on Decision-Making and Cognitive Control in Adolescent Development: A Review of Behavioral and Neuroscientific Studies

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A number of recent hypothetical models on adolescent development take a dual-systems perspective and propose an imbalance in the maturation of neural systems underlying reward-driven and control-related behavior. In particular, such models suggest that the relative dominance of the early emerging subcortical reward system over the later emerging prefrontal-guided control system leads to higher risk-taking and sensation-seeking behavior in mid-adolescents. Here, we will review recent empirical evidence from behavioral and neuroscientific studies examining interactions between these systems and showing that empirical evidence in support for the view of a higher sensitivity to rewards in mid-adolescents is rather mixed. One possible explanation for this may be the use of different kinds and amounts of incentives across studies. We will therefore include developmental studies comparing the differential influence of primary and secondary incentives, as well as those investigating within the class of secondary incentives the effects of monetary, cognitive, or social incentives. We hypothesized that the value of receiving sweets or sours, winning or losing small or large amounts of money, and being accepted or rejected from a peer group may also changes across development, and thereby might modulate age differences in decision-making and cognitive control. Our review revealed that although developmental studies directly comparing different kinds of incentives are rather scarce, results of various studies rather consistently showed only minor age differences in the impact of incentives on the behavioral level. In tendency, adolescents were more sensitive to higher amounts of incentives and larger uncertainty of receiving them, as well as to social incentives such as the presence of peers observing them. Electrophysiological studies showed that processing efficiency was enhanced during anticipation of incentives and receiving them, irrespective of incentive type. Again, we found no strong evidence for interactions with age across studies. Finally, functional brain imaging studies revealed evidence for overlapping brain regions activated during processing of primary and secondary incentives, as well as social and non-social incentives. Adolescents recruited similar reward-related and control-related brain regions as adults did, but to a different degree. Implications for future research will be discussed.

Keywords: adolescence, incentive type, decision-making, cognitive control, social-emotional system

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INTRODUCTION

The development throughout adolescence has received an immense scientific interest in the past decades. Researchers from various disciplines have investigated the typical and atypical development in this period of the lifespan to describe and understand biological, social-emotional, cognitive control, and neurological changes. As a transition phase between childhood and adulthood, adolescence has been considered as a sensitive period with heightened vulnerability and demands for adjustment in behavior (Steinberg, 2005; Crone and Dahl, 2012) and sociocultural processing (e.g., Blakemore and Mills, 2014). A number of significant developmental tasks have to be mastered, such as becoming independent from parents, dealing with dramatic hormonal and physical changes, finding a peer group and close interpersonal relationships, and regulating emotions and feelings. If adolescents fail to solve such developmental tasks, their higher vulnerability may result in major problems of behavioral regulation expressed in delinquent behavior, abnormal substance use, such as binge drinking and drug use, and risky behavior, such as reckless driving, as well as in emotional dysfunctions, such as developing depressions and eating disorders. Scientists and also politicians became sensitive to these problems, as adolescents have a four time higher risk of death as a consequence of accidents, injuries, or suicide than children or adults (cf. Eaton et al., 2008).

Evidence from developmental neuroscience about the interplay between emotional/motivational and cognitive development and brain maturation has strongly inspired new ideas and hypothetical models about changes in brain structure and function and their relation to behavior throughout adolescence. To date, quite a number of comprehensive and excellent reviews addressing this interplay, already exist in the literature (Yurgelun-Todd, 2007; Casey et al., 2008; Steinberg, 2008; Geier and Luna, 2009; Luna et al., 2010; Somerville and Casey, 2010; Somerville et al., 2010; Richards et al., 2013; Crone, 2014; Shulman et al., 2016; for a critical comment, see Van den Bos and Eppinger, 2016). Therefore, we will only briefly summarize the most prominent theoretical conceptions and then highlight the potential advantages of applying neuroscientific methods for providing empirical support of differential functions of incentives (rewards and punishments) on decision-making and cognitive control behavior. In particular, we will focus on the questions whether different kinds and amounts of incentives are processed similarly, have a similar impact on control behavior, and have the same function and importance throughout adolescence. Therefore, we will summarize recent evidence on the influence of primary incentives (e.g., food, liquids, etc.) and secondary incentives (e.g., monetary, cognitive, and social) on decision-making and cognitive control functioning. Given that empirical findings of higher risk taking and reward sensitivity in adolescents seem rather mixed, we have the working hypothesis that the type of incentive may explain the inconsistent findings in the literature. To date, it is relatively unknown whether the subjective value of incentives will change in the transition from childhood to adulthood, and if so, how this might influence current theoretical models and interpretation of research findings. Because our main interest is on developmental changes in processing incentives, we will include only studies investigating a relatively large age range around adolescence and studies comparing at least two age groups, thereby one group of children or adolescents.

THEORETICAL VIEWS ON THE INTERPLAY BETWEEN THE DEVELOPMENT OF SOCIAL-EMOTIONAL AND COGNITIVE CONTROL PROCESSING

Researchers from the field of developmental cognitive neuroscience have suggested that a differential maturation of two brain systems associated with socio-emotional and cognitive control processes can explain the higher reward sensitivity, impulsivity, and risk-taking behavior in adolescence. These so-called dual-system models propose that the social-emotional system including the striatum, medial and orbital prefrontal cortices matures earlier than the cognitive control system including the lateral prefrontal, lateral parietal, and anterior cingulate cortices. According to these models, risk-taking behavior is primarily increased in mid-adolescence as the socio-emotional system is highly activated by incentive-related information whereas the cognitive control system is not yet efficiently developed to regulate this bottom-up driven behavior (e.g., Casey et al., 2008; Steinberg, 2008; Luna and Wright, 2016). Although these models vary in their specific assumptions about the developmental course in these two brain systems, they all agree on a differential maturation of these two brain systems as a source of higher impulsivity, sensation seeking, and risky decision-making during adolescence (for a detailed review, Shulman et al., 2016). The triadic model is the only one that posits three interacting subsystems (Ernst and Fudge, 2009; Ernst, 2014). This model builds upon dual-system models but assumes a third brain system (mainly the amygdala) recruited for processing the intensity of emotions and avoidance behavior.

Clear empirical support in favor for the one or the other model is currently lacking. Most studies did not measure indicators reflecting the socio-emotional and cognitive control brain systems, as well as risky decision-making in common across a wider age range, which makes it difficult or impossible to test the theoretical assumptions of different dual-system models against each other. Moreover, the existing empirical evidence on whether incentives either enhance or hamper decision-making and cognitive control functioning and more so for adolescents than for both children and adults is rather inconsistent. Several reasons might explain these inconsistencies. First, studies vary a lot in the investigated age ranges and most studies only included two age groups to examine age differences (i.e., non-linear age trends cannot be determined). Second, studies also vary in the type of tasks and experimental paradigms applied to measure cognitive control processes in decision-making situations (Richards et al., 2013). Third, the impact of incentives has been investigated with different methods, ranging from questionnaires and behavioral data to neuroscientific methods [mostly, functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG)]. The major advantage of neuroscientific methods here is that the influence of incentives can be observed in different phases of goal-directed behavior, such as during the anticipation/preparation, the decision/response selection, and finally during the feedback/evaluation phase. Indeed, there is already evidence that the same type of incentive can result in a hypoactivation or hyperactivation of the same brain system (e.g., the striatum) in adolescents relative to adults, depending on the processing phase (incentive anticipation or response selection; e.g., Geier and Luna, 2009). Hence, the differential functions of incentives for controlling and regulating behavior may also contribute to the inconsistent findings in the literature and need to be considered as well (cf. Richards et al., 2013). Fourth, one aspect that has been largely neglected is the role of the type and amount of incentives. Receiving 5 cents, a sweet, or a smile can have a different subjective value for individuals and the relative preference for specific incentives may change during developmental transitions. Here, we aim to review recent evidence from neuroscientific studies to answer the question of whether similar or different mechanisms and brain systems are at work when different kinds of incentives motivate behavior.

DIFFERENTIAL FUNCTIONS OF INCENTIVES ON DECISION-MAKING AND COGNITIVE CONTROL BEHAVIOR

How goal-directed behavior is motivated is differently conceptualized across research fields in psychology (for a review, see Braver et al., 2014). For the purpose of this review, we will use the term incentive or incentive value as it is used in the reinforcement learning and cognitive neuroscience literature. Stimuli leading to a larger probability that a specific behavior will be shown more often in the future, and leading to more engagement of individuals toward approaching and consuming them, are positive reinforcers or rewards. In contrast, stimuli leading to a larger probability that a specific behavior will be shown less in the future, and leading toward avoiding them, are negative reinforcers or punishments. Primary incentives are innate, such as food, liquids, or sex, and are often used to modify behavior in animals, while secondary incentives are learned, such as monetary, cognitive, or social ones. Both primary and secondary incentives can vary in their amount, magnitude, probability of occurrence, delay, and so on. Whereas the delay of rewards is relatively well examined in infant research, researchers only recently have started to systematically investigate the effects of the amount, magnitude, and probability of incentives on the development of goal-directed behavior and decision-making (Defoe et al., 2015).

Interestingly, recent advances in cognitive neuroscience have identified different neuronal structures that are associated with incentive value coding in separate phases of goal-directed and choice behavior (for a review, Ruff and Fehr, 2014). Dopamineric neurons in the ventral tegmental area and substantia nigra are assumed to code the anticipation of rewards. The discrepancy between an anticipated value and the received outcome value during learning is also encoded in dopamineric neurons and this prediction error signal is used to update the anticipated value of stimuli to optimally learn and adapt the behavior to actual task demands. Changes in the neuronal activity of the orbitofrontal cortex (OFC) have been observed during receipt or consumption of rewards, while the anterior cingulate cortex (ACC), anterior insula and the amygdala are also activated during experiencing pain and receiving punishment. Finally, the ventromedial prefrontal cortex (vmPFC) is recruited during the decision process when anticipated values and response options need to be integrated (for details, see Ruff and Fehr, 2014). Although the types of cognitive processes and associated brain structures will vary along different experimental paradigms and task demands, we will distinguish between phases of anticipating incentives during preparation or response selection and receiving or consuming incentives during the feedback phase. This will help us to identify differential effects of the same incentives as well as similar effects of different incentives in these phases.

In sum, we will report and summarize results from developmental studies that have investigated the impact of primary and secondary incentives on decision-making (e.g., gambling tasks), on cognitive control (e.g., go-nogo tasks or anti-saccade tasks), and on learning from feedback (e.g., reinforcement learning tasks). Our aim is to examine (a) whether different kinds of incentives may have a common or a different function in different stages of motivated behavior, (b) whether the effects are age-invariant or not, and (c) whether similar brain networks are involved in incentive processing across age. Therefore, we include the main findings from behavioral, EEG, and fMRI studies that are briefly summarized in **Tables 1–3**, respectively, along with information about age ranges, type of task and incentive, and processing stage (only in **Tables 2**, **3**). Note that we include only developmental studies in these tables that at least compared two age groups or investigated a broader age range during adolescence.

HOW DO DIFFERENT INCENTIVES INFLUENCE DECISION-MAKING AND COGNITIVE CONTROL?

Primary Incentives

Primary incentives have mainly been applied in animal research to motivate behavioral changes and learning (cf. Schultz et al., 1997). In contrast, rather few developmental studies have investigated the impact of primary incentives on goal-directed behavior and decision-making. In comparison to secondary incentives, primary incentives can be delivered immediately, and therefore may be more valuable, motivating, and salient in children than in adolescents or adults (cf. Luking et al., 2014).

We found three studies that have examined the influence of primary rewards on decision-making (Hayden and Platt, 2009; Galván and McGlennen, 2013; Luking et al., 2014). For instance, Luking et al. (2014) were interested in whether receiving or losing candies modulates behavioral choices. Children and young adults were more likely to repeat the same choice after receiving a candy than after losing one, known as “win-stay—lose-shift”

TABLE 1 | Overview of behavioral studies.

Authors	Age groups (age range in years)	Task	Incentive type	Main results
Galván and McGlennen, 2013	- Adolescents (13–17) - Young adults (23–35)	Passive reward-delivery task	Primary (water, sucrose, salty or no liquid in neutral option)	- No age differences in reaction to water, sucrose, salty and neutral liquid - Higher positive ratings to sucrose than salty liquids in adolescents than adults on a liquid rating scale
Luking et al., 2014	- Children (7–11) - Young adults (22–26)	Gambling task (card guessing game)	Primary (high and low gains, 4 or 2 pieces; high and low losses, 2 or 1 pieces)	- No age differences in win-stay lose-shift strategy - Children reported more overall positive feelings during the task than adults in a post-scan questionnaire
Grose-Fifer et al., 2014	- Adolescents (13–17) - Young adults (23–35)	Gambling task (card guessing game, reward probability 50%)	Monetary (high and low gains, 32–40 Cents; high and low losses, 6–11 Cents)	Both age groups selected high-monetary incentive cards more often than low-monetary incentive cards
May et al., 2004	Children and adolescents (8–18)	Gambling task (card guessing game)	Monetary (neutral trials, no reward; gain trials, 1 Dollar; loss trials, 50 Cents)	No age differences in win-stay lose-shift strategy
Van Duijvenvoorde et al., 2014	- Adolescents (10–16) - Young adults (18–25)	Gambling task (slot machine task, reward probability 33 and 66%)	Monetary (passed trials, no reward; gain and loss trials, ±10 Cents)	Tendency for risky decisions was not related to age, pubertal development, or reward sensitivity
Ernst et al., 2005	- Adolescents (9–17) - Young adults (20–40)	Gambling task (Wheel of Fortune, reward probability 50%)	Monetary (high and low gains, 4 Dollar or 50 Cents; or reward omission)	- Both age groups more satisfied with high than low gains - Adolescents reported more positive feelings than adults in gain trials in a post-scan questionnaire on incentive delivery
Bjork et al., 2010	- Adolescents (12–17) - Adults (22–42)	Monetary Incentive Delay (MID) Task	Monetary (neutral trials, no reward/ loss; high and low gain and loss trials, 50 Cents or 5 Dollar)	Faster responding and higher accuracy with increasing incentives irrespectively of the valence, but no age differences therein
Bjork et al., 2004	- Adolescents (12–17) - Adults (22–28)	Monetary Incentive Delay (MID) Task	Monetary (neutral trials, no reward/loss; high and low gain and loss trials, 20 Cents, 1 Dollar or 5 Dollar)	No effect of reward magnitude or age group on accuracy or reaction times
Galván et al., 2006	- Children (7–11) - Adolescents (13–17) - Young adults (23–29)	Two-choice reaction time task (reward probability 100%)	Monetary (low, medium, and high number of monetary coins)	Faster reaction times to high than medium and low rewards and this effect is most pronounced in adolescents
Cohen et al., 2010	- Children (8–12) - Adolescents (14–19) - Aduts (25–30)	Probabilistic learning task (83% predictable and random condition)	Monetary (no-reward vs. high and low gain trials, 25 or 5 Cents)	Faster responding to large than small incentives only for the adolescent group
Unger et al., 2014	- Children (10–11) - Mid adolescents (13–14) - Late adolescents (15–17)	Reinforcement learning task (100% valid feedback)	Monetary (no-incentive vs. gain and loss trials, 37 Cents)	- Faster responding and better accuracy on win and loss trials for all age groups - Faster learning for older participants but no age differences in interaction with incentives

(Continued)

TABLE 1 | Continued

Authors	Age groups (age range in years)	Task	Incentive type	Main results
Santesso et al., 2011	- Adolescents (16–17) - Young adults (18–29)	Gambling task (60:40% win-loss ratio)	Monetary (high and low gains and losses, 195–205 Cents or 45–55 Cents)	- Adolescents and adults do not differ in reward and punishment sensitivity in personality scales and post-experimental questionnaires - Slower response times when two low or high cards were presented compared to one low and one high card
Van Leijenhorst et al., 2006	- Early adolescents (9–12) - Young adults (18–26)	Gambling task (cake task, high and low risk trials)	Cognitive (gain and loss trials; 1 point)	- Both age groups made better predictions under low-risk than high-risk trials and this performance difference was most pronounced in young adolescents
Teslovich et al., 2014	- Adolescents (11–20) - Adults (22–30)	Random Dot Motion Task	Cognitive (high and low gain trials, 5 or 1 points)	Slower responding for large rewards in the group of adolescents relative to adults, who showed slower responding to small rewards
Paulsen et al., 2015	Children and adolescents (10–22)	Inhibitory control (antisaccade task)	Cognitive (no-reward vs. gain and loss trials, 5 points)	- No differences in reaction times between neutral, gain or loss condition - No age differences in incentive processing
Padmanabhan et al., 2011	- Children (8–13) - Adolescents (14–17) - Adults (18–25)	Inhibitory control (antisaccade task)	Cognitive (no incentive vs. potential gain of points)	Adolescents improved inhibitory control with gains to the adults' performance level
Geier and Luna, 2012	- Adolescents (13–17) - Adults (18–29)	Inhibitory control (antisaccade task)	Cognitive (neutral vs. gain and loss trials, 1–5 points)	No age interaction on loss trials but adolescents made more errors on gain trials
Hämmerer et al., 2010	- Children (9–11) - Adolescents (13–14) - Young adults (20–30) - Older adults (65–75)	Probabilistic learning task (65, 75, or 85% positive feedback probability)	Cognitive (gain and loss of feedback points, 10 points)	- Higher variability in decision-making after loss than gain feedback over all age groups - Adolescents and young adults needed less trials to learn correct responses from trial feedback, showed less variability in decision-making and learned more from gains than from losses as compared to younger and older age groups
Chein et al., 2011	- Adolescents (14–18) - Young adults (19–22) - Adults (24–29)	Risk-taking task (Stoplight task)	Social-induced (alone and peer condition: two friends)	Adolescents but not older age-groups exhibited more risk-decisions when being observed by peers
Jones et al., 2014	- Children (8–12) - Adolescents (13–17) - Young adults (18–25)	Social reinforcement learning task (33, 66, and 100% positive feedback probability)	Social-induced (positive and no positive social feedback)	- Independent of age, rare probability of positive feedback led to more false answers than both continuous or frequent positive feedback - Adolescents demonstrated a lower positive learning rate than children and adults - Participants with a higher positive learning rate were more sensitive to feedback probabilities

TABLE 2 | Overview of EEG findings.

Authors	Age groups (age range in years)	Task	Incentive type	Phases	Main results
Crowley et al., 2013	- Children (10–12) - Early adolescents (13–14) - Late adolescents (15–17)	Gambling task (Balloon task, reward probability 50%)	Monetary (no-reward vs. gain trials, 10 Cents)	Receiving incentives	- Larger FRN amplitude to neutral than gain trials - Larger FRN amplitude for males than females - Larger FRN for 10–12 and 13–14 year-olds than 15–17 year-olds irrespective of gains and losses - Longer FRN latency for gain than neutral trials - Longer FRN latency for males than females on gain trials - Reduced latency from 10–12 to 15–17 year-olds irrespective of gains and losses
Gonzalez-Gadea et al., 2016	Adolescents (8–15)	Gambling task (high and low advantageous and disadvantageous decks)	Monetary (high and low gains, 2–4 Dollar; and losses, 1–14 Dollar)	Receiving incentives	- Larger FRN amplitude to losses than gains
Grose-Fifer et al., 2014	- Adolescents (13–17) - Young adults (23–35)	Gambling task (Card guessing game, reward probability 50%)	Monetary (high and low gains, 32–40 Cents; high and low losses, 6–11 Cents)	Receiving incentives	- Larger FRN amplitude for losses than gains - Larger FRN amplitude for low than high gains in males - FRN ratio (low gains vs. losses) smaller in adolescent males - Longer FRN latency to losses than gains - Longer FRN latency to high than low outcomes - Longer FRN latency to high gains and losses than to low gains and losses in adolescent males
Santesso et al., 2011	- Adolescents (16–17) - Young adults (18–29)	Gambling task (60 and 40% win-loss ratio)	Monetary (high and low gains and losses, 195-205 Cents and 45–55 Cents)	Receiving incentives	- Larger FRN amplitude for losses than gains - Larger FRN amplitude for low than high gains - FRN amplitude to gains and losses larger for individuals with high score on sensitivity to punishment scales in a personality questionnaire
Unger et al., 2014	- Children (10–11) - Mid adolescents (13–14) - Late adolescents (15–17)	Reinforcement learning task (100% valid feedback)	Monetary (no-incentive vs. gain and loss trials, 37 Cents)	Receiving incentives	- Larger ERN/Ne amplitude for younger and older adolescents than children - Larger ERN/Ne and Pe in incorrect than correct trials - Reduced Pe in late adolescents compared to younger age groups - Larger Pe in gain than neutral and loss trials - No interaction of age and incentive condition in the ERN/Ne amplitude or Pe amplitude
Lukie et al., 2014	- Children (8–13) - Adolescents (14–17) - Young adults (18–23)	Gambling task (virtual maze, reward probability 50%)	Cognitive (reward and non-reward trials in form of fruits)	Receiving incentives	- No age differences in reward positivity - Longer latency for children in reward positivity

(Continued)

TABLE 2 | Continued

Authors	Age groups (age range in years)	Task	Incentive type	Phases	Main results
Hämmerer et al., 2010	- Children (9–11) - Adolescents (13–14) - Young adults (20–30) - Older adults (65–75)	Probabilistic learning task (65, 75, or 85% positive feedback probability)	Cognitive (gain and loss of feedback points, 10 points)	Receiving incentives	- Children showed largest overall FRN of all age groups - Children and older adults showed smaller differences between FRN after gains and FRN after losses - Younger adults showed larger enhancement of FRN after losses than children

FRN, Feedback-related negativity; ERN/Ne, Error-related Negativity; Pe, Error Positivity.

strategy. In a post-experimental questionnaire, children reported more overall positive feelings during the task, suggesting a higher subjective value of sweet incentives for children than for adults. A similar finding has been reported by Galván and McGlennen (2013), who compared the effects of appetitive (i.e., sugary) and aversive (i.e., salty) liquids between adolescents and young adults. Both groups reported positive feelings toward appetitive (i.e., sugary) and negative feelings to aversive (i.e., salty) liquids, and this difference was even more pronounced for adolescents than for adults. Hence, both studies support the view that primary incentives are particularly salient to children and adolescents when compared to adults. A third study investigated only younger adults but considered individual differences in risk taking which is often higher in adolescents (Hayden and Platt, 2009). This study directly compared primary and secondary incentives (sugary liquid vs. money) within subjects. The results indicated that although there were individual differences in either preferring or avoiding risks, these were independent of the kinds of incentives given.

Neuroscientific methods like fMRI are suitable to investigate whether age differences in brain activity occur during the processing of primary incentives, i.e., during anticipating or consuming those (Geier and Luna, 2009; Galván and McGlennen, 2013; Luking et al., 2014). For instance, Galván and McGlennen (2013) found no age differences during the anticipation of positive and negative primary incentives in the ventral striatum (VS), OFC, insula, and inferior frontal gyrus. In contrast, during consumption, they found larger activations in the VS in adolescents than young adults, and this activation was positively correlated with increasingly positive ratings for appetitive sugary liquids in adolescents, but not in adults. However, substantial developmental differences in reward delivery have been detected particularly for aversive primary incentives and the omission of rewards. Here, adolescents relative to adults showed exaggerated striatal responses to the delivery of aversive salty liquids (Galván and McGlennen, 2013), and children had a larger activation in the dorsal/posterior insula after candy losses than adults (Luking et al., 2014).

Taken together, primary incentives seem particularly salient in childhood and adolescence as revealed by self-reports, but had no influence on the behavioral choices itself. On the neural level, adolescents relative to adults showed an increased sensitivity in the VS only during consummatory, but not during anticipatory incentive processing. This pattern of results may support a bias in decision-making in adolescents in a way that behavior is less motivated by potentially rewarding activities but is more tuned toward consumption of risk-related rewards, such as alcoholic drinks, drugs, and future choices (Bjork et al., 2010). More importantly, when carefully controlling for the separation between incentive anticipation and delivery as well as for applying child-friendly incentives to equate motivation between age groups, adolescents tend to be highly sensitive to the loss of incentives, suggesting that the striatum codes susceptibility to punishment regimes in adolescence.

Secondary Incentives

Secondary reinforcers are learned by definition and can be characterized as monetary, cognitive, or social (Montague and Berns, 2002). In the following, we will first review empirical studies examining the effects of monetary incentives, before we turn to cognitive and social ones. Within each section, we will first report behavioral findings (see **Table 1**), and then the neuronal signatures of incentive processing during different stages as measured with even-related potentials (ERPs) and fMRI (see **Tables 2**, **3**).

Monetary Incentives

Most of the developmental studies to date applied monetary incentives to investigate age-related differences in incentive processing (cf. Bjork et al., 2004, 2010; Galván et al., 2006; Crowley et al., 2013; Gonzalez-Gadea et al., 2016). Although monetary incentives are easily applicable, studies markedly differ (a) in reward magnitude, ranging from a few cents to several euros per trial, (b) in whether monetary feedback is provided in a trial-based or block-wise manner, and (c) in whether wins and losses are presented with equal probability or loss aversion is considered (Santesso et al., 2011; Kujawa et al., 2014). These differences modify the relative "risk" within the decision-making process that subjects may discount on each trial and need to be considered for comparison across different studies. A further major problem for developmental studies is to compare a fixed amount of money across age groups, as receiving, for instance, 50 cents has a different meaning for children and late-adolescents.

TABLE 3 | Overview of fMRI findings.

Authors	Age groups	Task	Incentive type	Phases	Main results
Galván and McGlennen, 2013	- Adolescents (13–17) - Young adults (23–35)	Passive reward-delivery task	Primary (water, sucrose, salty, or no liquid in neutral option)	- Anticipating incentives - Receiving incentives	- No age and condition interactions in the OFC, IFG, insula and caudate - Stronger activation to sugary liquids in adolescents than young adults in the VS - Adolescents show exaggerated striatal activity to aversive salty liquids relative to young adults
Luking et al., 2014	- Children (7–11) - Young adults (22–26)	Gambling task (card guessing game)	Primary (high and low gains, 4 or 2 pieces; high and low losses, 2 or 1 pieces)	Receiving incentives	- Stronger activation in the dorsal/posterior insula after losses in children than in adults - Stronger activation in the anterior insula after losses in adults than in children
May et al., 2004	- Children and adolescents (8–18)	Gambling task (card guessing game)	Monetary (neutral trials, no reward; gain trials, 1 Dollar; loss trials, 50 Cents)	Receiving incentives	- Larger and later peak activations in the striatum and OFC to gains than losses - No age or gender differences in these activations
Van Leijenhorst et al., 2010	- Children (10–12) - Adolescents (14–15) - Young adults (18–23)	Gambling task (slot machine task, reward probability 50 %)	Monetary (neutral and gain trials; 5 Cents)	- Anticipating incentives - Receiving incentives	- Children and adolescents showed larger activation of the anterior insula to potential gain cues / to neutral cues which were more similar to gain cues - Larger striatal activity to reward delivery in adolescents - Young adults showed larger OFC activation to omission of incentives
Van Duijvenvoorde et al., 2014	- Adolescents (10–16) - Young adults (18–25)	Gambling task (slot machine task, reward probability 33 and 66%)	Monetary (passed trials, no reward; gain and loss trials, ±10 Cents)	Receiving incentives	- Larger medial PFC and VS activations to gains than losses - Activation in medial PFC and VS was related to the tendency to choose the risky option - No age differences in these activations - Individual differences in reward sensitivity were related to activation of VS during development
Ernst et al., 2005	- Adolescents (9–17) - Young adults (20–40)	Gambling task (wheel of fortune, reward probability 50%)	Monetary (high and low gains, 4 Dollar or 50 Cents; or reward omission)	Receiving incentives	- Larger nucleus accumbens and bilateral amgydala activation for gain than loss trials - Larger nucleus accumbens activation in adolescents than young adults during reward omission - Larger amygdala activity to incentive omission in young adults than adolescents - Negative emotion correlated with amygdala response to losses in young adults, positive emotions correlated with nucleus accumbens activity in adolescents
Cohen et al., 2010	- Children (8–12) - Adolescents (14–19) - Adults (25–30)	Probabilistic learning task (83% predictable and random condition)	Monetary (no-reward vs. high and low gain trials, 25 or 5 Cents)	- Anticipating incentives - Receiving incentives	- Greater striatal activation with increasing age - Hypersensitive response to unpredicted rewards in striatum and angular gyrus in adolescents as compared to children and adults - Medial PFC was sensitive to reward magnitude, showing a linear increase in sensitivity with increasing age

(Continued)

TABLE 3 | Continued

Authors	Age groups	Task	Incentive type	Phases	Main results
Bjork et al., 2010	- Adolescents (12–17) - Adults (22–42)	Monetary Incentive Delay (MID) Task	Monetary (neutral trials, no reward/loss; high and low gain and loss trials, 50 Cents or 5 Dollar)	- Anticipating incentives - Receiving incentives	- Reduced activation in the nucleus accumbens for gain than neutral trials in adolescents relative to adults - No age differences in brain activations
Bjork et al., 2004	- Adolescents (12–17) - Adults (22–28)	Monetary Incentive Delay (MID) Task	Monetary (neutral trials, no reward/loss; high and low gain and loss trials, 20 Cents, 1 Dollar or 5 Dollar)	- Anticipating incentives - Receiving incentives	- Reduced activation in the VS and amygdala for gain than neutral trials in adolescents relative to adults - No age differences in brain activations
Galván et al., 2006	- Children (7–11) - Adolescents (13–17) - Young adults (23–29)	Two-choice reaction time task (reward probability 100%)	Monetary (low, medium, and high number of monetary coins)	Both anticipating and receiving incentives	- Stronger activation in the nucleus accumbens and lateral OFC with increasing incentives - Adolescents showed larger activation in reward-related brain regions relative to children and young adults
Van Leijenhorst et al., 2006	- Early adolescents (9–12) - Young adults (18–26)	Gambling task (cake task, high and low risk trials)	Cognitive (gain and loss trials; 1 point)	- Anticipating incentives - Receiving incentives	- Higher activation in the OFC and DLPFC for high- than low-risk trials, but no age differences - Larger ACC activation in adolescents on high- than low- risk trials relative to young adults - Both age groups showed a larger activation for receiving negative than positive incentives in the VLPFC - Stronger activation in the OFC for negative vs. positive feedback in early adolescents relative to adults
Teslovich et al., 2014	- Adolescents (11–20) - Adults (22–30)	Random Dot Motion Task	Cognitive (high and low gain trials; 5 or 1 points)	Receiving incentives	- Larger VS activation for larger than smaller incentives for both age groups - Stronger activation in the DLPFC and IPS for adolescents relative to adults when incentives are large
Paulsen et al., 2015	- Adolescents (10–22)	Inhibitory control (antisaccade task)	Cognitive (no-reward vs. gain and loss trials, 5 points)	Receiving incentives	- No age differences in VS activation - Striatal activation was associated with better inhibitory control in neutral trials - Activation in the VS on no-incentive trials was associated with better inhibitory control, especially in adolescents $<$ 17 years, whereas these activations dampened performance for adolescents $>$ 17 years - Negative correlation between age and activation of the amygdala in loss trials
Padmanabhan et al., 2011	- Children (8–13) - Adolescents (14–17) - Adults (18–25)	Inhibitory control (antisaccade task)	Cognitive (no incentive vs. potential gain of points)	Receiving incentives	- Adolescent-specific enhanced striatal activity, associated with reward processing, and enhanced activity in areas responsible for inhibitory control during reward trials

(Continued)

TABLE 3 | Continued

Authors	Age groups	Task	Incentive type	Phases	Main results
Chein et al., 2011	- Adolescents (14–18) - Young adults (19–22) - Adults (24–29)	Risk-taking task (Stoplight Task)	Social-induced (alone and peer condition: two friends)	Anticipating incentives	- Stronger activation of reward-related brain areas (VS, OFC) during risky decision making in adolescents when peers were watching - Independent of social context, adults engaged lateral PFC more strongly than adolescents - Activity in VS and OFC was associated with risky-decision making in adolescents only
Smith et al., 2015	- Adolescents (14–19) - Adults (24–32)	Decision making (guessing task without risk)	Social-induced (alone and peer condition: two friends)	Receiving incentives	- Stronger activation in the VS in adolescents during decision making when peers were watching
Gunther Moor et al., 2010	- Pre-pubertal children (8–10) - Early adolescents (12–14) - Older adolescents (16–17) - Young adults (19–25)	Feedback processing (social judgment task)	Social-induced (feedback whether a person would like them or not)	- Anticipating incentives - Receiving incentives	- Stronger activation of ventromedial PFC and striatum during the expectation to be liked in older adolescents and adults - Similar activation in ventromedial PFC and striatum in all age groups when expectation to be liked was followed by social acceptance feedback - Linear increase in activation with age in striatum, subcallosal cortex, paracingulate cortex, lateral PFC and OFC when expectation not to be liked was followed by negative social feedback
Jones et al., 2014	- Children (8–12) - Adolescents (13–17) - Young adults (18–25)	Social reinforcement learning task (33, 66, and 100% positive feedback probability)	Social-induced (positive and no positive social feedback)	Receiving incentives	- Anterior to mid insula activation was correlated with the positive prediction error in adolescents - Adolescents engaged putamen and supplementary motor area more than children or adults in response to positive reinforcement - VS and medial PFC equally engaged across age

Behavioral findings

Studies that have used gambling tasks to examine the impact of monetary incentives on age differences in decision-making often found that choice behavior was age-invariant to the magnitude of monetary incentives (Grose-Fifer et al., 2014) and of risk (Van Duijvenvoorde et al., 2014). For instance, Grose-Fifer et al. (2014) applied a card-gambling task in which monetary wins and losses were either small or large (for details, see **Table 1**). On each trial, adolescents and adults were to choose either a high- or a low-monetary incentive card. Both age groups did not differ in choice behavior and selected high-monetary incentive cards more often than low-monetary incentive cards. Likewise, Van Duijvenvoorde et al. (2014) used a slot-machine task and compared adolescents and adults in risk taking by manipulating the chance to win (66 vs. 33%) or to lose 10 cents. Again, both age groups did not differ in their choices to play and by this in risk taking (Van Duijvenvoorde et al., 2014). However, monetary incentives were probably too low to induce risky decisions in the later study. May et al. (2004) investigated age differences in a two-choice card guessing game in which children and adolescents had to guess whether the hidden number of an upcoming card was greater or less than five. Correct guesses resulted in a gain of one Dollar and incorrect guesses in a loss of 0.5 Dollar, relative to a neutral condition. This ratio was selected to control for loss-aversion in human decision-making (May et al., 2004). Results showed that age did not account for the amount of variability of choosing the same response after a previous reward (i.e., win-stay strategy) or the opposite response after a previous loss (i.e., lose-shift strategy), suggesting that children and adolescents do not differ in choice-behavior when loss-aversion is considered.

In two studies by Bjork et al. (2004, 2010), the effects of magnitude of the monetary incentives was measured by a modified Monetary Incentive Delay (MID) task in which different cues indicated monetary incentives and risks (e.g., win or lose 0, 0.5, 1, or 5$). While the first study did not reveal an effect of incentive magnitude on task performance (Bjork et al., 2004), in the second study adolescents and adults showed faster responding to target stimuli as incentive magnitude increased on both gain and loss trials and again, there were no age differences in these effects (Bjork et al., 2010).

A similar finding has been reported in a study of Unger et al. (2014) who investigated how monetary incentives change performance in a learning task. Results indicated better performance in the two incentivized conditions, that is, children, mid-adolescents, and late adolescents responded faster and more accurately on gain and loss trials relative to the neutral condition (for details, see **Table 1**). Again, there were no age differences in performance benefits when incentives were provided during learning. However, Galván et al. (2006) applied a learning task in which children, adolescents, and adults had to respond as quickly as possible to a cue that was associated with either a low, medium, or large incentive value. Although all age groups responded faster to large incentives, the RT-difference between incentive values was largest in the group of adolescents. Similarly, Cohen et al. (2010) found that only adolescents responded faster to large than small incentives as compared to children and adults in a probabilistic learning task.

Considering individual differences, personality scales as well as post-experimental questionnaires further revealed that adolescents and adults do not differ in reward and punishment sensitivity (Santesso et al., 2011), as well as in positive feelings related to large compared to small monetary incentives (Ernst, 2014). However, adolescents reported more positive feelings than adults during winning money, but not during reward omission (Ernst et al., 2005). The latter result has been explained by the larger motivational salience of monetary incentives in adolescence than adulthood (e.g., Ernst, 2014).

In sum, the behavioral data mostly show that children, adolescents, and adults do not differ in choice behavior and risk-taking, as all age groups are more likely to select high than low monetary reward trials in gambling tasks. All age groups also respond faster on high than low incentive trials, achieve higher accuracy on incentive trials than on neutral trials, and there were no age differences in win-stay and lose-shift strategies in learning tasks. There is some evidence that adolescents respond faster to large than small monetary incentives, and that they report more positive feelings after receiving monetary incentives than adults do.

EEG findings

Most ERP-studies so far have focused on the processing of incentive delivery. A number of studies applied gambling tasks and measured feedback processing, as indexed by the amplitude of the feedback-related negativity (FRN). Researchers found a larger FRN for loss or neutral than for gain trials (Santesso et al., 2011; Crowley et al., 2013; Grose-Fifer et al., 2014; Kujawa et al., 2015; Gonzalez-Gadea et al., 2016) as well as for small than large monetary gains (Santesso et al., 2011), with only small age differences therein. However, differences in FRN amplitudes to monetary incentives may be modulated by individual differences in emotionality, punishment sensitivity, and gender (Crowley et al., 2013; Kujawa et al., 2015). For instance, Santesso et al. (2011) found larger FRN amplitudes to both gains and losses for those individuals that reported higher levels of punishment sensitivity, also irrespective of age. With regard to gender differences, Grose-Fifer et al. (2014) reported that adolescent males showed larger FRN amplitudes to small than large wins, less FRN-differentiation between low gains and losses, as well as delayed FRN latencies to high losses as compared to females. Furthermore, FRN amplitudes in females (adolescents and young adults) were only modulated by the valence (i.e., larger for losses than for gains), suggesting that females may represent incentives only in the two categories positive and negative. In contrast, males seem more sensitive to the value of incentives, and thereby more prone to risk-taking. As most studies did not report age differences, these findings need to be replicated before strong conclusions can be drawn.

Another study focused on the investigation of error processing, as indexed by the error-related negativity (ERN/Ne) and error positivity (Pe), during response execution, when monetary incentives were anticipated. Applying a reinforcement learning task, Unger et al. (2014) showed a larger ERN/Ne for younger (13–14 years) and older adolescents (15–17 years) than for children (10–11 years) but no modulation of the ERN/Ne by monetary incentives, suggesting that adolescents were better able to represent correct and incorrect responses during learning, irrespective of anticipating positive and negative monetary incentives. The Pe, that is often interpreted as subjective evaluation of responses, was also larger for erroneous than correct responses. Moreover, it was also larger for monetary gains than losses and no-incentives, and was reduced for older adolescents relative to the other two age groups. Again, these effects were not modulated by the incentive manipulation. Hence, although the Pe was sensitive to the value of incentives as well as to age, the two factors did not interact with each other.

To summarize, neuronal correlates associated with coding prediction errors clearly indicate that the magnitude and valence of monetary incentives impact processing of feedback delivery, as reflected in a larger FRN to losses than wins and to small than large wins (at least in males), as well as error evaluation, as reflected in a larger Pe to wins than losses. In contrast, error processing (as reflected in the ERN/Ne) during anticipation of monetary incentives was insensitive to the magnitude and valence of monetary incentives. However, although these neuronal correlates are age-sensitive, no interactions of age with the value of monetary incentives were obtained.

fMRI findings

Most of the neuroimaging studies also have investigated processing of monetary incentives with variants of gambling tasks. For instance, May et al. (2004) used a card guessing game to investigate children and adolescents between 8 and 18 years when receiving either a positive incentive (i.e., possibility to win 1 Dollar) or a negative incentive (i.e., risk to lose 0.5 Dollar). They found similar brain activations in the striatum and lateral and medial OFC to the delivery of rewards as compared to previous results in adults. Interestingly, the possibility of receiving positive monetary incentives led to larger and later peak activations in the aforementioned brain regions than that of negative incentives, in line with the view that the striatum and OFC are involved in anticipating and encoding the value of incentives. However, no gender and age differences were obtained in this effect. It should be noted that the positive incentive was twice as much as the negative one. Hence, differences in incentive magnitude might have driven the latter effect (May et al., 2004). Nevertheless, Van Duijvenvoorde et al. (2014) found a similar result in adolescents and adults using a so-called slot-machine task. In this study, neuronal responses to feedback delivery after decisions to take a gamble showed larger activation in bilateral VS and medial PFC for gains than losses. In this study, both gains and losses were equivalent (i.e., winning or losing 10 cents). In line with the previous study, they also found no evidence for age differences in reward-related brain activations.

Cohen et al. (2010) examined feedback processing during the delivery of incentives in children, adolescents, and adults in a reinforcement learning task with large (25 cents) and small (5 cents) monetary incentives for correct responses. This condition was contrasted with a non-incentive condition for incorrect responses. In contrast to the findings from the gambling studies reported above, they found that adolescents had a hypersensitive response to unpredicted rewards in the striatum and the angular gyrus as compared to children and adults. Additionally, a region in the medial PFC was sensitive to reward magnitude, but here, a linear increase in sensitivity was found with increasing age. Galván et al. (2006) also found age differences in incentive processing between children, adolescents, and adults in a learning task in which responses to three types of cues were rewarded with high, medium, and large incentives. Across the whole trial, they found an increased activation in the nucleus accumbens and lateral OFC with larger incentive values. In contrast to the aforementioned studies, adolescents showed enhanced incentive-related activity in the nucleus accumbens relative to both children and adults, whereas larger lateral OFC activity was found in children as compared to the two older age groups. These results suggests a different developmental maturation of incentive-related brain regions, as subcortical structures, such as the nucleus accumbens, seem to become disproportionally activated as compared to the later maturing lateral OFC, supporting top-down cognitive control. The difference between studies might be due to different incentive schedules, as the study by Galván et al. (2006) applied a 100% reward probability schedule whereas the previous study did not.

Other studies not only investigated incentive delivery, but also the anticipation and omission of incentives in order to answer the question of whether increased risk-taking in adolescence results from an overestimation of anticipated incentives, from a higher responsiveness to receiving incentives, or both. To this end, Van Leijenhorst et al. (2010) applied the slot-machine task in early and mid-adolescents and young adults. In the incentive anticipation phase, both groups of adolescents showed larger activation in the anterior insula on trials signaling potential gains, but this effect was absent in the group of young adults. In the outcome phase, the two adolescent groups, but not the young adults, also showed larger activations in the striatum during trials signaling incentive delivery. This finding was corroborated by a quadratic age trend of the VS to rewards. In contrast, young adults showed larger activation of the OFC on trials, signaling incentive omission. These findings support the view that middle adolescence is characterized by overactive incentive-related brain regions, especially during reward delivery. Conversely, OFC activations in young adults to the omission of reward may signal the need for increased attention and adjustment of behavior following negative outcomes that is reduced in adolescents (Van Leijenhorst et al., 2010).

In a similar study, Ernst et al. (2005) investigated brain activations specifically to the omission of incentives (i.e., possibility to win either 4 or 0.5 Dollar or nothing) in a wheel-of-fortune task. For both adolescents and young adults, they found larger brain activations for the delivery than the omission of incentives in the bilateral amygdala and the nucleus accumbens. Whereas reductions in neuronal activations to the omission of rewards were encoded in the amygdala in adults, adolescents showed the same activation difference in the nucleus accumbens. Hence, adolescents and adults seem to differ more reliably in response to negative (i.e., omission) than positive monetary incentives. The weaker involvement of the amygdala in response to the omission of incentives may reflect a lower sensitivity to potential harm and less avoidance of negative situations in adolescents, accompanied by a more active reward-related system as reflected by nucleus accumbens activity. This pattern in turn might explain the higher propensity for risk and novelty seeking in adolescents.

Concerning the anticipation and delivery of monetary rewards during cognitive control, the studies by Bjork et al. (2004, 2010) point to a different pattern of age-related differences. In both studies, they applied a MID task in which five different cues indicated monetary incentives and risks (for details, see **Table 3**). During incentive anticipation, Bjork et al. (2004, 2010) reported reduced nucleus accumbens, VS, and amygdala recruitment by monetary gains relative to no gains in adolescents as compared to adults. In contrast to the previous studies, age differences in incentive-related brain regions were not obtained during the delivery of rewards. Hence, the results suggest that when incentives are bound to individual performance instead of choice behavior, and are measured in separate stages during anticipation and consummation, differential activation patterns in reward-related and control-related brain regions are observed in adolescents (Bjork et al., 2004; for a similar result using a longitudinal design, see Lamm et al., 2014).

Apart from age differences in neuronal correlates of reward anticipation, delivery, and omission, both the study by Van Duijvenvoorde et al. (2014) and Ernst et al. (2005) emphasized the role of individual differences in personality traits and affective states during gambling. In the former study, activations of the VS and medial PFC for play decisions were related to individual differences in scores on the BAS sub-scale Fun-Seeking: Subjects, who were more willing to approach potentially rewarding events in daily-life, showed a larger activation to incentives in the VS and medial PFC (Van Duijvenvoorde et al., 2014). In the latter study, Ernst et al. (2005) showed reduced amygdala responses to omission of incentives to be correlated with self-reported negative affect in adults, whereas adolescents showed correlations between nucleus accumbens activity and positive affect.

Taken together, results on age differences in brain activations in reward-related and control-related regions are mixed, and vary with the magnitude and probability of monetary incentives as well as with the type of task and stage of processing. When incentive values are high and the uncertainty of receiving them is rather low, an imbalance between the highly activated reward region and low activated control regions may lead to more impulsive and risky decision-making in adolescence.

Cognitive Incentives

Regarding cognitive incentives, one can differentiate between written feedback concerning performance accuracy on the preceding trial (e.g., Kim et al., 2014) and visual feedback indicating points for correct responses that are counted during performing the task and can be exchanged for monetary compensation at the end of the task (e.g., Paulsen et al., 2015). Also, some studies employ abstract feedback symbols (i.e., smiley, circles, or shapes, cf. Bjork et al., 2004; Kujawa et al., 2015) or category members (i.e., fruits, cf. Lukie et al., 2014) whose (often monetary) value is learned beforehand. These types of incentives are used to reduce the potential impact of age differences in the perceived value of, for instance, monetary incentives, that otherwise could lead to age differences in motivated behavior (e.g., Teslovich et al., 2014).

Behavioral findings

Van Leijenhorst et al. (2006) applied a gambling task called "cake task" involving high- and low-risk trials. Early adolescents and young adults had to predict choices of the computer and received either one point for a correct prediction that was in accordance with the computer's (random) choice or a loss of one point for an incorrect prediction. Early adolescents and adults made better predictions under low-risk conditions. Under high-risk conditions, early adolescents were in tendency more prone to risk-taking than adults, as they made more incorrect predictions than adults. However, the high-risk condition in that study might also have induced larger response conflict due to higher perceptual demands. Therefore, it is difficult to conclude whether children were indeed more sensitive to risk taking under high-risk conditions (Van Leijenhorst et al., 2006).

As gambling tasks *per se* do not give rise to age-related differences in task performance (Lukie et al., 2014), other studies investigated the role of cognitive incentives in simple and more complex tasks requiring cognitive control. For instance, using a simple perceptual RT task, Teslovich et al. (2014) found that adolescents were in particular sensitive to high positive cognitive incentives. They showed slower response times when large rewards could be lost, while young adults showed a speeded responding under this condition. Hence, age differences occur with larger magnitude of positive incentives (which acquire a negative value when large rewards are lost). Groom et al. (2010) investigated whether cognitive incentives would increase inhibitory performance in adolescents by varying not only the amount but also the valence of cognitive incentives (see **Table 1**). The high incentive condition enhanced inhibitory control performance, irrespective of the valence of incentives. Thus, positive and negative cognitive incentives, when strictly comparable in task design, are equally appropriate to foster performance in adolescence. Padmanabhan et al. (2011) also found that children and adolescents showed improvements to adults' performance levels in inhibitory control when potential incentives could be received (Padmanabhan et al., 2011). In contrast, Paulsen et al. (2015) applied an anti-saccade task to measure inhibitory control and investigated the impact of positive and negative cognitive incentives (i.e., gain or loss of 5 points). Their results indicated no effect of incentives on task performance, irrespective of age. Moreover, Geier and Luna (2012) even found negative effects of abstract reward cues (indicating trials with potential wins or losses of points, or neutral trials) on inhibitory control. In this anti-saccade study, adolescents committed more errors on gain trials than adults but not on loss trials. Thus, whether cognitive incentives influence inhibitory control may also depend on the type of response or the demands on inhibitory control.

The effect of cognitive incentives has also been investigated in reinforcement learning tasks (Hämmerer et al., 2010), in which participants performed a probabilistic two-choice learning task resulting in gains and losses of feedback points after each trial. Here, in contrast to children and older adults, adolescents and young adults learned faster from feedback and showed less switching of choices, and this difference was more pronounced after a positive than after a negative cognitive incentive. However, the switching of choices was more frequent after a negative incentive in all age groups.

Together, the behavioral results reveal that cognitive incentives can facilitate inhibitory control in adolescent, but not in children, depending on the type of inhibitory task. While behavioral adjustment after negative cognitive incentives is found across all age groups, adolescents' performance in decision-making is driven by response conflict on high-risk tasks (e.g., not receiving a large positive incentive). The latter effect suggests that losses involve emotional processing that is target to profound maturational changes during adolescence (Hämmerer et al., 2010; Paulsen et al., 2015).

EEG findings

Only rather few studies have investigated the neuronal signatures of incentive anticipation and delivery. For instance, the study by Groom et al. (2010) compared ERP correlates during response selection during a go-nogo task in which positive and negative cognitive incentives (gaining vs. losing points vs. neutral condition) were compared between blocks, so that the effects of incentives on task preparation cannot be investigated. Adolescents showed a larger N2-amplitude in positive than negative incentive and neutral blocks, indicating an early attentional process toward processing the positive valence of cues. However, this effect did not interact with demands on inhibitory control, that is, the positive valence effect was not different between no-go and go trials. They also showed a larger P3 amplitude in incentive blocks than in neutral blocks, suggesting a higher processing effort on motivated salient conditions. Again, this effect did not interact with inhibitory control demands (for a similar finding in young adults, see Schmitt et al., 2015).

A larger number of studies has focused on error- and feedback-related components (the ERN/Ne and FRN; for a review on developmental changes in these components, see

Ferdinand and Kray, 2014) in order to investigate the impact of cognitive incentives on learning and monitoring processes. One study reported larger amplitudes of the ERN/Ne and Pe for errors than correct responses during an inhibitory control task in adolescents (Groom et al., 2013). However, there was no effect of incentive value (i.e., differences between high or low positive or negative cognitive incentives) on ERN/Ne and Pe. In a similar vein, Lukie et al. (2014) found no age differences in processing different cognitive incentives (i.e., symbolic gains and losses) on amplitudes of the FRN. However, the study was a pure gambling task and therefore one cannot assess the impact of reward feedback on ERP measures of cognitive control and reinforcement learning. To investigate this issue, Hämmerer et al. (2010) applied an incentivized probabilistic learning task in more fine-grained age groups. They found that although having the largest FRN amplitudes overall, children showed smaller differences between FRN amplitudes after gains and losses relative to adolescents and young adults. This pattern remained stable even after controlling for baseline FRN size and for changes in the FRN after gain feedback in each age group. The findings suggest that children are less able to yield a differentiated classification of favorable and less favorable outcomes for task-specific goals, as indicated by FRN ratio scores, and to use cognitive feedback for adapting to task-specific goals (for a similar result, see Ferdinand et al., 2016).

fMRI findings

Brain imaging studies on developmental changes during anticipating and receiving cognitive incentives have revealed large activation overlap in brain networks between early adolescents and adults (Van Leijenhorst et al., 2006). In particular, Van Leijenhorst and colleagues examined age differences in brain activations during the decision-making process itself and processing feedback between low- and high-risk conditions in selected regions of interest. During decision-making, they found higher activations in the OFC and DLPFC for high- than low-risk conditions but no age effects in this difference, suggesting similar recruitment of brain regions known to be involved in anticipation of incentives and representation of risk options in early adolescents and adults. However, adolescents mainly differed from adults in higher activations of the ACC on high- than low-risk trials, suggesting that they perceived either more conflict or needed to engage more heavily in performance monitoring during high-risk choices. This finding was in line with the behavioral results, showing more incorrect decisions in early adolescents during higher uncertainty for correct predictions (Van Leijenhorst et al., 2006).

The study by Van Leijenhorst et al. (2006) also assessed age differences in receiving cognitive incentives (i.e., during feedback processing). They found that both age groups showed a larger activation for receiving negative than positive feedback in the VLPFC, known to be recruited during punishment. Moreover, early adolescents showed a larger activation in the right lateral OFC for negative than positive cognitive incentives, irrespective of the risk level, while for young adults this difference in brain activation was less pronounced. The age difference was due to differences in brain activations on negative feedback trials, suggesting that early adolescents were more sensitive to negative than positive feedback. This region is associated with coding the magnitude of both positive and negative outcomes and with implementing behavioral adjustments after negative feedback (Tsuchida et al., 2010). However, the study did not manipulate the magnitude of incentives as, for instance, the study by Teslovich et al. (2014). They compared receiving a small (1 point) and a large (5 point) positive incentive between adolescents and adults in three regions of interest, in the VS, IFC, and DLPFC. The results indicated a larger activation in the VS for larger than smaller positive incentives, but no age differences in this effect. In contrast, adolescents showed larger activations in the IPS and DLPFC for larger than smaller rewards. The increased activation of the fronto-pariatal network for higher incentives in adolescents has been interpreted as a bias in response selection in order to slow down responding until enough evidence is accumulated for a correct decision. Unfortunately, this latter study did not separate anticipation and delivery of incentives, and did not manipulate the magnitude of negative incentives so that the results of both studies are difficult to compare.

Padmanabhan et al. (2011) examined the effects of rewards on inhibitory control in an anti-saccade task. They investigated children, adolescents, and adults and compared conditions with an abstract cue indicating a potential win (that was later converted into a monetary bonus) and with an abstract cue that served as a neutral trial. They found an adolescent-specific enhancement in VS activity, and in areas responsible for inhibitory control during reward trials. Paulsen et al. (2015) investigated the contribution of age and inhibitory control performance on fronto-striatal activations in the anti-saccade task in 10–22 year-olds during positive and negative cognitive incentives (gaining vs. losing points vs. neutral). Although striatal activation during the decision-making process on neutral trials was associated with overall better inhibitory control, younger and older subjects did not differ in striatal activation during positive incentive conditions. However, inhibitory control performance in adolescents younger than 17 years benefitted from fronto-striatal activation during neutral trials, whereas these activations hampered anti-saccade performance in adolescents from 17 years on. Interestingly, age was negatively correlated with activation in the amygdala during loss trials only, suggesting that the amygdala of younger adolescents was more sensitive to losses. The results suggest a transition phase of fronto-striatal recruitment in adolescence, in which fronto-striatal regions benefit cognitive control performance and in which emotional processing in the amygdala mediates bottom-up processing during inhibitory control in younger adults (Paulsen et al., 2015).

Together, although ERP and fMRI methods are well suitable to examine whether (cognitive) incentives influence decision-making and cognitive control behavior in different stages, the existing studies have rarely made use of it. From EEG studies, we have learned that during the decision-making processing (anticipation of incentives) both children and adults show enhanced attention and processing effort under motivated conditions as compared to neutral ones, indexed by larger N2 and P3 amplitudes. Children and adults are also similarly sensitive to risky decisions, as they show similar changes in brain activation in prefrontal regions (OFC, DLFPC) when positive incentives are less likely. Here they differ only in higher ACC activation, signaling higher conflict processing in such situations. During response selection and receiving feedback, it seems that children are less able to differentiate between positive and negative cognitive incentives as reflected in smaller FRN difference scores than in adolescents and adults. Both adolescents and adults are sensitive to negative cognitive incentives, indicated by a larger recruitment of the VLPFC on negative than on positive incentive trials. In contrast, adolescents show a larger recruitment of cognitive control networks, and a lower amygdala activation in response to losses.

Social Incentives

Given that the processing of social information underlies dramatic developmental changes over the course of adolescence, and that the social context might be the most salient factor influencing the behavior of youth (Crone and Dahl, 2012), it is somewhat surprising that most developmental studies so far have focused on the impact of cognitive and monetary incentives on decision-making and goal-directed behavior. In recent years, some researchers suggested that adolescents may be specifically sensitive to perceiving, processing, and responding to social information (e.g., Blakemore and Mills, 2014). In particular, adolescents spend a greater amount of time with peers (Csikszentmihalyi and Larson, 1984) and are increasingly preoccupied with peer opinions (Brown, 1990) and acceptance (Parkhurst and Hopmeyer, 1998). The influence of positive and negative social incentives can be measured in different ways, for instance, by inducing social acceptance/inclusion or social rejection/exclusion from a peer group (e.g., induced with the Cyberball paradigm). Moreover, already the presence of peers or its simulation (e.g., by a chatroom) is sufficient to create a social context that affects decision-making and goal-directed behavior, known as the peer-effect (e.g., Gardner and Steinberg, 2005).

Behavioral findings

A number of studies, applying experimental decision-making tasks, have already shown that the presence of peers leads to higher risk taking in adolescents than in adults (Gardner and Steinberg, 2005; Chein et al., 2011; O'Brien et al., 2011; for a review, Albert et al., 2013; Weigard et al., 2014). For instance, researchers have used the so-called Stoplight task, a driving game in which participants advance through several intersections to reach a goal as fast as possible (e.g., Chein et al., 2011). They compared adolescents and two groups of adults in their risky decisions (driving across the stoplight and risking a crash) under conditions in which they performed the simulated driving task either alone or under observation of peers. Only adolescents took more risky decisions under the peer observation compared to the alone condition, while this peer effect was not present in the two groups of adults (Chein et al., 2011). The peer effect can also be obtained by the simulated presence of peers in late adolescents (e.g., Weigard et al., 2014). Interestingly, the peer effect disappeared when a slightly older adult is included into the peer group (Silva et al., 2016), in the presence of the mother (Telzer et al., 2015), and in the presence of an unknown adult (Guassi Moreira and Telzer, 2016), suggesting that this effect is highly sensible to the social context. However, one may argue that the Stoplight task is a rather specific risk-taking setting so that the peer effect cannot be generalized to other risk-taking tasks. Two recent studies have used the Balloon Analogue Risk Task (BART; Lejuez et al., 2002) or an adapted version of it in which a simulated balloon can be inflated via a balloon pump (button press). Each pump signifies a small win that can be accumulated within a trial. After each pump, participants have the choice to either save the money, or to inflate the balloon further, taking the risk for the balloon to burst and to lose the already accumulated money. Indeed, both studies were not able to replicate the peer effect when measuring risk taking by the overall number of inflated balloons (Reynolds et al., 2014; Kessler et al., 2017).

The direct reaction of peers, such as including or excluding an individual into the peer group, may be a stronger incentive for adolescents than the sole presence of a peer. Feelings of exclusion and inclusion from a group often have been induced with the so-called Cyberball paradigm (for details, see Williams et al., 2000). It has been shown that the Cyberball task induces distress (Masten et al., 2009; Bolling et al., 2011; Sebastian et al., 2011), threat (Abrams et al., 2011; Sebastian et al., 2011; Van Noordt et al., 2015), and worse mood (Gunther Moor et al., 2012). Evidence for the effects of inclusion/exclusion from a peer group on decision-making and cognitive control are rather scarce so far. Peake et al. (2013) showed that adolescents revealed a tendency for increased GO-decisions in the Stoplight task after being excluded in a preceding Cyberball game. Adolescents with greater susceptibility to peer influence also displayed larger increases in risky decisions after being socially excluded by peers (Peake et al., 2013).

Recently, Jones et al. (2014) investigated whether children, adolescents, and adults learned an association between the probability of receiving positive feedback and a particular peer (feedback stimulus). Unbeknownst to the participants, the probability of receiving a positive incentive from the three peers was experimentally manipulated, with one peer providing incentives rarely (33% of trials), the other frequently (66% of trials), and the last peer on all trials (continuous). Independent of age, rare probability of positive feedback led to a higher error rate than the other two peer conditions. Learning from positive feedback showed a quadratic age trend, with adolescents demonstrating a lower positive learning rate than children and adults. Thus, while children as well as adults reacted faster to peers that were associated with more frequent positive feedback, adolescents seemed to be motivated equally by all positive social incentives.

The reported quadratic age effect has not been found in other learning tasks (Van den Bos et al., 2012; Christakou et al., 2013). Therefore, either adolescents did not learn to discriminate between the peers associated with different amounts of positive social feedback, or the reinforcement learning predictions did not represent the adolescents' behavior. Accordingly, their learning rate profile could be associated with a general higher sensibility for receiving peer approval (Collins and and Steinberg, 2007).

In sum, social-induced feedback, like acceptance and rejection by peers, but also their mere presence, has an impact on adolescent decision-making. When observed by peers, whether they were present during testing and close friends, or simulated and unknown, adolescents show heightened propensities for risky decisions and immediate rewards. However, only the minority of studies compared different age groups and no study included longitudinal data, making it difficult to account for developmental differences in the influence of social incentives on decision-making and cognitive control behavior over the course of adolescence.

EEG findings

Only a handful of ERP studies have investigated the influence of social incentives on electrophysiological markers of decision-making and cognitive control in developmental samples. These studies have revealed several important findings. First, they have shown that the mere presence of peers can influence the significance of (negative) feedback as reflected in the size of the FRN. However, peer presence does not uniformly lead to weakened processing of negative as compared to positive, rewarding feedback, but also depends on the specific situational context (Segalowitz et al., 2011; Kessler et al., 2017). Second, social rejection feedback elicits early (as indexed by the FRN) and later (as indexed by the P3b) feedback processing similar to the FRN after cognitive or monetary feedback with the later processes also depending on peer relationship (Kujawa et al., 2014; Gonzalez-Gadea et al., 2016; Kuo et al., 2017). And third, social exclusion as examined in the Cyberball game elicits larger slow-wave activity (Crowley et al., 2010; White et al., 2012) as well as enhanced medial frontal theta oscillations (Van Noordt et al., 2015), both related to the distress this exclusion causes. However, none of these studies actually examined developmental effects by comparing different age groups or analyzing correlations with age.

fMRI findings

fMRI findings on decision-making corroborate the above reported behavioral results by demonstrating adolescent-specific neuronal activations when making risky decisions under conditions of peer observation. The study by Chein et al. (2011) found that 14–18 year-olds had significantly stronger activation of reward-related brain areas, like the VS and OFC, during the execution of risky decisions in the Stoplight task when their peers were watching them. Additionally, activity in these brain regions was associated with risky decision-making as indicated by significantly increased activity for GO relative to STOP trials. In contrast, adults showed no such difference as a function of social context. Moreover, they found that adults engaged several lateral PFC areas more strongly than adolescents, indicating enhanced recruitment of cognitive control. This activation pattern, however, was independent of social context, meaning that an immature cognitive control system in adolescents cannot account for peer influences during risky decision-making. Thus, these findings are conceptually in line with the idea of an enhanced reward-seeking motivation in mid-adolescents.

Similarly, Smith et al. (2015) examined adolescents and adults in a card guessing task that included rewarded and non-rewarded trials. Additionally, social context was manipulated by having participants complete the task both alone and while being observed by peers. When observed by peers, adolescents exhibited greater VS activation than adults, but no age-related differences were found when the task was completed alone. These findings suggest that during adolescence, peer presence influences recruitment of reward-related regions in a reward-processing task even when this task involves no risk taking at all.

Concerning the processing of social acceptance and rejection feedback, Gunther Moor et al. (2010) examined children, early adolescents, older adolescents, and young adults in a social judgement task. They presented photographs of peers and asked their participants to predict whether they would be liked by this person. This was followed by feedback ("yes" vs. "no") indicating whether the person actually liked them or not. Their results showed that the expectation to be liked was accompanied by activation of the ventromedial PFC (a region known to be involved in processing of self-relevant information) and the striatum. This activation was similar in older adolescents and adults, but less pronounced in children and early adolescents. Furthermore, when the expectation to be liked was followed by social acceptance feedback, the ventromedial PFC and the striatum were similarly responsive across all age groups. In contrast, when the expectation to not be liked was followed by negative feedback, the striatum, subcallosal cortex, paracingulate cortex, later PDF and OFC showed linear increases in activation with increasing age. Because this activation was also positively correlated to the resistance to peer influence, the authors interpret this finding as adults being better in regulating the negative feelings that are linked to social rejection. These results are not consistent with the notion of an enhancement of social feedback processing in adolescence. However, they highlight the importance of positive social feedback in general, because already children at the age of 8–10 years were rather sensitive to acceptance feedback.

In contrast, a very similar study by Jones et al. (2014) demonstrated an enhanced sensitivity to unexpected social acceptance feedback in adolescents as compared to children and adults. The authors compared the effects of social reinforcement (receiving a note vs. receiving no note) by peers that differed in the amount of positive reinforcement they gave (rare to frequent). The results showed that especially in adolescents, the anterior to mid insula response was correlated with the positive prediction error (receiving a note from a peer that gave positive reinforcement only rarely). This finding may indicate an enhanced salience of positive social reinforcement during adolescence. Additionally, adolescents activated regions responsible for response planning (putamen and supplementary motor area) more than children and adults when they received positive social reinforcement, which suggests that peer approval may motivate adolescents toward action. VS and medial PFC were equally engaged across age, which could reflect that the perceived value of peers based on their reinforcement history was equivalent for children, adolescents, and adults. These findings suggest that fundamental reinforcement learning mechanisms support social reinforcement learning from late childhood to adulthood. In contrast, the heightened activity in the insular cortex and regions within response planning circuitry of adolescents may suggest an affective-motivational sensitivity toward any peer approval.

Together, the reported fMRI data reveal that risky decisions seem to be rewarding for adolescents because they lead to activation in reward-related neuronal circuitry. Additionally, peer presence enhances the recruitment of these reward-related brain areas and can also dampen activity in a fronto-parietal network responsible for performance in cognitive tasks. As opposed to the studies on peer presence, the results of the few studies examining social acceptance and rejection feedback are less consistent and clearly further research is needed comparing several age groups or even groups differing in pubertal status.

Direct Comparisons of Secondary Incentives

Only a small number of studies so far have directly compared the impact of different kinds of incentives on decision-making and goal-directed behavior in adolescence and the underlying neuronal circuitry. These studies are primarily motivated by the claim that different types of incentives share the same neuronal basis, supporting the idea of a "common neural currency" of rewards, and investigating atypical processing of rewards in clinical subsamples that will be not reported here (e.g., Autism Spectrum Disorder, Internet-addicts). We found one study that directly compared primary and secondary incentives that is reported in section Primary Incentives, so that we will focus here on comparisons between secondary incentives. We will also not include studies investigating only adults (e.g., Izuma et al., 2008; Flores et al., 2015), clinical subsamples (e.g., Lin et al., 2012; Kim et al., 2014; Gonzalez-Gadea et al., 2016), or one age group (Op de Macks et al., 2017).

In an attempt to compare social and monetary feedback, Ethridge et al. (2017) tested differential neural responses to social and monetary incentives in young-adolescents and emerging adults. Social feedback was induced through acceptance and rejection feedback while participants engaged in the so-called Doors task (Proudfit, 2014). Positive and negative feedback in the social condition was indicated by a green "thumbs up" for acceptance or by a red "thumbs down" for rejection. In the monetary condition, a green arrow pointing up indicated a win of \$0.50 and a red arrow pointing down indicated a loss of \$0.25. In addition, adults were informed that they could win up to \$10, whereas young-adolescents were informed that they could win only up to \$5, while all participants were given in fact \$5 following the monetary decision-making task. During feedback presentation, the author reported an enhanced reward positivity for social acceptance and winning money as compared to social and monetary negative feedback. The results revealed that the young adolescents showed this effect on both types of incentives, thus did not differentiate between them. In contrast, the adults showed a larger positivity to monetary than social positive incentives, suggesting at first glance developmental changes in the relative importance of incentive cues. However, the findings are difficult to interpret as adults could win twice as much as adolescents which can also explain the differences between the age groups.

DISCUSSION

The overarching aim of this review was to provide an overview on the impact of different kinds of incentives, in particular, monetary, cognitive, and socials ones, on age differences in decision-making and cognitive control tasks. We were specifically interested in answering the following questions: (1) Do we find age differences in how different kinds of incentives motivate behavior in these tasks; (2) if so, do these age differences primarily occur during anticipation or consuming/receiving incentives; (3) is there evidence for common or distinct neuronal activations across incentives, as well as for age differences in recruiting incentive-related brain regions.

Do Different Kinds of Incentives Motivate Behavior Differently During Adolescence?

Considering the overall findings at the behavioral level, most of the studies did not find age differences in the impact of different kinds of incentives on decision-making and cognitive control. Although primary incentives are more salient in childhood and adolescence than in adults (based on subjective self-reports), they did not modulate age differences in behavioral choices itself. Monetary as well as cognitive incentives led to better task performance in most studies, but again there were no age-differential effects in these benefits or on behavioral adjustments. Again, adolescents differed from other age groups in self-reported positive feelings about gaining money and there was only few evidence that adolescents were more prone to receiving or not receiving larger monetary incentives. If at all, it seems that social incentives have an age-differential effect on adolescents' decision-making in terms of taking higher risks in the presence, acceptance or rejections of peers. However, only rather few studies compared different age groups and it remains unclear whether the peer effect is restricted to very specific task settings. These findings suggest that different kinds of incentives did not differ in their impact on age differences in decision-making and cognitive control behavior. Only one recent developmental study directly compared monetary and social incentives and found that adults were more responsive to monetary than social ones, while no such difference was obtained for young adolescents. However, given the small number of developmental studies so far, future research directly comparing the differential functions of incentives throughout adolescent development is clearly warranted.

Do Different Kinds of Incentives Influence Neuronal Mechanisms During Anticipating and Receiving Incentives Differently in Adolescents?

Although an ERP approach is well suitable to examine cognitive and neuronal mechanisms separately in stages of anticipating and receiving incentives, only rather few developmental studies have made use of it to determine age differences in decision-making and cognitive control. Studies investigating the impact of monetary incentives mostly used reinforcement learning tasks and clearly found that both the magnitude and valence of incentives influence feedback processing, in contrast to the anticipation of incentives (here error processing). There is scarce evidence for gender by age interactions on processing monetary incentives but these findings need to be replicated before strong conclusions can be drawn. Studies investigating the impact of cognitive incentives focused on the examination of receiving incentives and again found no evidence supporting the view that adolescents process cognitive incentives differently from adults. Only children were less able to differentiate between positive and negative cognitive incentives as compared to adolescents, due to their immature cognitive control system.

Age Differences in the Recruitment of Incentive-Related Brain Regions During Anticipating and Receiving Incentives

In adults, there are first reviews and meta-analytic studies pointing to an overlapping processing network for different types of incentives including the ventral medial PFC, OFC, medial PFC, ACC, the posterior cingulate cortex (PCC), the inferior parietal lobule and some regions of the lateral PFC in decision-making (e.g., Liu et al., 2011; Sescousse et al., 2013). Such overlap in recruitment of incentive-related brain regions was found when comparing the processing of primary and secondary incentives (e.g., Lieberman and Eisenberger, 2009; Bartra et al., 2013; see Sescousse et al., 2013, for a review), as well as when comparing social and non-social decision-making (for reviews, Amodio and Frith, 2006; Ruff and Fehr, 2014; see also Saxe and Haushofer, 2008).

To determine age-related differences between adolescents and adults in recruiting incentive-related processing, Silverman et al. (2015) recently reported results of a meta-analysis including 26 fMRI studies. Although they found overlapping brain activation in the incentive-related network, including major nodes such as the ventral and dorsal striatum, insula and the PCC, suggesting that adolescents activate a similar incentive-related network as adults do, adolescents showed a greater likelihood for activation in a number of these regions. However, they also reported age differences in activating brain regions during anticipation and consumption/receipt of rewards. Adolescents showed a larger activation in the insula, amygdala, and putamen during anticipation and larger amygdala activation during receiving feedback, suggesting a higher sensitivity to salient stimuli. When comparing positive to negative incentives, adolescents showed larger activation in the accumbens, PCC, and OFC. Relative to adults, adolescents showed a reduced activation for negative incentives in the amygdala, OFC, and ACC (Silverman et al., 2015).

Concerning the different types of incentives, as reviewed here, it has been shown that adolescents were particularly sensitive to consuming or not receiving primary incentives as reflected in increased activation in the VS relative to adults. A much larger number of studies investigated the impact of monetary incentives and yielded very mixed results: Age differences in brain activations in reward-related and control-related regions were rather inconsistently found depending on the type of task and stage of processing. Generally, it seems that adolescents were sensitive to a "hot" context, that is, when incentive values are high and the probability of receiving them is rather low, an imbalance between the highly activated reward region and low activated control regions may lead to more impulsive and risky decision-making in adolescence. Moreover, receiving negative cognitive incentives led to higher recruitment of control brain regions as well as to a lower amygdala activation, signaling lower sensitivity to potential negative outcomes in adolescents.

CONCLUSIONS AND OUTLOOK

Most of the developmental studies included in this review compared only two age groups or investigated a restricted age range in a cross-sectional research design. These limitations make it impossible to evaluate current neurobiological developmental models against each other. Comparing different types of incentives and their impact on age differences in decision-making and cognitive control revealed that the effects were quite similar on the behavioral level and mostly age differences were not observable. These findings seem to conflict with the current theoretical models as well as with the research findings on the neuronal level that often showed higher recruitment of control-related brain regions in adults and higher activation in reward-related brain regions in adolescents. Future research thus needs to better integrate and relate the results of different data levels. We also recommend that future research in this field should make more use of neuroscientific methods in order to directly compare differential functions of primary and secondary incentives in different stages of processing (i.e., preparation, response selection, outcome evaluation). This will help us to determine the relative importance of different kinds of incentives on cognitive and neuronal mechanisms. However, the review of findings also revealed that if monetary incentives were rather high, decision options were unknown, or in a social context (presence of peers), adolescents indeed behaved differently compared to adults (and children), at least in particular tasks. Hence, one challenge for future studies will be to further specify in well-controlled studies, which contextual factors are critical for inducing an imbalance between reward and control networks in adolescents, and to also consider the role of individual differences in the subjective valuation of different kinds of incentives across age.

AUTHOR CONTRIBUTIONS

All authors contributed to the writing of the review. JK wrote the Introduction and Discussion part. HS summarized research findings on cognitive and monetary incentives. CL summarized the behavioral findings of social incentives and NF the neuroscientific findings of social incentives. All authors provided feedback to the other parts. Tables were created by HS, CL, and NF.

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Are Mid-Adolescents Prone to Risky Decisions? The Influence of Task Setting and Individual Differences in Temperament

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Recent developmental models assume a higher tendency to take risks in mid-adolescence, while the empirical evidence for this assumption is rather mixed. Most of the studies applied quite different tasks to measure risk-taking behavior and used a narrow age range. The main goal of the present study was to examine risk-taking behavior in four task settings, the Treasure Hunting Task (THT) in a gain and a loss domain, the Balloon Analogue Risk Task (BART), and the STOPLIGHT task. These task settings differ in affective task moderators, like descriptive vs. experienced outcomes, anticipation of gains vs. losses, static vs. dynamic risk presentation, and time pressure vs. no time pressure and were applied in a sample of 187 participants from age 9–18. Beneath age trends, we were interested in their association with individual differences in approach behavior, venturesomeness, impulsivity, and empathy above age, gender, and fluid intelligence. Our findings revealed that risk-taking behavior is only low to moderately correlated between the four task contexts, suggesting that they capture different aspects of risk-taking behavior. Accordingly, a mid-adolescent peak in risk propensity was only found under time pressure in the STOPLIGHT that was associated with higher impulsivity and empathy. In contrast, risky decisions decreased with increasing age in task settings, in which losses were anticipated (THT Loss), and this was associated with higher cognitive abilities. We found no age differences when gains were anticipated, neither in a static (THT Gain) nor in a dynamic task setting (BART). These findings clearly suggest the need to consider affective task moderators, as well as individual differences in temperament and cognitive abilities, in actual models about adolescent development.

Keywords: experimental risk-taking, risky decision-making, adolescence, affective task setting, individual differences, temperament, age trends

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INTRODUCTION

Recently, there is an immense increase in studying developmental changes in cognitive, emotional, and social functioning throughout adolescence (for reviews, see Spear, 2000; Steinberg, 2008; Blakemore, 2012; Crone and Dahl, 2012; Shulman et al., 2016). Several research groups have also investigated the association between the development in specific brain regions and decision-making behavior in adolescence (Spear, 2000; Dahl, 2004; Casey et al., 2008; Steinberg, 2008; Smith, Chein, and Steinberg, 2013; Laube and van den Bos, 2016; Luna and Wright, 2016; Sherman et al., 2017). On the basis of such findings, recent theories and models about the neurobiological development in adolescence have proposed divergent developmental pathways over the course of adolescence: an early-maturing incentive-processing system (or socioemotional system) and an only gradually developing cognitive control system may explain why risky and potentially harmful impulses specifically arise in mid-adolescence. Accordingly, while the socioemotional system strengthens motivation to pursue rewards in adolescence, the cognitive control system is not yet matured enough to restrain impulses to achieve rewards and to seek for sensations (cf. Dual Systems Model, Steinberg, 2008; Maturational Imbalance Model, Casey et al., 2008; Driven Dual Systems Model, Luna and Wright, 2016; and Triadic Model, Ernst, 2014). These neuroscientific insights into brain development over the course of adolescence (Giedd et al., 1999; Sowell et al., 2002; Paus, 2005; Casey et al., 2008) might explain the adolescent-specific tendency for exploration and higher risk-taking, as well as the rise in mortality rates during mid-adolescence (see Dick and Ferguson, 2015). Given this, there is a strong need to better understand under which situations higher risk-taking is induced in mid-adolescents, so that in the last decade, a number of quite different laboratory tasks have been created to measure different aspects of risk-taking behavior (for a review, see Defoe et al., 2015).

In such decision-making tasks, adolescents are usually confronted with decisions to engage in gambles for outcomes that differ in their value and probability of occurrence. Risk-taking is, thus, defined as the tendency to choose the option with a higher variability in the range of possible outcomes (cf. Defoe et al., 2015). For instance, preferring gamble options (e.g., 30% vs. 70% chance to win 10€ or nothing) over safe options for which outcomes are known and stable (e.g., a safe win of 2€). Meanwhile, there is also empirical evidence that stands in contrast to the assumptions of neurobiological developmental models, as adolescents did not show the highest tendency for risk-taking (e.g., Spear, 2000; Dahl, 2004; Willoughby et al., 2013). Therefore, a recent meta-analytic review aimed at investigating age differences in several behavioral risk-taking tasks between children (aged 5–10 years), early- and mid-adolescence (aged 11–13 and 14–19 years, respectively), and adults (aged 20–65 years, Defoe et al., 2015). This study indicated that adolescents take more risks than adults do, but only show a higher tendency for risk-taking than children under specific context conditions and characteristics of decision-making tasks.

The Impact of the Task Setting on Decision-Making in Adolescence

At first, the way risky situations are created is thought to influence decision-making. One type of task setting investigates decision-making behavior for which information about outcomes and their probabilities is given and thereby enables individuals to calculate the profitability of options. These types of tasks are termed description based (e.g., Hertwig et al., 2004; Hertwig and Erev, 2009). Decision-making tasks in which all outcome probabilities are known have usually been seen as less-affective contexts and engage cognitive abilities, like the calculation of expected values (Figner et al., 2009; Defoe et al., 2015). However, associated cognitive abilities are still developing over the course of adolescence (e.g., Luna et al., 2004); thus, children and adolescents may not fully make use of the given descriptive information. Accordingly, two studies compared adolescents to adult tendencies to take risks in a description-based decision-making task, the so-called CUPS task (Levin et al., 2007). While adolescents (aged 14–17 years) and emerging adults (aged 18–21 years) showed no differences in risk-taking propensity (Galván and McGlennen, 2012), middle-aged parents (mean age = 45 years) showed a different choice behavior than their children (aged 8–17 years) in this task (Levin et al., 2014). More specifically, adolescents took more risks than middle-aged parents did. Thereby, parents indeed tended to be more sensitive to expected values than adolescents, and this sensitivity was, in turn, associated with numeracy abilities (Levin et al., 2014). Hence, age, or life experience, and the consequential development of cognitive abilities seem to influence decision-making in description-based tasks.

In addition, the task setting can be influenced by affective task factors, such as the expectation of positive or negative outcomes (e.g., monetary wins or losses, respectively). Especially, adolescents are thought to be biased by the hyperactive socioemotional system to pursue the potentially most rewarding choice (Casey et al., 2008; Steinberg, 2008; Ernst, 2014; Luna and Wright, 2016). However, most findings in the developmental decision-making literature are limited to the effects of different kinds and degrees of gains, while the investigation of the impact of negative outcomes (losses) has been neglected (Kray et al., 2018). This is somewhat surprising, as according to the influential prospect theory (Kahneman and Tversky, 1979), risky decision-making differs depending on whether positive (gains) or negative outcomes (losses) can be expected. For instance, this assumption holds true for adults, as they have been shown to take more risks to prevent losses than to maximize gains in many decision contexts (for a review, see Barberis, 2013). For instance, the CUPS task distinguishes between gain and loss situations. In this task, middle-aged adults took more risks to prevent losses than to win money, while adolescents did not differentiate as much between gain and loss situations as adults did (Levin et al., 2014). Nonetheless, most age groups were rather risk-seeking for potential losses with known outcome probabilities (Reyna et al., 2011; Levin et al., 2014; van den Bos and Hertwig, 2017). One study furthermore showed that the proportion of risk decisions decreased from childhood to early adulthood for losses (aged 8–22 years) but increased for gains in adolescence only (van den Bos and Hertwig, 2017). In sum, the valence of outcomes may influence decision-making in adolescence as well.

Beneath these considerations, potentially risky decisions in everyday life seldom rely on fully known probabilities. Therefore, particularly in the adolescent literature, researchers aimed to raise the ecological validity of experimental decision-making tasks by inducing ambiguity about upcoming positive or negative outcomes and their probabilities. In these so-called experienced-based task settings, the outcome probabilities are unknown and have to be learned through exploration. As such, to learn about outcome probabilities in these tasks, one has to actively engage in risks while only being encouraged to do so by motivators, like gains in money or time. Thereby, experience-based tasks also differ in the way they induce an affective and arousing task setting. In some task settings, the risk levels change dynamically after each decision. For instance, in the Balloon Analogue Risk Task (BART; Lejuez et al., 2002), participants decide to pump balloons when pumping behavior is rewarded, but balloon explosions cause losing all previous gains. Hence, after each decision to inflate the balloon, instead of saving previous gains, the value of outcomes (larger wins) but also the risk for the balloon to explode increase. In other task settings, the risk level remains stable, but the situation becomes arousing through time pressure that is induced for each of the decisions. For instance, one maneuvers a car through multiple intersections for which traffic lights turn yellow when approaching in the STOPLIGHT task. As such, crossing the intersections (GO-decisions) instead of stopping at the lights saves time, but in half of the intersections, the lights turns red beforehand and participants cause accidents in doing so. Thus, participants must choose the most profitable option in a gamble between winning and losing time to earn money (Chein et al., 2011), or reach a social event in a timely fashion (Steinberg et al., 2008).

Decisions that are based on previous experiences are associated with emotion-based learning and should be more affectively arousing (Figner et al., 2009; Defoe et al., 2015). Given that adolescents are thought to be specifically sensitive to affectively engaging situations (e.g., Steinberg, 2008), they may also show more risky decisions in experienced-based than description-based task settings. Indeed, there is some evidence for risk propensity to be highest in adolescents as compared to children and adults in experienced-based task settings. For instance, an inverted U-shaped developmental trend has been found for experienced-based tasks (aged 8–25 years, Braams et al., 2015; aged 10–30 years, Duell et al., 2018), such as the BART and the STOPLIGHT task. Furthermore, adolescents (aged 14–17 years) took more consecutive risk decisions than middle-aged adults (aged 35–55 years) and showed to be specifically sensitive to previous outcomes in the BART (Mitchell et al., 2008). Similarly, early- to mid-adolescents (aged 10–11 years, 12–13 years, and 14–15 years) took more risky decisions than older age groups (aged 16–30 years) in the STOPLIGHT task (Steinberg et al., 2008). Moreover, both task settings showed adolescent-specific influences on risky decisions, such as an association with real-life risk-taking behavior, like dangerous driving under peer presence (Chein et al., 2011), and other health risk behavior (Lejuez et al., 2003; Kim-Spoon et al., 2016). However, little is known about the specific influence of dynamic risk levels and induced time pressure on adolescent decision-making, though adolescents are thought to be more aroused by and take more risky decisions under contextual motivators (e.g., peer observation, Chein et al., 2011) and stressors (for a review, see Galván and Rahdar, 2013). In a recent study, Duell et al. (2018) investigated age trends of the STOPLIGHT task (static risk level with time pressure) and the BART (dynamic risk level without time pressure) in a broad age sample from childhood to mid-adulthood (aged 10–30 years). They found risk-taking in both tasks to develop in an inverted U-shape but showed differing slopes for the two tasks across adolescence. To sum up, it seems that developmental trends in risk-taking throughout adolescence depend on the type of task setting, like whether the expected values for each decision are known or unknown, whether gains or losses can be expected, whether risk itself changes throughout the task, or whether time pressure is induced.

Relations Between Individual Differences in Temperament and Risk-Taking

A second goal of the present study was to also consider individual differences in temperament that may explain individual differences in risk propensity beyond age. As such, temperament has been proposed to reflect innate characteristics that influence behavior already early in life, while personality rather depicts traits that are acquired in interaction with the environment. However, there is reason to believe that temperament and at least some personality measures share an endogenous nature and, thus, an intrinsic maturation (for a review, see McCrae et al., 2000), and that a clear dissociation between temperament and personality is not reliable. We here refer to temperamental differences instead of the overarching term personality, as we intend to describe basic dispositions that influence adolescent behavior rather independent from life experiences. Thereby, individual differences have been assumed to be associated with real-life risk-taking, while reviews on the role of temperament and personality in experimental decision-making showed inconsistent and contradictory findings (Appelt et al., 2011). Appelt et al. (2011) also pointed to the theoretical and methodological shortcomings of not integrating personality measures in decision-making research and encouraged future studies to consider them on the theoretical basis of various factors. Hence, for the purpose of the present study, we included different temperament factors that have been found to be related to risk-taking behavior in previous studies.

On the one hand, adolescents show a tendency to engage in novel and exciting experiences regardless of potential risks, also known as sensation seeking (Zuckerman, 2007). An associated personality cluster is approach behavior, which is defined as the motivated behavior to pursue potentially rewarding situations. Captured by the Behavioral Activation System (BAS; Gray, 1972), behavioral approach has also been associated with activity in brain regions known for their role in reward processing [nucleus accumbens (Nacc), Urošević et al., 2012; Braams et al., 2015]. Moreover, higher BAS sensitivity has been linked to substance use, dangerous driving, and risky sex in adolescence (e.g., Loxton and Dawe, 2001; Knyazev et al., 2004; Reyna et al., 2011). Despite its rapid rise in adolescence (e.g., Duell et al., 2016), sensation-seeking tendencies do not seem to capture socioemotional imbalance (cf. Romer et al., 2017), as it has been shown to be positively correlated with indicators of executive function (e.g., Zuckerman, 2007).

On the other hand, sensation-seeking tendencies have to be distinguished from the temperamental factor impulsivity that rather reflects decisions for immediate urges without adequately considering potential consequences. Impulsive tendencies are low to moderately associated with sensation seeking, or BAS, as it also peaks during adolescence (Collado et al., 2014; Shulman et al., 2015). However, impulsivity is inversely correlated to executive function, like working memory. Moreover, adolescents with high behavioral approach tendencies might more likely explore risk behaviors, but adolescents with impulsive tendencies are more likely to experience maintained health risk behaviors across development, like addiction (cf., Romer et al., 2017). Nonetheless, many self-report questionnaires capture different facets of "impulsive" behavior. For instance, it can be distinguished between the factor impulsiveness that rather reflects the tendency to act rashly without considering consequences, and the factor venturesomeness that is a characteristic of people who are conscious about potential risks and are willing to take them (I6, Eysenck and Eysenck, 1978). As such, the factor impulsivity might reflect tendencies to engage in risks as one does not consider potential consequences or is less capable in doing so. Though, venturesomeness rather depicts a tendency to engage in situations for which risk is known and is an inherent characteristic (e.g., bungee jumping).

In addition, it has been argued that the most salient types of rewards in adolescence are in the social domain (social feedback like being admired, included, or excluded, or positive and negative emotions; Crone and Dahl, 2012). In support of this view, social contexts like peer presence have been shown to have an age-differential effect, with adolescents taking more risks in these situations than other age groups (for a review see Kray et al., 2018). Correspondingly, adolescence is thought as a period of heightened social–affective engagement and sensitivity (Crone and Dahl, 2012) that might promote empathic responses (Blakemore and Mills, 2014) and, thus, the gradual development of empathic skills over the course of adolescence (e.g., Allemand et al., 2015). Hence, individual empathic functioning might also be predictive of risk-tendency in youth.

Goals of This Study

In sum, it seems that developmental trends as well as the occurrence of age differences in decision-making tasks vary with the type and characteristic of the task setting. So far, most studies rely on one task setting and a comparison of two or three age groups, which does not allow to draw conclusions about differential influences of task contexts on age differences in the transition from childhood to adulthood (cf. Defoe et al., 2015; Kray et al., 2018).

Therefore, the first goal of this study was to examine whether the type of decision-making task modulated age differences in risk-taking. In order to achieve these goals, we collected data from a relatively broad age sample ranging from 9 to 18 years, which allows to test for linear or quadratic age trends in decision-making. To keep the continuous nature of the age variable and to determine at which age differences between age groups are still significant, we stratified participants into five age groups: 9–10, 11–12, 13–14, 15–16, and 17–18 years. In order to examine whether age differences in risk-taking are modulated by the type of decision-making task, we analyzed age trends in four widely used decision-making contexts: a modified version of the CUPS task [termed in the following Treasure Hunting Task (THT)] in a gain and a loss domain, the BART, and the STOPLIGHT task. We selected these tasks in order to determine whether potentially affective task moderators, like a) description- vs. experience-based outcome probabilities, b) incentive valence in description-based task settings (gains vs. losses), or c) dynamic risk level without time pressure vs. static risk level under time pressure in experience-based task settings, modulate age differences in risk-taking throughout adolescent development.

As a first task, we applied a modified version of the CUPS task, the THT, which reflects so-called description-based decision-making, as decisions are taken under known risk. The THT, moreover, allows us to examine whether age differences in risk-taking are influenced by the valence of anticipated gains and losses. In this task, participants made decisions either in a gain block, in which they could win money (THT Gain), or a loss block, in which they could lose money (THT Loss). On the one hand, we expected risk propensity of the THT to decline over age in the loss domain, as the generally risk-seeking tendencies in such task settings have been found to show a linear decrease over the course of adolescence (e.g., van den Bos and Hertwig, 2017). Regarding the hypothesized reward sensitivity of adolescents and given indices in the literature (for high reward condition; Reyna et al., 2011; van den Bos and Hertwig, 2017), we expected risk propensity in the THT Gain, on the other hand, to show an inverted U shape across adolescence. That is mid-adolescents should take the highest propensity of risk decisions in gambles for gains. In contrast, decisions are taken under ambiguity in experience-based decision-making task, as not all outcome probabilities are known. Therefore, we expected risk propensities to show an adolescent-specific peak in the BART (Braams et al., 2015; Duell et al., 2018) and STOPLIGHT task (Duell et al., 2018). Yet, differences in risk and outcome presentation [dynamic risk level without time pressure (BART) vs. static risk level under time pressure (STOPLIGHT)] might also lead to differential developmental patterns over the course of adolescence for the two experience-based tasks (cf. Duell et al., 2018).

As a second goal of the present study, we determined whether individual differences in temperament, such as approach behavior, impulsivity, venturesomeness, and empathy could explain individual differences in experimental risk-taking beyond age, as these factors have been found to be related to decision-making in a number of studies (see Appelt et al., 2011 for a review). Moreover, we also considered gender and individual differences in fluid intelligence. Male adolescents have consistently been found to engage in higher levels of real-life risk behaviors (e.g., Byrnes et al., 1999; Harris et al., 2006), while higher risk propensity has been shown for male adults in some experimental task contexts, like the BART (Lejuez et al., 2002; Cazzell et al., 2012). However, other task contexts in the adolescent literature revealed no moderator effect of gender (Steinberg et al., 2008; Figner et al., 2009). Given these inconsistent findings, we controlled for possible gender differences in the prediction of risky decision-making across adolescent development, especially as most studies do not provide their results separately for males and females in the literature (cf. Defoe et al., 2015). Furthermore, referring to neurodevelopmental imbalance models, individual differences in cognitive abilities might be associated to tendencies in risky decision-making that reflect an increase in experience and cognitive abilities with age. Usually stated as a factor that decreases risk-taking in these models, findings concerning financial choices assumed that intelligence rather predicts heightened risk-taking behavior, or rather less risk aversion, in the sense of an optimal choice behavior to maximize outcomes (e.g., Donkers et al., 2001; Benjamin and Shapiro, 2005). Moreover, a related factor, namely, numeracy, accounted for differences in sensitivity to expected values, thus in the advantageousness of risk choices between middle-aged adults and adolescents in experimental decision-making (Levin et al., 2014). Therefore, we were interested in the role of individual differences in fluid intelligence in predicting risky decisions across adolescence. In sum, beyond age, we considered gender, as well as individual differences in temperament and fluid intelligence, as predictors for individual susceptibility to risky decisions in experimental decision-making (Appelt et al., 2011; Lauriola et al., 2014; Frey et al., 2017). However, it is an open question whether they differentially explain risky behavior in the four different decision-making settings.

MATERIALS AND METHODS

Participants

Overall, 193 children and adolescents between age 9 and 18 were recruited for this study from a subject pool of our research unit at Saarland University, as well as via flyers and newspaper advertisements. Participants received 8€ per hour as monetary compensation and a small reward that they could choose themselves at the end of one session, measuring cognitive performance and decision-making. Informed consent was given by the participant's parents or themselves when they were 18 years or older. A local ethic committee at Saarland University gave ethical approval for the project "The Influence of Motivational Processes on Developmental Changes in Adaptive Behavior."

Five participants were excluded from the analysis of the decision-making tasks because of missing data in one or more tests and tasks. To control for outliers, we first performed tests for uni- and multivariate normality for each of the five age groups: 9–10, 11–12, 13–14, 15–16, and 17–18 years. To this end, we computed Mahalanobis $D^{2;}$ probability values for all dependent measures, and if D^2 probability values were lower than 0.001, cases were excluded from the analysis. This was the case for one participant in the 13- to 14-year-olds. Thus, the final sample consisted of 187 participants. **Table 1** shows the characteristics of the final sample, including the number of participants in each of the five age groups, gender ratio, socioeconomic status (SES), and two intelligence subtests, one from the fluid domain and one from the crystallized domain of intelligence (for a description of these variables, see the next section). Neither the gender ratio nor the SES differed significantly across the age groups ($p = 0.12$, $p = 0.67$, respectively). In line with results in the literature, we found an increase in reasoning, $F(4,182) = 22.87$, $p < 0.001$, = 0.34, and verbal knowledge, $F(4, 182) = 36.44$, $p < 0.001$, = 0.45, with increasing age (e.g., Li et al., 2004; Nook et al., 2017).

Procedure

To assess decision-making in children and adolescents, we used four common decision-making contexts that are described in detail in the next section. Participants conducted the tasks in the context of a larger cross-sectional and longitudinal study to investigate the development of cognitive control and motivational functioning over the course of adolescence (age range = 9–18 years). The first measurement time T1 consisted of three sessions. In one session, participants received a comprehensive test battery, including cognitive tasks and the three decision-making tasks that lasted about 2–3 h. These tests and tasks were conducted on a computer using a 19-inch monitor, the computer keyboard, and a response box. In two further sessions, we collected electroencephalogram (EEG) data and measured task switching and reversal learning that will be reported elsewhere. Participants further completed various online self-report questionnaires conducted with the software program SoSci Survey (Leiner, 2014). These questionnaires collected information about, for example, demographic characteristics or traits such as reward responsiveness or impulsivity and were filled out at home between the sessions. The instructions of these questionnaires requested the children to fill out the questionnaire preferably undisturbed, but to ask their parents or the research team if problems occurred.

To keep motivation high, participants were told that their performance in the three decision-making tasks of the test battery were relevant to heighten the probability of winning a more valuable reward out of a box marked with three stars, rather than out of a one-star box, which were placed visibly for the participant in the laboratory. Unbeknown to the participants, all subjects received the feedback that they gained enough points to choose from the more valuable three-star box.

Decision-Making Tasks

Treasure Hunting Task

This task is a modified version of the original CUPS tasks of Levin et al. (2007). In order to make it more child-friendly and to create a motivating context, we programmed a new version of this task, named THT, which is identical in the structure and conditions of the original CUPS task but different in task setting. As can be seen in **Figure 1**, the cups of the original task were replaced by treasure chests that were labeled with the containing number of 1€ coins. Like in the original CUPS task, participants were instructed to choose between a safe and a risky side, on which a varying number of treasure chests (2, 3, or 5) and its content (0 to 5 euros) were displayed (see **Figure 1**). Thereby, choosing the safe option always resulted in a sure gain or loss of 1€. Choosing the risky side resulted in either winning or losing a higher amount of money or winning or losing nothing. Risk-taking was measured as the percentage of risky side choices.

The experimental conditions consisted of two incentive values (gain or loss), three levels of expectancy (0.20, 0.33, or 0.50) by varying the number of cups on each side (2, 3, and 5), and three levels of outcome values for the risky side (2€, 3€, or 5€). In total,

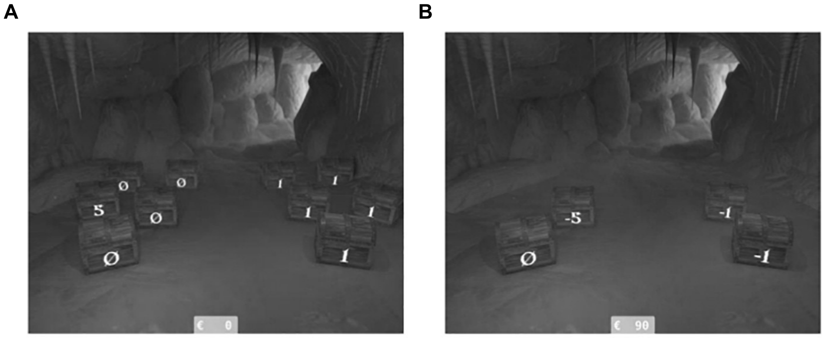

FIGURE 1 | Illustration of the THT for the two valence domains, THT Gain **(A)** and THT Loss **(B)**, in which participants had to choose between a safe side (outcome is always the same) and a gamble between a high gain/loss or nothing, while all outcome probabilities are calculable.

TABLE 1 | Descriptive statistics, control, and self-report measures on impulsivity and approach behavior.

Statistic	9–10 years old		11–12 years old		13–14 years old		15–16 years old		17–18 years old	
n	33		38		40		32		44	
Females/Males	10/23		17/21		19/21		15/17		27/17	
Age range (y;m)	8;8–10;10		11;0–12;11		13;0–14;11		15;0–16;11		17;0–18;11	
Mean age (y;m)	9;5		11;7		13;5		15;5		17;5	
SES (SD)	12.7	(2.4)	12.1	(2.3)	12.8	(2.7)	12.6	(2.2)	12.3	(2.7)
	n = 31		*n* = 34		*n* = 38		*n* = 30		*n* = 37	
Raven (SD)	24.9	(12.6)	33.3	(14.0)	38.6	(14.5)	50.4	(13.5)	53.0	(17.9)
Verbal Knowledge (SD)	35.7	(9.6)	48.8	(15.5)	55.8	(15.2)	67.1	(13.2)	69.8	(14.0)
IVE Impulsivity (SD)	8.4	(4.5)	7.2	(3.6)	7.7	(3.6)	6.4	(3.8)	7.0	(3.7)
IVE Venturesomeness (SD)	8.6	(3.9)	8.8	(4.7)	10.3	(3.3)	9.9	(4.3)	10.8	(3.5)
IVE Empathy (SD)	12.2	(3.5)	10.9	(4.7)	11.6	(3.1)	10.9	(3.7)	12.2	(3.2)
BAS (SD)	0.25	(0.75)	0.05	(0.71)	-0.18	(0.68)	-0.05	(0.82)	-0.02	(0.93)

Scores on the Raven and Verbal Knowledge Tasks reflect percentage of correctly solved items. Possible range of values for all IVE subscales is 0–16. BAS composite scores reflect z-scores (standardized for the whole sample).

participants performed 54 trials. The trials were presented in a gain and a loss block, counterbalanced in order of presentation across participants in each age group. The other experimental conditions were randomized within each block. The blocks were further treated as separate task conditions, namely, as THT Gain and THT Loss conditions. In the THT Gain condition, gains were added to an account displayed on the lower screen starting from 0€, while in the THT Loss condition, losses were subtracted from the account starting from 90€ (see **Figure 1**). At the beginning of each block, participants conducted three practice trials to familiarize them with the task.

For the safe side, the expected outcome value (EV) was always 1€. For the risky side, three conditions in the gain and loss blocks resulted in an equal EV (0.20 × 5€, 0.33 × 3€, or 0.50 × 2€). Moreover, some combinations resulted in risk-advantageous EVs in which the EV of the risky option was more positive for gain (0.33 × 5€, 0.50 × 3€, or 0.50 × 5€) or less negative for loss trials (0.20 × 2€, 0.20 × 3€, or 0.33 × 2€) than the sure gain/loss of 1€. In other combinations, the EV was risk disadvantageous, as the EV of the risky option for these trials was less positive for the gain trials (0.20 × 2€, 0.20 × 3€, or 0.33 × 2€) or more negative for the loss trials (0.33 × 5€, 0.50 × 3€, or 0.50 × 5€) than the sure gain of the safe option. As we were mainly interested in a comparison of the three decision-making tasks in this study, we only used the overall percentage of risky side choices in the THT Loss and THT Gain conditions, respectively.

BART Task

In the BART (adapted from Lejuez et al., 2002), participants make decisions under increasing risk. They were instructed to inflate a virtual balloon with each pump signifying a temporal gain of 5 cents and the goal to collect as much money as possible. In this version, balloons could be inflated via a keypress activating a red button shown on the computer screen, which was visibly connected to the balloon (see **Figure 2**). The temporal gain of each balloon could be saved on a permanent "bank account" but would be lost if the balloon explodes before doing so. As the balloon could explode with any pump (probability of 1/128 for an explosion in first trial), participants had to weigh the increasing risk of the balloon to explode (probability of 1/128-n in the n-th trial) against the potential gain of pumping the balloon further. Therefore, risk-taking in the BART task was defined as the mean number of pumps taken, as more pumps signify a greater propensity for risk.

The task consisted of 30 balloons that were treated as separate trials and three practice trials, in which the participants were familiarized with the controls. During the task, participants had insight into how many of the 30 balloons are left, how much money was on their permanent bank account, and how much money they made with the previous balloon. Note that we again used the structure of the original BART task but changed the presentation of the balloon environment (see **Figure 2**). The BART was performed under two conditions: alone and under the observation of a fictitious peer. For the purpose of this study, we will include only the alone condition and used the mean number of pumps as dependent variable.

STOPLIGHT Task

The STOPLIGHT task (adapted from Chein et al., 2011) is a simulated driving task that has often been used as a behavioral measurement of risky decision-making. Again, we modified the original task to make the task environment similar to the other two decision-making tasks (see **Figure 3**). In this task, participants saw a car on a straight track from a bird's eye view on a computer screen. Their goal was to reach a friend's party as fast as possible. A timer on the upper screen counted time spent on the track visibly for the participant.

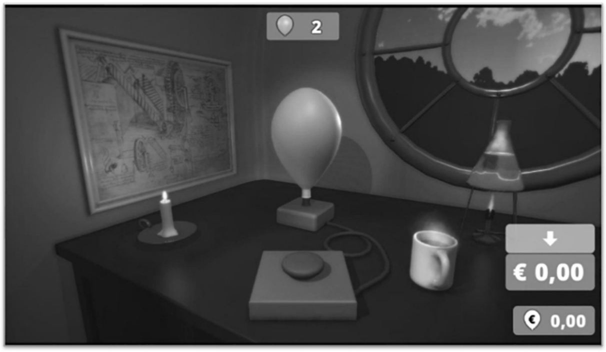

FIGURE 2 | Illustration of the BART in which participants had to decide to inflate balloons, with each pump signifying an increase in respective outcome value but also in the risk for the balloon to burst and, thus, to lose all previous earnings.

To progress on the track, participants had to advance through 20 intersections (10–16 s apart from one another) where a traffic light changed from green to yellow, as the vehicle approached. They had to decide whether to stop the otherwise automatically progressing car or to override the traffic light. To stop the car, participants had to press the space key of the computer keyboard in a time limit (2.5–4 s), which was indicated by an orange bar getting shorter as the car approached the intersection. Participants learned to control the car along the track through a tutorial that showed and instructed all three scenarios (stop at traffic light, override the traffic light without consequences, and causing a crash). At the end of the 20 intersections, which were treated as separate trials, participants arrived at the party that was animated in picture and sound. Stopping at the traffic light caused a time loss of 3 s. While overriding a yellow light could save the time else spent waiting, it also could cause a crash when the light changed to red, which resulted in an even bigger time loss of 6 s. The first 4 traffic lights were programmed to stay in the yellow phase, while the following 16 traffic lights changed from yellow to red in 50% of all cases. Risk-taking in the STOPLIGHT task was defined as the percentage of GO-decisions across all trials.

Self-Report Measures on Impulsivity and Approach Behavior

Impulsiveness Questionnaire

We used the German adaption of the Impulsiveness Questionnaire I6 (IVE; Stadler et al., 2004) originally developed in English by Eysenck and Eysenck (1978). The IVE is a self-assessment questionnaire consisting of three subscales: impulsivity, venturesomeness, and empathy, with 16 items each. The subscales impulsivity and venturesomeness include items concerning cognitive and motivational impulsivity, as well as risk- and sensation-seeking behavior, while the subscale empathy inquires about the sensitivity for the feelings of others. The items consist of statements about the participant's behavior

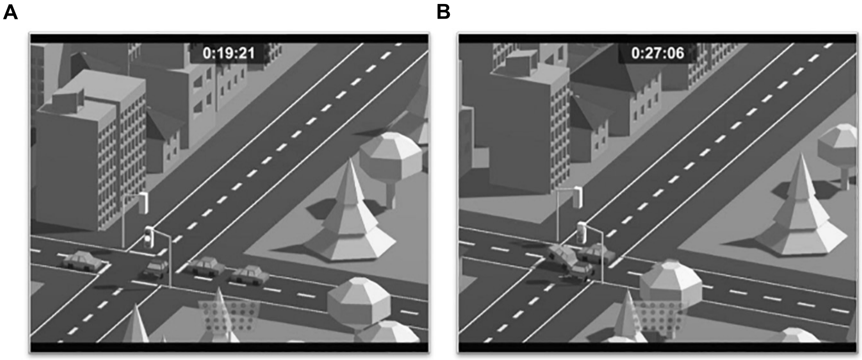

FIGURE 3 | Illustration of the simulated driving task, the STOPLIGHT task, in which participants had to decide to break on or to overrun yellow traffic lights on a simulated track. Outcome options are either to lose a safe amount of time (STOP) or to gamble between losing no time (safe GO-decision, **A**) and causing an accident **(B)**.

(e.g., "Do you quite enjoy taking risks?"), which they could declare to be true ("yes") or not ("no"). The authors provided data regarding the internal consistency of the German adaption with alpha coefficients ranging from 0.77 to 0.86. In this study, internal consistencies were 0.81, 0.84, and 0.84 for impulsivity, venturesomeness, and empathy, respectively.

BAS Scales

We used a translated version of the BAS scales (Carver and White, 1994) to assess approach behavior. The items were translated by members of our research team into child-friendly German. The BAS contains three subscales: reward responsiveness (five items), drive (four items), and fun seeking (four items). The items reflect statements (e.g., "When I want something, I usually go all out to get it") that are answered via a four-point Likert scale, ranging from 1 ("strongly disagree") to 4 ("strongly agree"). As subscales of the BAS were highly correlated (all r's > 0.42), the z-standardized subscale scores were averaged. In this study, internal consistency for the BAS score reached an alpha coefficient of 0.80 for the whole sample.

Fluid Intelligence and Control Variables

Advanced Progressive Matrices

To assess fluid intelligence, we used a computerized version of the Raven's Advanced Progressive Matrices (APM; Raven et al., 1985). For time reasons, the test was time limited in our study, and participants had 15 min to solve the matrices. As scores, we used the percentage of correctly solved items during this time.

SES

The participants' parents filled out a self-report questionnaire regarding socioeconomic information, family status, and health issues concerning the participating child. As these are the most widely used dimensions relevant for the SES, the highest education and highest occupation of the parents (cf. Nucci et al., 2012) as well as the monthly household net income were used to compute an SES score (Lampert et al., 2014). The SES was mainly used to describe our sample (see **Table 1**).

Verbal knowledge

To assess crystallized intelligence, we adapted two measures of verbal knowledge, the Word Puzzle and Word Similarities, of a German test for cognitive abilities for children and adolescents from 9 to 18 years (Kognitiver Fähigkeits-Test für 4. bis 12. Klassen, Revision: KFT 4-12+R, Heller and Perleth, 2000). Each task includes 12 words or word bundles, where participants either had to find the word with the same meaning (word puzzle) or they had to state which word would fit into specific word groups (word similarities). Each task ended after 4 min. As scores, we used the percentage of solved items in both tasks.

Power Analyses

We conducted a *post hoc* power analysis with the program G*Power (version 3.1, Faul et al., 2007) to find out whether our design had enough power to detect developmental trends in the four decision-making tasks. The analysis revealed that based on the means, standard deviation (SD), and correlation matrix of the four task settings, we would expect a large effect size in the within-between interaction (f = 1.49). Given our sample size (N = 187), the power of this effect to reach the 5% significance level was larger than 99%. For effect sizes as justified by Cohen, 1977; Cohen, 1988, we still obtained a power larger than 99% for a medium effect size of f = 0.25.

Concerning out hierarchical regression models, *post hoc* power analyses revealed a power of 69% to detect an R^2 increase of 0.05. Such an increase in R^2 was found for the four predictors of individual differences (BAS, impulsivity, venturesomeness, and empathy) when entered as the last step into the model including overall eight predictors for the THT Loss and STOPLIGHT. Given our sample of N = 187, we still obtained considerable power in detecting smaller effect sizes at the 5% significance level.

RESULTS

The present study examined the influence of age and individual differences in temperament components on four types of decision-making contexts. The Results section is structured along our main questions. First, we tested for differential age effects from late childhood to late adolescence on risk propensity of the four decision-making tasks. Second, we examined whether individual differences in temperament (i.e., approach behavior, impulsivity, venturesomeness, and empathy) can explain individual differences in risky decisions above and beyond age, gender, and fluid intelligence, and whether these influences differed depending on the task context. All analyses were conducted using SPSS (Version 24).

Is There a Differential Influence of Age on Experimental Risk-Taking Contexts?

To answer this question, we performed a multivariate analysis of variance (MANOVA) with age group (9–10, 11–12, 13–14, 15–16, and 17–18 years) as between-subjects variable and task types (THT Gain, THT Loss, BART, and STOPLIGHT) as dependent variables. For the within-factor task type, we predefined three contrasts: the first contrast compared mean differences in risk propensity between description-based and experience-based tasks, that is, between known and unknown outcome probabilities (contrasts: -1 -1 1 1). The second contrast determined the effect of valence for known outcome probabilities by comparing mean differences in risky decisions between gain and loss blocks of the THT (contrasts: -1 1 0 0). In the third contrast, we compared the mean of risky decisions between the BART and STOPLIGHT task (contrasts: 0 0 -1 1). For the between-factor age group, we contrasted for linear and quadratic age trends also in interaction with task type and furthermore tested for potential differences between age groups in a *post hoc* analysis. The corresponding data that entered into the analyses are shown in **Table 2** as a function of task and age group, and mean z-scores for each task are displayed in **Figure 4** as a function of age group.

The results revealed a significant difference in risky decisions between description- and experience-based task settings, $F(1,186) = 425.59$, $p < 0.001$, $\eta^2 = 0.70$, that was further modulated by a quadratic age trend, $F(1,186) = 7.92$, $p < 0.01$,

TABLE 2 | Percentage of Risky Decisions (SD) in the four risk-taking settings as a function of age group.

	THT Gain		THT Loss		BART		STOPLIGHT	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
9–10 years old	56.5	(16.0)	70.5	(17.7)	26.9	(13.6)	40.2	(19.7)
11–12 years old	50.2	(12.9)	63.0	(13.5)	28.0	(10.7)	42.6	(19.4)
13–14 years old	52.4	(15.8)	66.0	(11.8)	30.2	(10.4)	45.1	(12.5)
15–16 years old	50.0	(15.2)	60.2	(12.6)	31.2	(10.3)	48.7	(12.4)
17–18 years old	53.8	(13.7)	60.9	(14.3)	30.8	(12.8)	40.7	(16.6)

$\eta^2 = 0.04$. This finding indicated less risky decisions under unknown than known outcome probability and that this difference was less pronounced in mid-adolescents (see **Table 2** and **Figures 4A,B**). We also obtained an effect of incentive valence, $F(1,186) = 83.17$, $p < 0.001$, $\eta^2 = 0.31$, suggesting that more risky decision were taken in THT Loss than in THT Gain conditions (see **Figure 4A**). However, this effect was not further modulated by linear (only marginal) or quadratic age trends ($p = 0.07$ and $p = 0.45$, respectively). Finally, we also found a significant difference between the BART and STOPLIGHT, $F(1,186) = 100.88$, $p < 0.001$; $\eta^2 = 0.35$, indicating more risky decisions in the STOPLIGHT (see **Figure 4B**). Again, this effect was not further modulated by linear or quadratic age trends ($p = 0.40$ and $p = 0.12$, respectively).

To better understand age differences, we performed multivariate age trend analysis for risk propensities in the tasks irrespective of task type. Thereby, age trend contrasts revealed a significant linear age effect in the THT Loss, $F(1,182) = 8.97$, $p < 0.01$, $\eta^2 = 0.05$, suggesting a decrease in risky side choices over the course of adolescence. *Post hoc* comparisons using Bonferroni correction revealed that the 9- to 10-year-olds ($M = 70.48$, $SD = 2.45$) showed significantly more risky decisions than the 15- to 16-year-olds ($M = 60.19$, $SD = 2.48$) and the 17- to 18-year-olds ($M = 60.94$, $SD = 2.12$) in the THT Loss, while other age groups did not differ in their risk-taking (all p's > 0.26). Moreover, no linear age effects were found for risk-taking in the THT Gain, the BART, or the STOPLIGHT (all p's > 0.07). However, risky decisions in the STOPLIGHT suggested a quadratic age trend, $F(1,182) = 4.00$, $p < 0.05$; $\eta^2 = 0.02$, that is, risk-taking was higher in mid-adolescents than in children and late adolescents. Thereby, *post hoc* comparisons using Bonferroni correction showed no differences in risk-taking between age groups in the STOPLIGHT (all p's > 0.36).

The Impact of Individual Differences in Temperament and Intelligence on Risk-Taking

At first, we analyzed correlations between sample characteristics and the outcome variables (the four risk-taking tasks) for the whole sample and the five age groups separately. As can be seen in **Table 3**, the correlations among the four risk-taking tasks are rather low and reached significance only for correlations between the two THT conditions ($r = 0.31$; $p < 0.01$) and the BART and STOPLIGHT ($r = 0.15$; $p < 0.05$). The pattern of results was quite similar for each of the five age groups. Therefore, separate hierarchical regression models were fitted for each of the four risk-taking contexts.

For each regression model, we first entered age and age^2 as we were interested in the explained variance beyond age effects. To reduce multicollinearity, age was centralized on the sample mean. In the next step, we entered gender and fluid intelligence to examine whether gender and individual differences in fluid abilities can explain some of the variance in risky decisions in the four task settings. In the final step, we entered the temperament measures (approach behavior, impulsivity, venturesomeness, and empathy) to examine their contribution in predicting risky behavior above age, gender, and development in fluid intelligence. Tests to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (age, tolerance = 1.00, VIF = 1.00; age^2, tolerance = 1.00, VIF = 1.01; gender, tolerance = 0.96, VIF = 1.04; intelligence, tolerance = 0.68, VIF = 1.47; impulsivity, tolerance = 0.69, VIF = 1.45; venturesomeness, tolerance = 0.74, VIF = 1.35; empathy, tolerance = 0.77, VIF = 1.31; BAS, tolerance = 0.78, VIF = 1.28).

For the THT Gain and the BART task, neither the predictor variables nor the overall model reached significance (see **Table 4**). In contrast, a significant regression equation was found for risk decisions of the THT Loss condition, $F(8,176) = 3.28$, $p < 0.01$, with an R^2 of 0.130. Adding age on the first step resulted in a significant increase in R^2, R^2 change = 0.050, $F(1,183) = 9.56$, $p < 0.01$. This partial effect of age ($\beta = -0.22$, $p < 0.01$) was further superseded by the effect of fluid intelligence ($\beta = -0.20$, $p < 0.05$) when added to the model, without increasing R^2 further, R^2 change = 0.028, $F(4,180) = 3.89$, $p < 0.01$. In the final model, there was a significant relationship between risk-taking propensity in the THT Loss condition and the venturesomeness subscale ($\beta = 0.20$, $p < 0.05$), with the final step including individual differences in temperament generally increasing the model fit significantly, R^2 change = 0.050, $F(8,176) = 3.28$, $p < 0.01$.

Furthermore, also 9% of the variance of risky decisions in the STOPLIGHT task could be explained by the final regression model, $R^2 = 0.091$ [$F(8,176) = 2.21$, $p < 0.05$]. Thereby, age^2 ($\beta = -0.20$, $p < 0.01$), impulsivity ($\beta = 0.17$, $p < 0.05$), and empathy ($\beta = 0.18$, $p < 0.05$) showed significant partial effects, with R^2 change = 0.033, $F(2,182) = 3.34$, $p < 0.01$ for the step including age^2 and R^2 change = 0.055, $F(8,176) = 2.21$, $p < 0.05$ for the step including the measures of individual differences in temperament, respectively.

DISCUSSION

The main goals of this study were to determine age differences in different decision-making tasks across a broad age range throughout adolescence and to explore the role of individual differences in temperament in understanding age differences in decision-making. Therefore, we applied four experimental decision-making tasks (THT Gain and Loss, BART, and STOPLIGHT) to analyze developmental trends from late

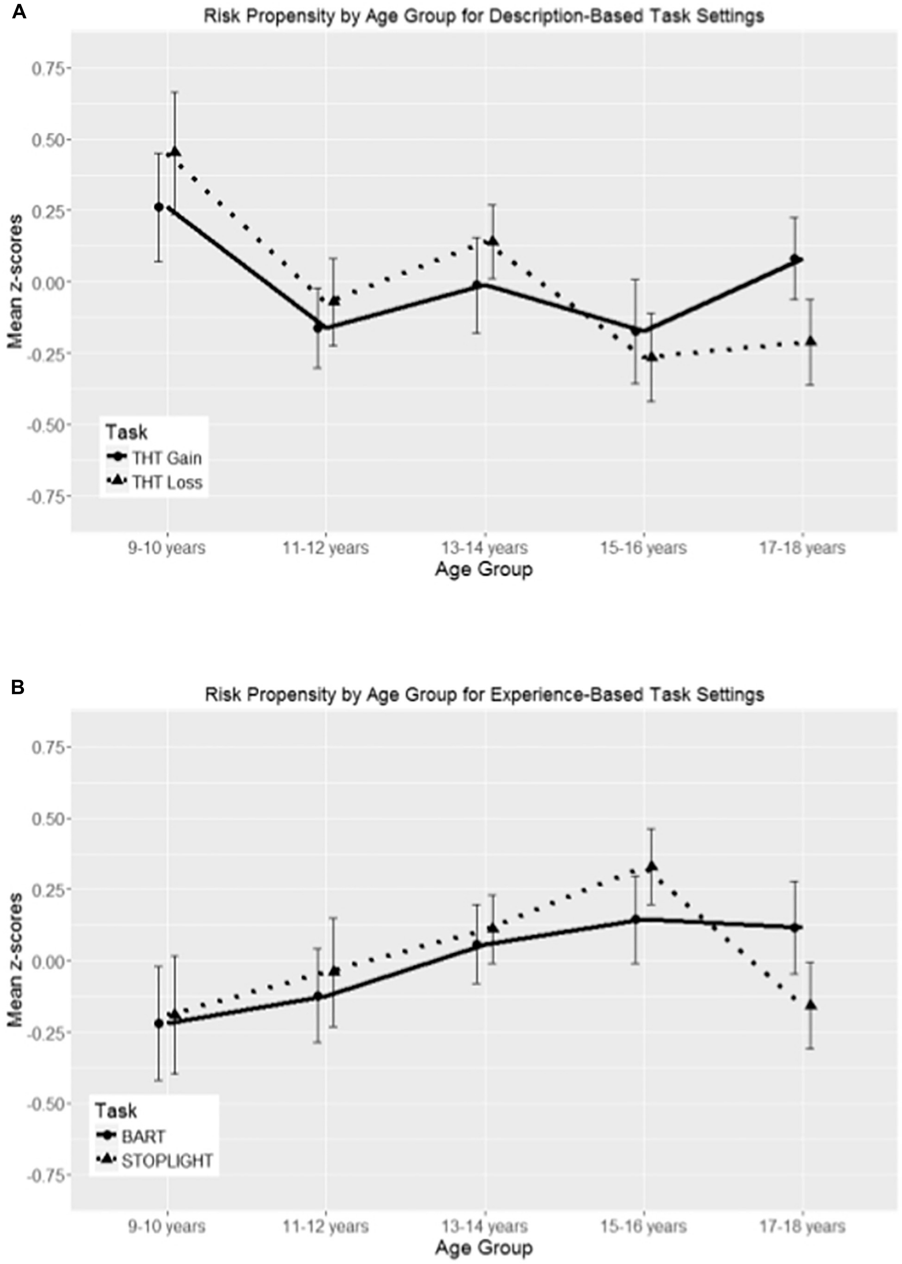

FIGURE 4 | Mean *z*-scores of the four experimental decision-making tasks as a function of age group, presented separately for experience- **(A)** and description-based **(B)** task settings. Error bars represent standard errors. Points are offset horizontally so that error bars are visible.

childhood to late adolescence. The tasks differed in task characteristics, such as known outcome probability, valence of anticipated outcomes (i.e., gains and losses), dynamic change of risk level, and induced time pressure. Additionally, we were interested in the (possibly differential) contribution of individual differences in temperament components, namely, approach behavior, impulsivity, venturesomeness, and empathy, in explaining risky decisions.

The results of our study revealed several important new insights. At first, the four decision-making tasks indeed showed differential developmental patterns throughout adolescence. Second, the experimental risk-taking tasks were only low to moderately correlated with each other, indicating that each of them captures a unique decision-making context. Moreover, only some decision-making were susceptible to individual differences in temperament and fluid intelligence.

Considering first decision-making in a loss context, results of our study clearly indicated that gambling to prevent losses diminished with increasing age for task settings under known outcome probabilities (THT Loss). This is in line with a recent

TABLE 3 | Intercorrelations among the study variables.

Measure	1	2	3	4	5	6	7	8	9	10	11
1. THT Gain	—	0.31**	0.13	0.13	−0.02	−0.02	−0.10	0.14	0.12	0.02	0.15*
2. THT Loss	0.31**	—	0.13	0.12	−0.12	−0.06	−0.17*	0.15*	0.23**	0.03	0.12
3. BART	0.12	0.10	—	0.15*	0.05	−0.12	0.08	0.06	0.16*	−0.02	0.06
4. STOPLIGHT	0.13	0.11	0.15*	—	0.07	−0.02	−0.02	0.16*	0.14	0.07	0.09
5. Age	−0.04	−0.22**	0.13	0.05	—	0.08	0.02	−0.04	0.04	0.11	0.00
6. Gender	−0.03	−0.10	−0.08	−0.01	0.20**	—	−0.04	−0.08	−0.15*	0.40**	−0.13
7. Intelligence	−0.10	−0.25**	0.14	0.01	0.56**	0.08	—	−0.30**	−0.11	0.02	−0.07
8. Impulsivity	0.14	0.17*	0.05	0.15*	−0.12	−0.10	−0.32**	—	0.37**	−0.23**	0.35**
9. Venturesomeness	0.11	0.18*	0.18*	0.15*	0.20**	−0.11	0.02	0.34**	—	−0.08	0.35**
10. Empathy	0.02	0.03	−0.02	0.07	0.04	0.40**	0.03	−0.23**	−0.07	—	−0.03
11. BAS	0.15*	0.14	0.04	0.08	−0.10	−0.15*	−0.11	0.36**	0.33**	−0.03	—

Intercorrelations with age group partialed out are presented above the diagonal, and intercorrelations for the whole sample are presented below the diagonal. THT Gain, THT Loss, BART, and STOPLIGHT are experimental decision-making tasks. Gender was categorized in 1 for male and 2 for female participants. Intelligence is a measure of fluid intelligence that derive from the Raven's Progressive Matrices. Impulsivity, venturesomeness, empathy, and BAS are measures of individual differences in temperament that derive from the IVE (German version) and the BAS, respectively. $^{*}p < 0.05$. $^{**}p < 0.01$.

TABLE 4 | Results of the stepwise regression analysis for the four risk-taking settings.

	Source of risk-taking behavior							
	THT Gain		THT Loss		BART		STOPLIGHT	
Predictor	R^2	β	R^2	β	R^2	β	R^2	β
Step 1	0.002		0.050**		0.018†		0.003	
Age		−0.040		−0.223**		0.133†		0.051
Step 2	0.003		0.002		0.008		0.033*	
Age^2		0.051		−0.039		−0.088		−0.182*
Step 3	0.010		0.028†		0.018		0.001	
Gender		−0.030		−0.058		−0.118		−0.024
Intelligence		−0.119		−0.195*		0.080		−0.035
Step 4	0.029		0.050*		0.023		0.055*	
Impulsivity		0.076		0.049		0.040		0.171*
Venturesomeness		0.062		0.195*		0.134		0.055
Empathy		0.054		0.087		0.059		0.180*
BAS		0.091		0.017		−0.003		0.027
Total R^2 n	0.043		0.130**		0.067		0.091*	
	185		185		185		185	

Intelligence is a measure of fluid intelligence that derive from the Raven's Progressive Matrices. Gender was categorized in 1 for male and 2 for female participants. Impulsivity, venturesomeness, empathy, and BAS are measures of individual differences in temperament that derive from the IVE (German version) and the BAS, respectively. $^{\dagger}p < 0.10$. $^{*}p < 0.05$. $^{**}p < 0.01$.

study that compared decision-making separately for the gain and loss domains (van den Bos and Hertwig, 2017). According to Reyna and Farley (2006), an increasing risk aversion with age can be explained by a developmental shift from basing decisions on quantitative to qualitative outcome dimensions (e.g., preferring to possibly lose nothing than to lose something) over the course of adolescence. In contrast, results of our study indicated that decision-making under gain conditions was not age sensitive, while other studies revealed a mid-adolescent peak in reaction to potential gains (e.g., van den Bos and Hertwig, 2017), or at least a small increase in risk propensity with age (aged 8–17 years; Levin et al., 2014). A possible explanation for these contradicting findings might be differential sensitivities to gains and losses depending on the value of potential outcomes across adolescence. As such, according to our findings, adolescents showed more risk-seeking behavior in the loss than in the gain domain (aged 14–17 years; Reyna et al., 2011), at least under the prospect of small to medium incentives ($5 and $20). Thus, in high-reward conditions ($150), adolescents showed a reversed framing effect with more risky decisions in the gain than in the loss condition (Reyna et al., 2011). Hence, in line with a recent review, a "hot" context, like when high incentive values are given, more consistently provoke an adolescent-specific reaction (cf. Kray et al., 2018). Moreover, van den Bos and Hertwig (2017) showed an inverted U shape in risk propensities for gain gambles under known risk across adolescence but also used a higher variability in incentive values (from 3€ to 32€) than we offered in the THT (2€, 3€, or 5€). This is also in line with the prospect theory that considers differential reference points, like incentive domain and value range, in the prediction of risky decision-making behavior. Thus, the development in processing multiple outcome characteristics, like referencing actual outcome with respect to the maximal earnable value, might further explain age differences in risky decisions.

In support of this view, we found not only decreasing risk-taking to prevent losses with age but also that this decreasing can mostly be accounted for by individual differences in fluid intelligence. In a previous study, individual differences in cognitive abilities, like numeracy, have also been associated with a higher sensitivity for expected values and thus more advantageous risk decisions with development (Levin et al., 2014). While adolescents have been shown to be capable decision-maker in age-appropriate and coherent decision situations (e.g., Crone et al., 2003), it may be that the level of information in the THT Loss was too demanding for the still immature cognitive abilities of children and young adolescents. Beneath individual differences in cognitive abilities, more risky decisions in the THT Loss were associated with a higher degree of self-reported venturesomeness. Venturesomeness is thereby the motivation to explore risk behaviors for which participants are aware of potential risks. Reyna and Farley (2006) described a similar phenomenon in risk preferences of youth, showing that even though adolescents tend to overestimate the true likelihood of negative outcomes of risk behaviors (e.g., HIV), they engage in heightened risk-taking (e.g., unprotected sex; Reyna and Farley, 2006). Importantly, the influence of individual differences in venturesomeness remained significant even after controlling for individual differences in age and thus may explain motivation to engage in known risks above adolescent development. However, an open question for future research remains whether influences of both individual differences in fluid intelligence and venturesomeness are adaptive or maladaptive in risky decision-making, that is, whether increasing risk aversion with fluid intelligence and/or the disposition to explore risk options will lead to more risk-advantageous choices or even to worse performance (choices for risk-disadvantageous options) in decisions to prevent losses with known probabilities. While our temperament measures generally increased the predictability of risk decisions in the THT Loss, no other individual difference except for venturesomeness predicted risk decisions in the THT Loss significantly. It has already been argued that task-based risk measures, like the THT, might reflect a different behavioral manifestation of risk-taking than risk propensity (e.g., self-reported reward sensitivity) and frequency measures (real-life risk behaviors, e.g., drinking). Nonetheless, task contexts might reflect states for which certain individual temperamental differences predict risk decisions more reliable than others (Frey et al., 2017). Thus, the tendency to engage in known risks (venturesomeness), for example, might rather reflect risk decisions under described potential losses but not gains.

Thus, and in accordance with several findings for the gain domain under known risk (for BAS, Blankenstein et al., 2018; for novelty-/thrill-seeking, van den Bos and Hertwig, 2017), risk propensity in the THT Gain cannot be predicted by any of the given individual differences. The lack of an association between risk-taking in the THT Gain and fluid intelligence is surprising, however. In contrast, risk propensity in the THT Loss and the sensitivity to expected values across valence domains of the CUPS task could completely be accounted by fluid intelligence or numeracy abilities (age range = 8–17 years; Levin et al., 2014), respectively. Thus, in an earlier study, Levin et al. (2007) could show that EV sensitivity had a more protracted development in the loss than in the gain domain of the CUPS, at least when compared between younger and older children (aged 5–7 and 8–11 years, respectively). Generally, it has been shown that resources are differentially involved in the processing of positive versus negative information in a variety of psychological processes, for which all losses have a higher impact (for a review, see Baumeister et al., 2001). Thus, they might allocate more cognitive resources than gains.

For dynamic risk conditions, such as choices to pump the balloon in the BART, we found no age sensitivity in the present study. Given the fewer risk decisions in experience-than description-based task settings, a lack of age differences in the BART matches the finding of Van Duijvenvoorde et al. (2012). They could show that participants under age 12 could not learn from experience at all during experimental decision-making, while learning from described outcomes was already present in late childhood. In addition, other studies reported that risk propensity seems to rather peak in late adolescence or young adulthood with a decline thereafter (Braams et al., 2015; Duell et al., 2018), hence a U-shaped developmental trend when including also young adults. However, as our sample did not include age groups above age 18, we might not be able to depict the plateau and consecutive decline of risk-taking in the BART. Given that this study is designed as a longitudinal study with a lag of 2 years, we might be able to obtain similar developmental trends as reported in the future. However, decisions for risky options under time pressure in the STOPLIGHT showed the hypothesized mid-adolescent peak, which is in line with previous findings (Steinberg et al., 2008; Duell et al., 2018). Moreover, adolescents engaged in higher risk in the STOPLIGHT than in the BART, which is in line with the finding of relatively risk-averse behavior in the BART with respect to the maximal number of possible consecutive risk decisions and the tasks' maximized point earnings (for a review, see Lauriola et al., 2014). As such, decisions to engage in risks when dynamic probabilities are only experienced might increase with rather protracted task and and/or life experience, as compared to tasks with static risk, like the STOPLIGHT.

Accordingly, the two experienced-based tasks showed different susceptibility to individual differences in temperament. Our regression model revealed that neither age nor gender, fluid intelligence, and temperamental differences did explain risk behavior in the BART. As the most profound correlations between risk propensity in the BART and temperamental differences in approach behavior and disinhibition seem to rise with age (BAS Drive, Braams et al., 2015; sensation seeking and impulsivity, Lauriola et al., 2014; for the BART-Y, MacPherson et al., 2010), here again, the chosen age range might not be not optimal to depict these associations. For the STOPLIGHT, however, our regression model indicated that, above age, gender, and fluid intelligence, two temperamental facets, namely, impulsivity and empathy, predicted risky behavior in the STOPLIGHT. Thereby, other studies did not find an association between risk propensity in the STOPLIGHT and impulsivity, as measured by the Barratt Impulsiveness Scale (BIS-11, Barratt, 1959), but with sensation seeking (Steinberg et al., 2008; Chein et al., 2011). Sensation seeking (Zuckerman, 2007) is thereby a measure for thrill-seeking tendencies with some overlap to the IVE subscale venturesomeness used in this study. However, these studies investigated older samples, and it has to be acknowledged that the BIS-11 was not conceptualized for children and younger adolescent samples, as it includes items that might not reflect impulsive behavior appropriate for these ages (e.g., "I spend more money than I earn"). Therefore, we applied the IVE in the present study as it showed sufficient validity and its impulsivity measure is adapted for younger samples. Hence, differences in sample characteristics and measurement instruments may explain the differences in outcomes. Interestingly, social context manipulations, like an observation by peers while performing the STOPLIGHT, have been shown to induce more risky decisions in adolescents (aged 14–18 years) but for no other age group (aged 19–22 years and 24–29 years, respectively; Chein et al., 2011). Similarly, in this study, the proportion of risky decisions can be explained by individual differences in a measure of social sensitivity, namely, empathy. Here, more empathic participants showed more risky behavior in the STOPLIGHT. One explanation might be that those participants that are empathic for the feelings of others are also those that feel rewarded to engage in a risk that has potential consequences for (accident) or is seen (virtual traffic or peers) by others. Thereby, it has to be acknowledged that we changed the visual environment of these tasks to make them dynamic and appealing in use for early to late adolescents. While we intended to maximize the affective context, participants could evaluate negative outcomes, thus accidents as less severe when seen from bird's eye view in a rather plastic surrounding like in this study (see **Figure 3**). This could account for the positive direction of the association between risk-taking in the STOPLIGHT and empathy. Another explanation might be on the side of the time pressure manipulation, as participants were asked to reach a friend's party in a timely fashion while being already late during the STOPLIGHT. Thus, empathic participants might be more driven and more willing to engage in risk to reach this goal to not be displeasing.

Limitations of the Present Findings

A limitation that can be drawn on most studies using experimental decision-making is that their relevance in explaining real-life risk behaviors in adolescence remains unclear. As such, even though we can show that several affective task moderators influence decision-making in the laboratory, we cannot conclude their meaning for decisions to engage in health-risk behaviors across adolescence. Generally, a study using psychometric modeling analyses found that self-reported behavioral tendencies in risky decision-making were more related to frequencies of real-life risk behavior (like alcohol or cigarette consumption) than risky choices in experimental tasks. Moreover, self-reported risk preferences appear to be more stable over time than experimental risk measures, which are thought to rather capture states than traits (Frey et al., 2017). The fact that quite variable and often undefined personality measures are used in the decision-making literature and often quite low sample sizes to detect associations between individual differences and task performance may further contribute to the difference between experimental and self-descriptive measures (Appelt et al., 2011). Yet, each behavioral task represents a specific choice frame that can be used to examine inter- and intraindividual differences in reaction to these decision contexts (Frey et al., 2017).

Moreover, to compare task settings that differ in affectively engaging task moderators, we implemented one representative of each decision-making context we were interested in. This leads to a main limitation in generalizing our findings to the numerous experimental risky decision-making tasks found in the literature. Specifically, the actual findings further emphasize to consider the role of affective contexts and individual differences in fluid intelligence and temperament instead of generalizing risk-taking behavior in adolescence. Nonetheless, the task settings used are counted among the most investigated experimental decision-making tasks in the adolescent literature and showed benefits in evoking specific affective states.

In this study, we found adolescent risky decision-making and the predictive value of their individual temperamental differences to be context dependent. Thereby, a main limitation, so far, is the reliance on only few age groups and tasks when investigating developmental trends in adolescent decision-making. Even though we overcame this limitation and made use of the full age range from early to late adolescence, age was not the most decisive predictor of experimental risk-taking. Thereby, literature drawing conclusions between motivated decision-making and pubertal development in adolescence is growing (for a review, see Laube and van den Bos, 2016). However, self-description measures of pubertal status often are closely related to age. This makes the comparison between influences of pubertal status and close age groups, without the intention to measure hormone levels in blood or salivary, difficult. Even though we draw our conclusions based on a wide age range and variable task contexts, cross-sectional data remain inferior to longitudinal data when detecting changes over time or individual pubertal development. As our findings derive from our first measurement period, which will be followed by a second measuring point within a 2-year gap, we can use the gathered information about the given task settings and their sensitivity to individual differences to formulate more specific predictions concerning changes in risk propensity over time.

CONCLUSION AND OUTLOOK

In conclusion, results of this study revealed that risk propensity across adolescence is highly context dependent. More specifically, while risk-taking propensity showed an adolescent-specific peak for experienced task settings under time pressure (STOPLIGHT), it declined with increasing cognitive abilities in gambles to prevent losses with known outcome probabilities (THT Loss).

For the comparison of the gain and loss domains under known outcome probabilities, the gain domain of the THT was not age sensitive in this study, and our measure of reward sensitivity (BAS) could not explain variance of any risk-taking measure. Adolescents moreover were more risk seeking when deciding between options to minimize risks than to maximize gains. Nonetheless, most findings in the adolescent literature are limited to gains, even though social contexts have been shown to have a high impact on decision-making in adolescence, with only few decision-making tasks being investigated under social context manipulations so far. In sum, one should consider the age-specific relevance of different kinds of contexts and incentives when exploring the impact of reward/punishment sensitivity on risk-taking behavior from childhood to adulthood (see Kray et al., 2018 for a review).

For the comparison of experience-based versus description-based outcome probabilities, adolescents engage in more risky decisions when outcome probabilities are known than unknown. In addition, description-based tasks in the loss domain are associated with more deliberate functioning (fluid intelligence and venturesomeness), while experience-based task settings under time pressure are rather associated with affective functioning (impulsivity and empathy). This finding underlines the importance to distinguish disinhibition behavior associated with more cognitive (to engage in known risks, venturesomeness) or more affective functioning (to act without thinking, impulsivity) (see Eysenck and Eysenck, 1978). Moreover, risk aversion in experience-based decision-making was higher when risk probability changed dynamically with each decision in the BART. In sum, the results of our study indicate adolescent risky decisions to be context dependent and differentially susceptible to individual temperamental differences in experimental decision-making settings with described as well as experienced outcome probabilities.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Declaration of Helsinki and approved by the local ethics committee of Saarland University. All subjects gave written informed consent and were paid 8€ per hour.

AUTHOR CONTRIBUTIONS

CL was responsible for the content of this original study. JK provided feedback regarding the analysis, interpretation and discussion, and gave advice in the writing process.

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PART II

Developmental Differences in Adjustment to Risk Uncertainty Under Peer Observation in Adolescence

Abstract

Social influence plays a crucial role in the adolescent-specific tendency for heightened risky decision-making. However, little is known about developmental trajectories, mechanisms, and moderators in, e.g., in the effect of peer observation on adolescents' risky choices. This study investigated the risky decision-making in 184 pre to late adolescents (9-18 years-old, *M* = 14.1 years) in a dynamic task setting, the Balloon Analogue Risk Task (BART, Lejuez et al., 2002). In the BART, adolescents heighten gains with each decision to pump balloons but simultaneously the risk for balloons to burst and to lose all previous earnings with an unknown probability of occurrence. Adolescents conducted the task once alone and once under the observation of a virtual peer. The study further included a questionnaire on self-reported resistance to peer influence (RPI, Monahan & Steinberg, 2007), and investigated gender differences in the prediction of age-differences in risky choices when peer observation was present than when it was absent.

Surprisingly, peer observation did not generally heighten risky decision-making, but adolescents with a low resistance to social influences increased risky choices when peer observation was present. The results suggested that all adolescents decrease risky choices following negative outcomes but increase them throughout the task, i.e., show learning. Older adolescents showed generally more adaptive decisions than younger adolescents, especially when observed. Results revealed no gender differences in reactivity to peer observation. The study suggests that adolescents become increasingly adaptive in risky decision-making and that not all risk situations and individuals are susceptible to risk-seeking behavior in the presence of peers.

1. Introduction

Even though adolescence is a developmental stage of physical health and increasing cognitive abilities, individuals are disproportionally represented in national and international statistics concerning suboptimal health outcomes related to hazardous behaviors during this period (for recent statistics from Germany, Ellsäßer, 2017). Recently, it has been suggested that adolescents are highly sensitive to the situational context when making decisions for risk (Defoe et al., 2015; Shulman et al., 2016; Romer et al., 2017). As such, whether adolescents are rash and impulsive risk-takers or capable decision-makers may lie in characteristics of the risk to be taken. One ubiquitous observation is that adolescents engage in most risk behaviors when in the presence of peers (Steinberg, 2008).

In this sense, some of the most driving events in adolescence are thought to be social (Crone & Dahl, 2012). As such, the social environment of adolescents undergoes dramatic changes, as do brain structures that are associated with social cue processing and social functioning, like abilities to infer about the other's mental state (mentalizing; Blakemore & Mills, 2014; Mills, Lalonde, Clasen, Giedd, & Blakemore, 2014). Thereby, a social reorientation towards peer groups might reflect an adaptive social strategy to pursue developmental goals that are specific for the adolescent period, like becoming independent from the family and integrating oneself into larger social networks (Blakemore & Mills, 2014; Nelson, Jarcho, & Guyer, 2016). These observations suggest adolescence to be a sensitive period of sociocultural processing (Blakemore & Mills, 2014).

In previous studies, peer influences on adolescents' risk-taking behavior have mostly been assessed in terms of similarities in risk-taking among peer groups that have been explained by social learning (e.g., Haynie & Osgood, 2005). It is only in the last decade that several studies investigated the direct effects of peer influences on adolescent risk-taking, mostly using risky decision-making tasks under various social contexts. Studies based on social learning showed merits in understanding how adolescents adjust their behavior to risk-averse or risk-seeking choices (e.g., Shepherd et al., 2011), or feedback (e.g., van Hoorn et al., 2017), of their peers. As such, adolescents not only increased risky choices when exposed to risk-seeking peer norms but also decreased, e.g., risky driving when exposed to risk-averse peers (e.g., Shepherd et al., 2011). However, even outside of adjustment to obvious or induced risk norms and social learning, social context is assumed to influence adolescents' brains and behavior (Albert, Chein, & Steinberg, 2013).

The empirical findings of studies that included peers to only observe adolescent risky decision-making have well established that such social context influences risky choices during this time (e.g., Chein et al., 2011; Gardner & Steinberg, 2005; Haddad et al., 2014; Kretsch & Harden, 2014; Pfeifer et al., 2011; Smith et al., 2014). While one study suggested that task observation, but not mere presence, would lead to peer effects (e.g., Somerville et al., 2019), other findings highlight the fundamentality of social motivation by pointing out that adolescents adjusted risk-taking independent from familiarity or actual presence of the observer (e.g., Haddad et al., 2014; Smith et al., 2014; Somerville et al., 2019; Weigard, Chein, Albert, Smith, & Steinberg, 2015).

One influential finding concerning the effect of peer observation derives from a study that investigated simulated driving in adolescents and adults when a familiar peer was remoted and observed task conduction (Stoplight task, Chein et al., 2011). In this task, individuals engage in decisions between the option to stop a car at intersections and lose time, or to run over intersections with an unknown probability of causing an accident and losing even more time than when stopping at lights. Not only was heightened risk-taking under peer observation an adolescent-specific effect, but the study was the first to show that social sensitivity might imply a biological factor for which development accounts for adolescent-specific behavior, like sensation-seeking and risk-taking.

Accordingly, social variants of neurodevelopmental models suggest that like other potentially rewarding situations, e.g., when in the prospect of monetary gains, risk-taking becomes more appealing when in the presence of peers (e.g., Steinberg, 2008). Based on social facilitation theory (Zajonc, 1965), such reward sensitivity models posit, e.g., peer presence to heighten arousal that is processed in brain regions that show a peak in maturation during adolescence. In contrast, brain regions and abilities associated with top-down control of socioemotional arousal are thought to only gradually develop during this time (e.g., Casey, 2015; Steinberg, 2008; Shulman et al., 2016; but see Pfeifer & Allen, 2016), rendering the adolescent more likely to explore situations, like socially accepted but also imprudent risk behaviors (Duell & Steinberg, 2019).

Besides the hypothesized reward sensitivity, a contrasting mechanism that has been discussed was blunted sensitivity to negative feedback during adolescence. As such, reduced neuronal reactivity to negative versus positive feedback was associated with less reduction of risky choices following negative outcomes and self-reported risk-taking in one study, but it did not include a social situation (McCormick & Telzer, 2017b). A further verbal model in terms of social facilitation is the distraction from the task at hand when under observation. This aspect has been mostly disregarded in adolescent risky decision-making (Ciranka & van den Bos, 2019). In a recent study, adolescents (ages 15-17 years) conducted a gambling task and a task testing inhibitive control either alone or under the belief that a virtual peer observed behavior. Peer observation increased risky choices and striatal reactivity in the brain but not had no effect on behavioral response inhibition. As peer presence had only minimal influence on activity in cognitive control regions, the researchers suggested that peers increase reward-sensitivity but does not disrupt cognitive control (Smith, Rosenbaum, Botdorf, Steinberg, & Chein, 2018). Thus, they did not test age differences herein.

Altogether, there are differing views on how peers might influence adolescent motivated behavior, but research mostly focused on negative consequences, like heightened tendencies for risk-taking. Recently, there is an increasing interest in studying adaptive outcomes of adolescent development (for a review, see Telzer, 2016), as increases in goal-directed behavior and flexibility in the engagement of cognitive control (for a review, see Crone & Dahl, 2012; Li, 2017). Concerning risky decision-making, it has been found that risk-taking decreases, while advantageous decision-making increases that could also be associated with increases in cognitive control during adolescence (for a review, see Li, 2017). In a recent study, pre to late adolescents (aged 8-17 years) have been shown to become more adaptive in risky choices with age, as late adolescents engaged in greater learning throughout a risky decision-making task than younger ages. Furthermore, increased neuronal activity and interconnectivity between brain regions with age explained the link between age and increases in flexible learning during the task (McCormick & Telzer, 2017a). However, it remains unclear whether social situations, such as peer observation, might influence age differences in adaptive outcomes of risk-behavior as well. At least, peer observation has been shown to increase late adolescents' risk exploration and learning from both positive and negative outcomes of risky choices in a dynamic task setting (aged 18-23 years, Silva, Shulman, Chein, & Steinberg, 2016).

Given greater flexibility in behavior during adolescence, risky decision-making may be highly influenced by peer observation, but this association might be further moderated by specific characteristics of the risk situation at hand. As such, findings were mostly drawn from one task setting, that is, simulated driving, like the Chicken (e.g., Gardner & Steinberg, 2005), or Stoplight Task (e.g., Chein et al., 2011). Simulated driving depicts risky choices under uncertainty when risk probabilities and outcomes can only be experienced across trials. Accordingly, one study found heightened risk-taking under peer presence in an ambiguous task but not in a task context in which all information is described and expected values for choice options can be calculated (Lloyd & Döring, 2019), while another study further suggests age differences in the effect of peer presence between described and ambiguous decision settings (hot and cold Columbia Card Task, Somerville et al., 2019). In contrast, some description-based gambling tasks also showed heightened risk-taking under peer observation (e.g., Haddad et al., 2014; Smith et al., 2014; van Hoorn et al., 2017), while some did not find an effect in a dynamic version of experience-based tasks, the Balloon Analogue Risk Task (BART, Lejuez et al., 2002; e.g., Harakeh & de Boer, 2019; Reynolds, MacPherson, Schwartz, Fox, & Lejuez, 2014), or more cautious behavior at the utmost when observed by a peer (Kessler et al., 2017). In sum, findings are conflicting concerning the suggested adolescent-specific social sensitivity that was assumed to lead to heightened risk-taking under peer observation during this period. Thereby, little is known about moderators and mechanisms behind the influence of social situations on adolescent risky-decision-making and developmental trajectories herein.

Following, social sensitivity during risky decision-making and subsequent heightened tendencies for risk under peer presence might be a characteristic of some adolescents, but not of others. Consequently, individual differences might further account for the inconsistent findings on heightened risky-decision making under peer observation (e.g., Defoe et al., 2015). On the one hand, evolutionary theories suggest males being specifically prone to risk-taking during adolescence, especially when in the presence of their male confederates (Wilson and Daly, 1985). Accordingly, one recent study indeed found only male adolescents to show heightened tendencies for risky choices under peer observation in the Stoplight task (Defoe et al., 2019a). However, only a few studies reported gender differences in risky decision-making that implies difficulties in comparing gender effects across studies (Defoe et al., 2015), while heightened risk tendency in males than females is an often observed phenomenon in real life (for a review, see Byrnes et al., 1999). On the other hand, adolescents are thought to increase in the ability to resist peer influences with the gradual increase in cognitive abilities, and females have been reported to be more resistant to social influences than males (Paus et al., 2008; Steinberg & Monahan, 2007; Sumter et al., 2009; but see Bell & Baron, 2015 for an extensive review). As such, how peer observation alters risky choice might not only depend on characteristics of the situation but also individual differences.

As a summary, peers are influential in real-life risk-taking during adolescence and experimental studies robustly show peer influences on risky decision-making. Thereby, little is known about developmental trajectories in the effect of peer observation, as most studies focused on one adolescent sample or another younger or older age group to investigate age differences in peer effects. Thereby, social influences might be higher in task contexts that are similar to decision situations in the real life, like when risk probabilities and outcomes are uncertain and need to be acquired dynamically through experience (Hertwig & Erev, 2009). Nonetheless, experience-based measures are differentially influenced by peer observation, and little is known about how peer observation might vary the integration of previous positive and negative experiences and learning in such task settings. Finally, not all adolescents may adjust risky choices to peer observation, as it might be an effect specific in males and individuals with certain expressions in resistance to social influences.

Goals of the present study

In this study, we examined developmental differences in the risky choice of an experience-based decision-making task, the Balloon Analogue Risk Task (Lejuez et al., 2002). In the BART, participants inflate balloons to increase the amount of money they can win when saving them on a virtual bank account. However, they also increase the risk for the balloon to explode and to lose all with each decision to pump a balloon further instead of saving previous gains. Given the robust association between risky decisions in the BART and real-life risk-behaviors (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Lejuez, Aklin, Zvolensky, & Pedulla, 2003), the BART is well suited to investigate developmental differences in risky decision making during adolescence.

Many previous studies relied on comparisons between few age groups, like one adolescent and one adult group, to assess age differences in risk-taking behavior. However, investigating differences in the effect of peer observation between developmental phases and moderating effects herein, such as gender and individual differences in social sensitivity, need studies about broad age ranges during adolescence. Thereby, only a few studies included younger samples but this study obtained risk decisions from a wide age-range from pre to late-adolescence (9-19 years) to infer about cross-sectional changes in risk choices and the effect of peer observation herein.

More specifically, we investigated whether peer observation had an impact on risky decisions in youth and possible age differences herein. To examine the role of peer observation on risk adjustment and its interplay with age, we used a within-task manipulation. That is, adolescents once experienced the BART alone and once believing a peer would observe them via a webcam from another lab. With this approach, we looked at the influence of peer observation while controlling for characteristics of the observer concerning the appearance or behavior, as well as for the relationship between peer and participant. Thereby, we attempted to keep the credibility of the peer being present in another lab as high as possible by introducing participants with the virtual peer in a chat scenario. Accordingly, previous studies reported effects of peer observation independent from familiarity or actual presence of the observer (e.g., Haddad et al., 2014; Smith et al., 2014, 2015; Weigard, Chein, Albert, Smith, & Steinberg, 2015; Somerville et al., 2019), highlighting the fundamentality of social motivation during adolescent risk-taking.

Participants were unaware of explosion probabilities in the BART and could only acquire them from experience, that is, trial-by-trial. As such, the dynamic nature of the BART allowed to infer about age differences and the influence of peer observation dependent on previous choices and experiences. Many previous studies relied on mean differences to look at the variation in risk behavior(e.g., Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Lejuez et al., 2002; Reynolds, MacPherson, Schwartz, Fox, & Lejuez, 2014, but see, e.g., Éltető et al., 2019; Kessler et al., 2017). However, performance in the BART has been shown to vary over time (trials) as participants learn from previous choice outcomes. That is, participants show rather risk-averse behavior with fewer pumps than the optimal amount to maximize monetary gains in the task. Furthermore, participants showed reduced pumps in reaction to previous balloon explosions but generally increase their risky choices over trials (e.g., Ashenhurst, Bujarski, Jentsch, & Ray, 2014; Kessler et al., 2017; Lejuez et al., 2002; Mamerow, Frey, & Mata, 2016; Mata, Hau, Papassotiropoulos, & Hertwig, 2012). In the following, we were interested in whether peer observation influences risky choices differentially from pre to late adolescence and whether developmental trajectories in the peer effect are moderated by dependencies in task behavior, like risk adjustment to previous successful and balloon bursts trials or general learning from trial to trial.

According to verbal models (for a review, see Ciranka & van den Bos, 2019), adolescents might increase risky choices under peer observation because of reward sensitivity that might further increase arousal induced by previous rewards when observed. In contrast, reward sensitivity because of peer observation might also lead to decreased sensitivity to previous negative outcomes, as risk-taking is more appealing in social situations, regardless of danger and negative outcomes. In contrast to both model assumptions, mid adolescents (aged 13-16 years) showed more cautious behavior at the utmost following successful trials in one study using the BART under peer observation manipulation (Kessler et al., 2017). However, the study relied on a male subsample, did not test age differences, and changed the characteristics of the task to allow to investigate neural measures of reactivity to previous trial outcomes. As such, beneath reward sensitivity, or blunted sensitivity to negative risk consequences as reported for some individuals (McCormick & Telzer, 2017b), peer observation might alter risky choices more generally by increasing or distracting from the integration of previous experiences from trial to trial, that is influence learning in the BART. It has to be noted that despite the potential mechanisms underlying the influence of peers, heightened risky choice across the task and reduction of risk only in response to negative outcomes would be adaptive in the BART, in which individuals have previously been shown to react risk-averse while exploration of the risky choice to a certain point (64 pumps per trial) heightens final gains (e.g., Mata et al., 2012).

Finally, developmental trajectories in the peer effect on risky choice might underly individual differences, like gender or individual resistance to peer influences. Therefore, we applied a questionnaire in which adolescents reported how influenceable by others they would describe themselves (Resistance to Peer Influence scale, RPI; Monahan & Steinberg, 2007), and investigated the moderating role of gender and RPI score on age differences in the effect of peer observation. We expected male adolescents to show more risky decisions and be more influenced by peer observation than female adolescents, also as one recent study suggested such gender differences in another task setting (Defoe et al., 2019a). Furthermore, we expected differential adjustment of risky choices to peer observation conditions dependent on whether adolescents reported being easily influenced by peers or more resistant to such influences (e.g., Kessler et al., 2017: Peake et al., 2013), possibly showing developmental differences herein (e.g., Mohanahan & Steinberg, 2007).

2. Methods

Participants

Overall, 193 participants were invited to be part of a larger cross-sectional study that investigated the development of cognitive control and motivational functioning during adolescence (age range = 9 – 18 years). Adolescents were recruited via flyers and newspaper advertisements or were invited from the subject pool of our research unit. Participants were paid a monetary compensation of 8 € per hour and could choose a small reward following the test battery that assessed cognitive performance and decision-making. Ethical approval was given by a local ethics committee for this study.

Five participants had missing data in at least one of the experimental conditions in the BART task and thus were excluded from data analysis. Moreover, four participants did not fill out the questionnaire including the Resistance to Peer Influences scale and thus, were excluded from all analyses. The mean age of the final sample (N = 184) was 14.1 years (min = 8.6, max = 19.0, SD = 3.0, 47% female). The gender distribution was similar across ten age groups, χ^2 (9) = 10.92, p = .28, as well as between groups of participants that conducted the BART either under peer observation first or second, χ^2 (1) = 1.36, p = .24. Moreover, there was no difference in the distribution of participants that performed the BART under peer observation first or second across ten age groups, χ^2 (9) = 5.96, p = .74.

Procedure

In this study, we focused on the effects of peer observation on decision-making and relations to resistance to peer influence. The data were collected as part of a comprehensive cross-sectional and longitudinal study on the interplay between motivational and cognitive control processes during adolescent development. The cross-sectional study consisted of three sessions, whereas participants received a comprehensive test-battery in one of those, among them, the BART. Participants further completed various online self-report questionnaires via the online survey platform SoSci Survey (Leiner, 2019). These questionnaires collected information about, for example, demographic characteristics, or traits such as resistance to peer influences, and were filled out at home between the sessions. The instructions of these questionnaires requested the children to ask the research team or their parents if problems occurred, but to complete the questionnaires preferably undisturbed.

Task and Questionnaire

Balloon Analogue Risk Task. The Balloon Analogue Risk Task (BART; Lejuez et al., 2002) is a decision-making task under dynamic risk, as participants must weigh the potential monetary gain when pumping a balloon against the increasing risk of it to explode (probability of 1/128-n in the n-th trial). Each pump thereby signified a temporal gain of 5 cents and participants were instructed to collect as much money as possible. The temporal gain of each balloon could be saved on a permanent "bank account" but would be lost if the balloon explodes before doing so. They were explicitly told that explosion risk and monetary gain increased with pumps, but they could only experience underlying outcome probabilities.

During the task, participants had insight into how many of their balloons (trials) were left, how much money was on their permanent bank account, and how much money they made with the previous balloon. Furthermore, participants were told that they would be additionally rewarded with a small gift. Thereby, the performance in the decision-making tasks, including the BART, was relevant to heighten the chance of winning a more valuable reward out of a three-star box instead of a one-star box, which were placed visibly for the participant in the laboratory. Unbeknown to the participants, all subjects received the feedback that they gained enough points to choose from the more valuable three-star-box.

We did not change the structure of the original BART but changed the presentation of its Balloon environment (see Figure 1). Balloon explosions were presented in picture and sound.

The BART was conducted on a computer using a 19-inch-Monitor and the computer-keyboard. As such, balloons could be inflated via a keypress activating a red button shown on the computer screen, which was visibly connected to the balloon.

The participants performed the BART consecutively under two conditions: alone and under the observation of a fictitious peer. The sequence in which participants conducted the task conditions was counter-balanced for each age group. In each condition, participants inflated 30 balloons that were treated as separate trials and 3 practice trials, in which participants were familiarized with the task.

As risk-taking in the BART is measured based on various numbers, e.g., the mean number of pumps for trials in which the balloon did not burst, we report some of these mean differences within the peer observation condition and its sequence. As we were further interested in whether adolescents adapt their risk-propensity depending on the number and outcomes of previously experienced trials, we analyzed the BART also on a trial-by-trial basis. Thereby, we determined risk propensity separately for trials following trials with positive (decision to save money; Cash-in) or negative outcomes, i.e., balloon bursts that resulted in no monetary gains (decision to pump further; Burst).

Virtual Peer Observation. To assess whether adolescent risk-decisions are influenced by the presence of peers, we introduced a virtual same-age, same-sex peer via chatroom manipulation (e.g., Smith et al., 2014; Weigard et al., 2014). As such, adolescents conducted the BART once when peer observation was absent and once believing that a peer would observe them via webcam. To introduce the peer, we told participants that they will chat with the peer sitting in another laboratory before the task starts. A software was used (Open Broadcaster Software, 2015) that broadcasted the webcam record and a screen-mirror to the second laboratory. Though its function was visible for the participant, the program was only started to increase the credibility of the peer scenario without truly broadcasting. Following, the computer was connected to the internet and the chatroom started. Participants were asked to state their age, grade, gender, and hobby, and to choose one of eight avatar pictures. The chatroom generated a preformulated chat message (see *Figure 2*) and participants had to confirm the message to be sent to the peer. The participants waited for the virtual peer to answer that was programmed to match the participants' gender with a random hobby and matched age and grade by plus/minus one. Following the introduction of the peer, participants were told to just show the peer how they conduct the BART without further information. Afterward, participants were told and shown that the internet connection and the broadcast tool will be shut down and that all other tasks will be conducted alone.

Resistance to Peer-Influence Scale. We administered a German version of the Resistance to Peer Influence scale (RPI, Steinberg & Monahan, 2007) to measure the extent to which participants describe themselves as being susceptible to peer pressure. In this questionnaire, participants are confronted with 10 pairs of options, of which they have to choose the option that describes themselves best (e.g., "Some people go along with their friends just to keep their friends happy. " BUT " Other people refuse to go along with their friends want to do, even though they know it will make their friends unhappy."). Moreover, the subject indicates whether this description is "really true for me" or "sort of true for me". High RPI scores indicate a high resistance with respect to peer influences. In this study, the RPI had a reliability index of .67 for the whole sample, suggesting the measure to be consistent across items and participants.

Data Analysis

The software *R* (R Development Core Team, 2015, version 1.2.5019) was used to analyze data and multilevel models were fitted using the package *lme4* (Bates, Mächler, Bolker, & Walker, 2015) for general linear mixed-effect modeling (*glmer*). Furthermore, *p* values were calculated from the model coefficients using Laplace approximation with the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017). We further provided measures of model fit between and within the learning and outcome models and compared nested models based on the *anova()* function (see *Table 3*).

3. Results

The main goal of the study was to examine how virtual peer observation influenced risk decisions from pre to late-adolescence. The results section is divided into four sections:

First, the study looked at baseline differences in the aggregated number of pumps within peer observation conditions and between groups with a different order in which peer observation was presented (see section *'Balloon Analogue Risk Task'* within the *Methods* section). To be able to speak about other measures that are commonly assessed from the BART, the analysis was also conducted in terms of tests of mean differences in the adjusted number of pumps (trials in which the balloon did not burst), the number of balloon bursts and the final payoff (see section *'The Effect of Peer Observation and Sequence on Aggregated Measures'*).

Second, to investigate developmental trajectories in the adjustment of risky choice to peer observation, the study analyzed pump behavior in the BART also on a trial-to-trial basis (see section *'Age Differences in Adjustment of Risky Choice to Peer Observation'*) using linear mixed-effects models (lme; Baayen, 2012, for evidence from the risk-taking literature see e.g., Ashenhurst et al., 2014; Mata et al., 2012; Mamerow et al., 2016). The advantage of using linear mixed-effects models over traditional analyses of variance (ANOVAs) is that it allows investigating differences in pumps per trial and account for both variances within (e.g. peer observation condition, trial number) and between participants (e.g. age, gender). Thereby, the mixed-effect approach allowed to model learning (effects of trial number) and reactivity to previous outcomes without losing variation and power through the aggregation of measures across participants. As the number and antecedents (previous outcome) of a certain trial are highly associated, separate models were fitted for effects of learning (learning models) and reactivity to previous burst trials (outcome models) to reduce potential multicollinearity and complexity in models.

In the following sections three and four, it will be reported how gender differences (see section *'The Influence of Gender on Age Differences in Risk Adjustment to Peer Observation'*) and individual differences in resistance to peer influences (see section *'The Role of Individual Differences in Resistance to Peer Influences (RPI)*) moderate age-related differences in the effect of peer observation. Therefore, tests concerning baseline differences in the RPI measure between adolescents of different ages and gender, as well as between groups of adolescents with different sequences of peer observation conditions, were conducted in section four. Please note that statistical results concerning regressors of dummy-coded variables (condition, previous outcome, and gender) represent differences between respective groups or conditions, not main effects.

The Effect of Peer Observation and Sequence on Aggregated Measures

Adolescents pumped balloons on average 26.5 times (*SD* = 9.3) with 14.6 balloons (*SD* = 6.0) that burst and an outcome of 64 € (*SD* = 18.5) across trials and conditions. *Table 1* presents summary means of risk behavior and outcomes as a function of peer observation conditions and tests of mean differences between the conditions (paired t-tests). There were no differences in pump behavior and outcomes when peer observation was absent or present across trials (all *p*'s > .231). *Figure 3* depicts that adolescents gained more money with a greater mean number of pumps in both peer observation conditions of the BART. In sum, previous findings were replicated that showed participants to react rather risk-averse with less (adjusted) mean pumps than the optimal amount to maximize monetary gains in the task (68 pumps) and greater outcomes with a higher propensity for risky choices (e.g., Mata et al., 2012; Lejuez et al., 2002, 2003).

To control for sequence effects due to the within-subjects design, the study also analyzed pump behavior between the two groups (t-tests) that conducted the BART under peer observation first or second (see *Table 2*). Even though the order of peer observation condition was randomized in each age group, adolescents engaged in more pumps experienced more balloon bursts and had a significantly higher payoff (p = .04, *Cohen's d* = .24) when they were observed by peers first than second. While carry-over effects between first (baseline) and second session of task conduction (peer condition) due to learning have already been reported in studies using between-subjects designs (e.g., Reynolds et al., 2014), the interaction with the order of peer observation condition in this study suggests that the variability in the effect of peer observation is dependent on experiences made or time spent within the BART setting.

Age Differences in Adjustment of Risky Choice to Peer Observation

In a second step, the behavior in the BART was analyzed on a trial-by-trial basis. All models included the following fixed effects: continuous age (range = 8.6 – 19.0 years, M = 14.1 years), peer observation condition (condition; absent/present; 0/1), trial number (trial; coded 2 to 30[1]), scaled for the respective peer observation condition block), whether the previous trial was a burst trial (previous outcome; cash/burst; 0/1) and an interaction term between age and condition. The models included both contrasts for linear and quadratic age trends, to account for potential non-linear effects of age, like a peak in general risk behavior or adjustment to peer observation in mid-adolescence.

To test whether the age-by-condition interaction was moderated by differences in learning and/or reactivity to burst trials (previous outcome), learning models included all interactions between age, condition, and trial number, while outcome models allowed for all

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[1] *Note:* Trial 1 was excluded as there were no previous responses at the beginning of the two peer observation condition blocks.

interactions between age, condition and previous outcome. *Table 3* depicts details about model terms and values of model fit for the two models that included interactions of age and condition with the trial number (learning model) or age, condition, and reactivity to previous outcomes (outcome model), respectively.

The linear mixed approach enables us to also account for variances in risk-taking that derive from random effects that may systematically vary across participants but not groups, such as peer observation conditions. The models allowed for random structures that were maximal for the higher-order interaction of interest (Barr et al., 2013). That is, by-subject random slopes were trial, condition, and the trial by condition interaction in learning models. Furthermore, by-subject random slopes were previous outcome, condition, as well as an interaction between previous outcome and condition in outcome models. The models did not include by-item random slopes. A general linear mixed-effects approach was used (glme) and error terms were calculated assuming a Poisson distribution given that the outcome measure was a count variable, which is the number of pumps in a given trial.

The learning model that included the highest-order interaction between age, condition, and trial, as well as random effects for condition, trial number, and their interaction, showed the best model fit (see *Table 3*). Results from a model that included all lower-order interactions between age, condition and trial (Model 1) replicated the findings of a reduction in pumps for trials that followed a balloon burst, $b = -.15$, $SE = .005$, $p < .001$, and an increase in pumps with trial number, $b = .06$, $SE = .023$, $p = .016$ when peer observation was absent (e.g., Ashenhurst et al., 2014; Lejuez et al., 2002; Mata et al., 2012; Mamerow, Frey, & Mata, 2016). Furthermore, there was a significant quadratic age trend, $b = -.26$, $SE = .130$, $p = .046$, suggesting a peak in pumps per trial in mid- to late-adolescence (see *Figure 4*) but there were no interactions with peer observation condition (all *p*'s > .100). The results from the outcome models revealed no higher- or lower-order interactions between age or condition and previous outcome (all p's > .311). This suggests that neither age differences nor differences in adjustment to peer observation conditions, nor their interaction, were informed by variance in reactivity to previous outcomes in this study.

Concerning learning, a significant higher-order interaction between the linear age term, condition, and trial number in Model 2 suggested that age differences in adjustment to peer observation were significantly informed by differences in learning, $b = .27$, $SE = .110$, $p = .015$. Visual inspection of the effects plots suggested older adolescents increase but younger adolescents rather decrease the number of pumps during the peer observation present condition but no moderation on age differences when peer observation was absent (see *Figure 4*). The moderation was followed up by several post-hoc analyses (at $p < .05$). Simple trends were calculated at the mean age (14 years), and age 1 SD above and below the mean age (around ages 11 and 17) and for trial numbers 8, 16, and 24, i.e. for rather early, mid and late trials in both peer observation conditions. Older adolescents engaged in a significantly higher extent of learning than younger adolescents in the peer observation present but not absent condition. Accordingly, tests of simple effects indicated a significant increase in age differences with the number of experienced trials for peer observation present but not the absent condition. However, analogical tests of simple effects for peer observation condition were all non-significant (all p's >.057), highlighting the moderative nature of the peer effect in this study. In sum, adolescents showed similar learning effects when peer observation was absent, but older adolescents showed more adaptive responses than younger adolescents and showed learning also when observed by a virtual peer.

The Influence of Gender on Age Differences in Risk Adjustment to Peer Observation

As the study further aimed at investigating how gender may modulate age differences in risk adjustment to peer observation, gender (female/male; 0/1) and all interactions with age and condition were added in a subsequent model. As the outcome models did not show any interactions between age, condition, and previous outcome, possible gender differences in the age-by-condition interaction will be reported for learning models only. The inclusion of the highest-order interaction between age, condition, and gender did not improve the model fit (ΔDIC = -1, $p = .784$) compared to a model that only included lower-order interactions between gender, age, and condition (DIC = 109157).

The results suggested that male adolescents showed a higher number of pumps per trial than female participants on the level of the mean, $b = .24$, $SE = .090$, $p < .01$ (see *Figure 5A*). There were no lower-order interactions between gender and condition, or between gender and age (all p's > .141). However, the quadratic age trend was no longer significant when including gender terms into the model ($p = .595$), suggesting gender to influence predictions by quadratic age trends. All variance inflation factors (VIF) concerning gender were smaller than 3.63, suggesting that shared variance (or multicollinearity), i.e., between age and gender, was likely not a concern. Visual inspection of the effects plot for the age-by-gender interaction suggested that a peak in pumps per trial during mid- to late-adolescence was rather true for male than female adolescents (see *Figure 5B*). This does likely account for the non-significant quadratic age trend when including gender into predictions of the model, but this interaction was not robust in this study.

The Role of Individual Differences in Resistance to Peer Influences (RPI)

Finally, the study tested whether individual differences in RPI scores may predict age differences in risk adjustment to peer observation in the BART in a subsequent model. First, baseline differences between subjects in self-description will be reported. The mean RPI score was 2.9 (*SD* = 0.4) which is comparable to RPI scores found in other adolescent samples (e.g., 14-17 year-olds, males, Peake et al., 2013; 13-16 year-olds males, Kessler et al., 2017). To assess baseline characteristics of the RPI measure, RPI scores were further analyzed with an ANOVA that included the continuous age variable, gender (female/male, 0/1), and the order in which adolescents conducted the BART under peer observation (first/second, 0/1) as independent variables. The results revealed that there were no differences in RPI scores, neither between adolescents from different age or gender groups nor between groups that conducted the BART under peer observation first or second (all *p*'s > 0.535).

Second, individual differences in RPI (mean-scaled) and all interactions with age and condition were added as predictors into a subsequent regression model. The inclusion of the highest-order interaction between age, condition, and RPI did not improve model fit (ΔDIC = -1, p = .470) compared to a model that only included lower-order interactions between RPI, age, and condition (DIC = 109150). RPI scores were found to moderate risk adjustment to peer observation condition, b = -.05, SE = .021, $p < .05$. Follow-up analysis revealed significant (at $p = .05$) simple effects of peer observation condition among adolescents with 1.8 SD's below the mean RPI score but no significant effects of condition for higher scores on RPI (see *Figure 5*). There were no significant interactions between RPI scores and age (all p's > .758), and inclusion of RPI terms did not further change the pattern of results concerning age or gender differences in the BART.

In sum, all adolescents showed adaptive risky decision-making on a trial-by-trial basis in the BART, as they reduced pumps following negative outcomes but generally increased pumping with the number of previously sampled trials, i.e. showed learning under risk uncertainty. Thereby, the observation by a virtual peer had overall no effect on risky choice, but moderated age differences in learning. Older adolescents increased pumping with general previous experiences rather irrespective of whether peer observation was absent or present, while younger ages did integrate previous experiences less than older ages when peer observation was present (see *Figure 4*). Concerning other moderators on the level of the individual, male adolescents showed more pumps per trial than female adolescents without significant influence of age or peer observation herein (see *Figure 5A*). However, self-described resistance to peer influence (RPI) predicted reactivity in the adjustment of risky choice to peer observation, such as that individuals with very low scores in self-described RPI tended to more pumps per trial when peer observation was present than absent (see *Figure 6*).

Table 1. Means (*M*) and standard deviations (*SD*) for measures of the Balloon Analogue Risk Task (BART) as a function of peer observation condition.

	Peer Observation						
	Absent		Present				
Measure	*M*	*SD*	*M*	*SD*	*t* (183)	*P*	*d*
Number of pumps	26.5	10.1	26.5	9.8	-0.05	0.957	-0.01
Adjusted number of pumps	29.5	12.7	29.6	12.3	-0.03	0.972	-0.01
Number of burst trials	7.4	3.6	7.1	3.2	1.20	0.231	0.09
Payoff	31.6	10.3	32.4	10.6	-1.04	0.298	-0.08

Note. Adjusted number of pumps = mean number of pumps in trials for which the balloon did not burst.

Table 2. Means (*M*) and standard deviations (*SD*) for measures of the Balloon Analogue Risk Task (BART) as a function of the sequence of peer observation condition (first or second).

	Peer Observation						
	First		Second				
Measure	*M*	*SD*	*M*	*SD*	*t* (71)	*P*	*d*
Number of pumps	28.1	9.3	25.5	9.2	1.93	0.055	0.22
Adjusted number of pumps	31.5	11.7	28.2	11.7	1.91	0.057	0.22
Number of burst trials	15.5	5.7	14.0	6.1	1.69	0.093	0.18
Payoff	67.4	18.9	61.7	18.1	**2.07**	**0.040**	**0.24**
n	72		112				

Note. Adjusted number of pumps = mean number of pumps in trials for which the balloon did not burst. Test measures in bold are significant at $p < .05$. Homogeneity of variance was given between the two groups that differed in the sequence of peer observation conditions (all *p*'s > 0.543).

Table 3. Model Terms and Fits of the Learning and Previous Outcome Models.

Model	Terms (fixed)	Terms (random)	Model fit		
Learning			DIC	AIC	BIC
Baseline		Trial + Condition + Condition:Trial	110201	110223	110303
Model 1	Outcome + Age²*Condition + Age²*Trial + Condition*Trial	Trial + Condition + Condition:Trial	Model 1 – Baseline -1031**	Model 1 – Baseline -1011**	Model 1 – Baseline -945**
Model 2	Outcome + Age²*Condition*Trial	Trial + Condition + Condition:Trial	Model 2 – Model 1 -6*	Model 2 – Model 1 -2*	Model 2 – Model 1 12*
Previous Outcome			DIC	AIC	BIC
Baseline		Outcome + Condition + Condition:Outcome	111942	111964	112044
Model 1	Trial + Age²*Condition + Age²* Outcome + Condition*Outcome	Outcome + Condition + Condition:Outcome	Model 1 – Baseline -254**	Model 1 – Baseline -225**	Model 1 – Baseline -152**
Model 2	Trial + Age²*Condition*Outcome	Outcome + Condition + Condition:Outcome	Model 2 – Model 1 -1	Model 2 – Model 1 3	Model 2 – Model 1 17

Note. DIC = Deviance information criterion; AIC = Akaike information criterion; BIC = Bayesian information criterion; Age² = orthogonal linear and quadratic contrast terms of continuous age. * = $p < .05$, ** = $p < .001$.

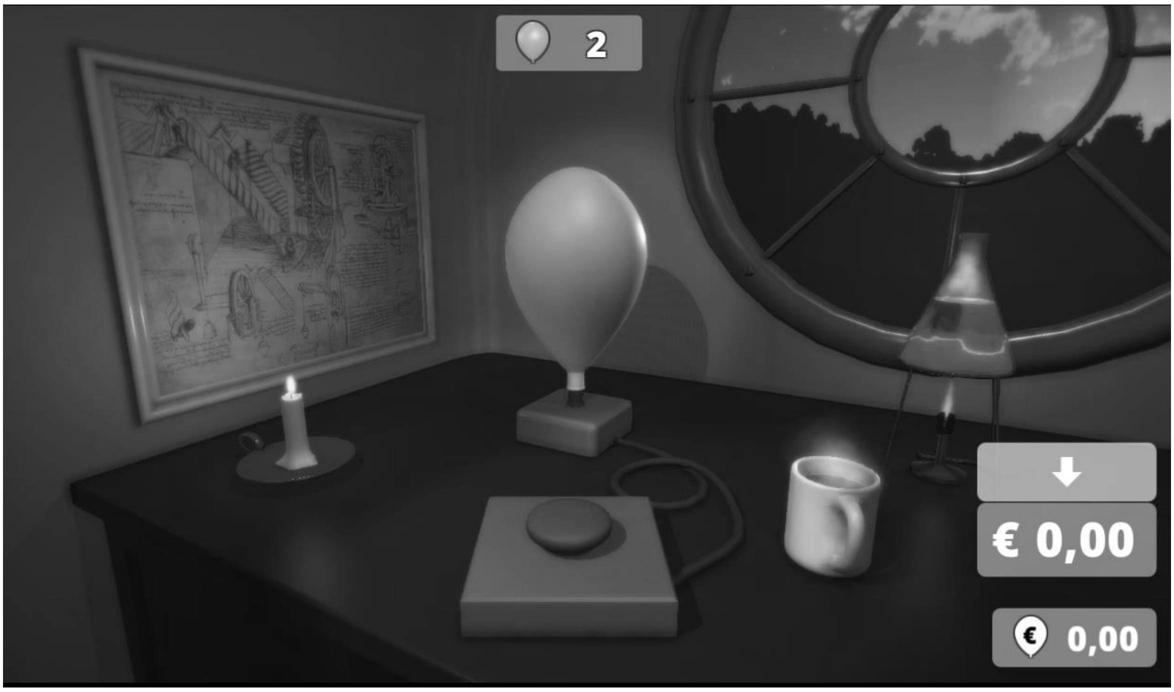
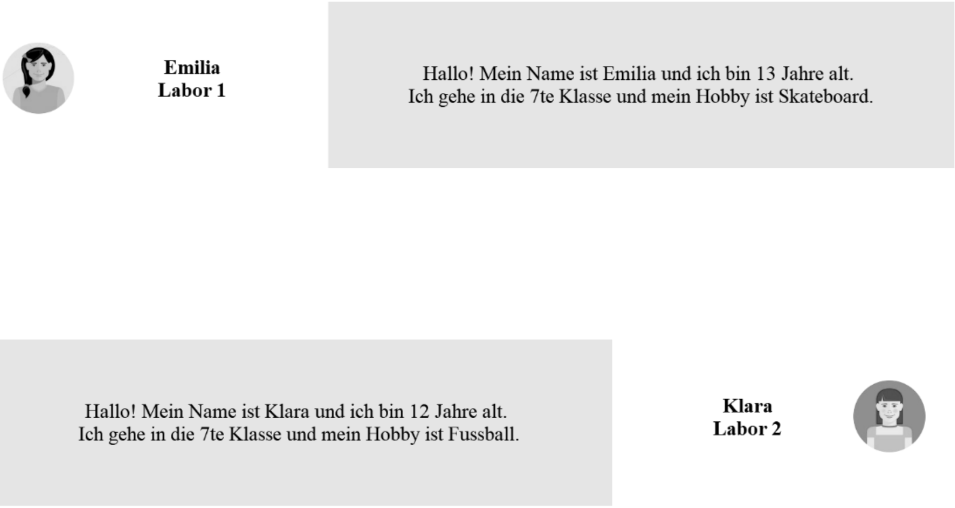


Figure 1. Illustration of the BART environment. Participants were instructed to gain as much money as possible by inflating balloons. Each balloon was treated as a trial and the number of balloons left was visible in the middle of the upper screen. At any time, participants had to decide to either pump a balloon by pressing the button in the middle of the screen (space key) or to save the amount gained through previous pumps (down arrow key) and begin with the next balloon. The money account and money earned with the previous balloon were visible on the upper right screen. Each pump increased the outcome of a balloon by 5 cents. However, participants were informed that the balloon could burst at a random inflation point and all temporary gains would be lost when not previously saved to the final account. No further information, i.e., about burst probabilities, was given.



Hallo! Mein Name ist Emilia und ich bin 13 Jahre alt.
Ich gehe in die 7te Klasse und mein Hobby ist Skateboard.

Hallo! Mein Name ist Klara und ich bin 12 Jahre alt.
Ich gehe in die 7te Klasse und mein Hobby ist Fussball.

Figure 2. Illustration of the Chat environment, exemplary for a female participant. Participants were informed about another unknown participant that would observe them via webcam during the conduction of the Balloon Analogue Risk Task (BART). Before the peer observation condition block, they were introduced to the peer via a chat environment. Participants provided information about their name, age, grade, and hobbies in an otherwise preformulated chat message. Unbeknownst to the participants, the peer′s answer that appeared after a short period was a randomly generated text message that matched the participant′s information about gender and grade, as well as age by plus/minus one year.

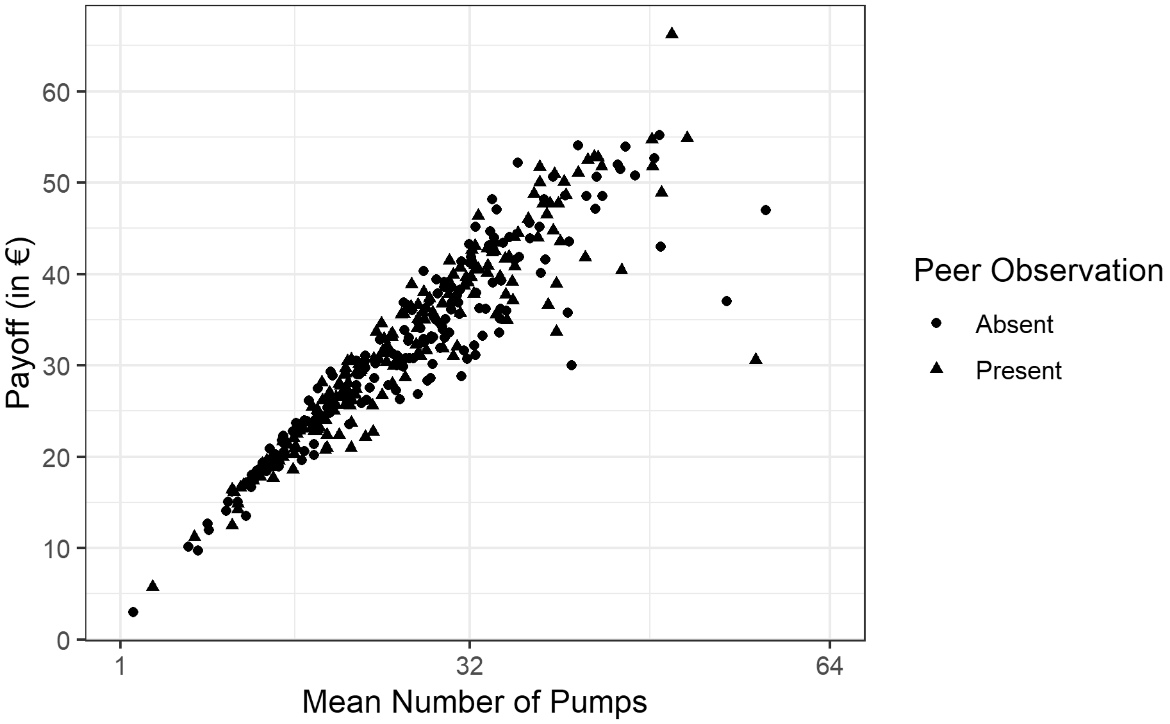


Figure 3. Payoff (in Euro) in the Balloon Analogue Risk Task (BART) by the mean number of pumps within conditions in which adolescents conducted the task alone (circles) and under the observation of a virtual peer (triangles).

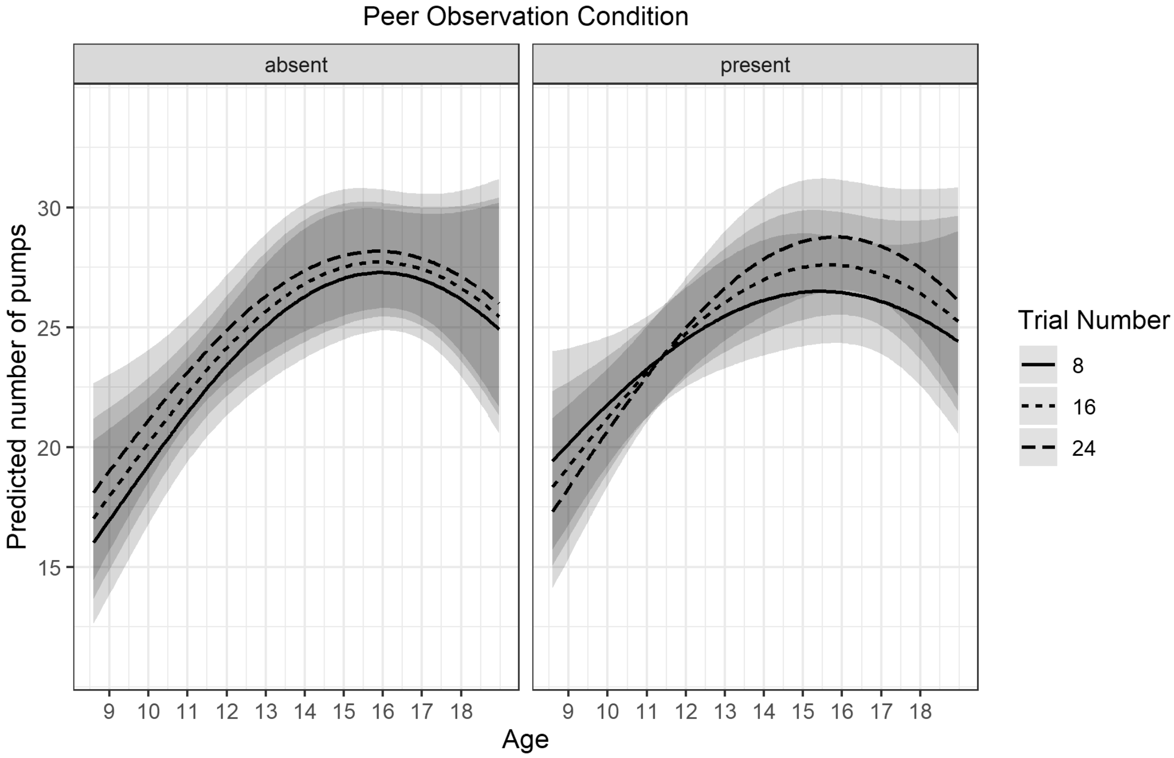


Figure 4. Moderation effect of peer observation condition (absent/present; 0/1) on age trends (range = 9-19 years, *M* = 14 years) in the predicted number of pumps by trial number (learning; range 2-30; normalized for each condition).

The predicted values and 95 % confidence intervals are from a model without covariates and with continuous age in its original scale. Age trends are shown for both peer observation conditions and trial numbers 8, 16, and 24, i.e., at rather early, middle, and late trials in which previous balloons did not burst (previous outcome = 0).

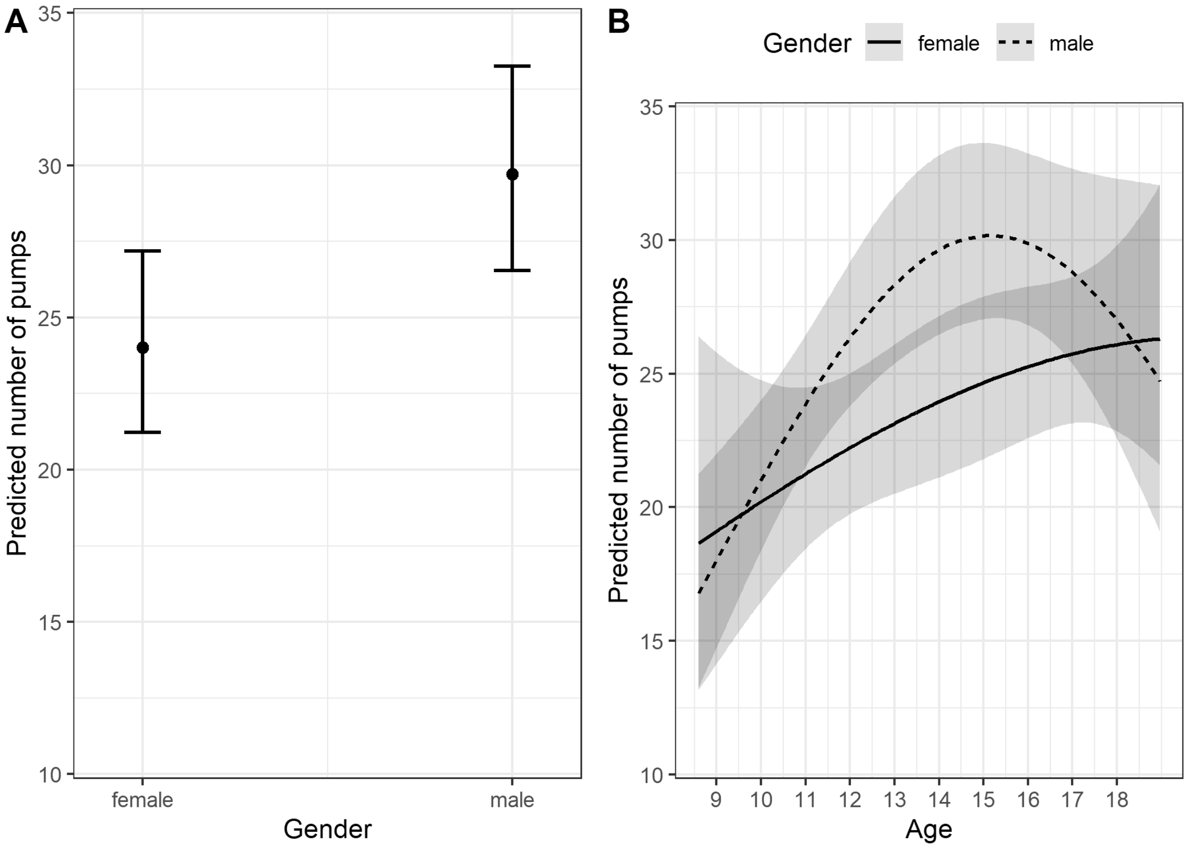


Figure 5. **(A)** Gender differences in the predicted number of pumps of the Balloon Analogue Risk Task (BART), adjusted for the mean age of the sample (14 years). **(B)** Age trends (range = 9-19 years, *M* = 14 years) in the predicted number of pumps of the Balloon Analogue Risk Task (BART) as a function of gender.

The predicted values and 95 % confidence intervals are from a model without resistance to peer influence (RPI) as a covariate and with continuous age in its original scale. Furthermore, values represent trials for which previous balloons did not burst (previous outcome = 0), in the middle of blocks (trial = 0), and averaged across peer observation conditions.

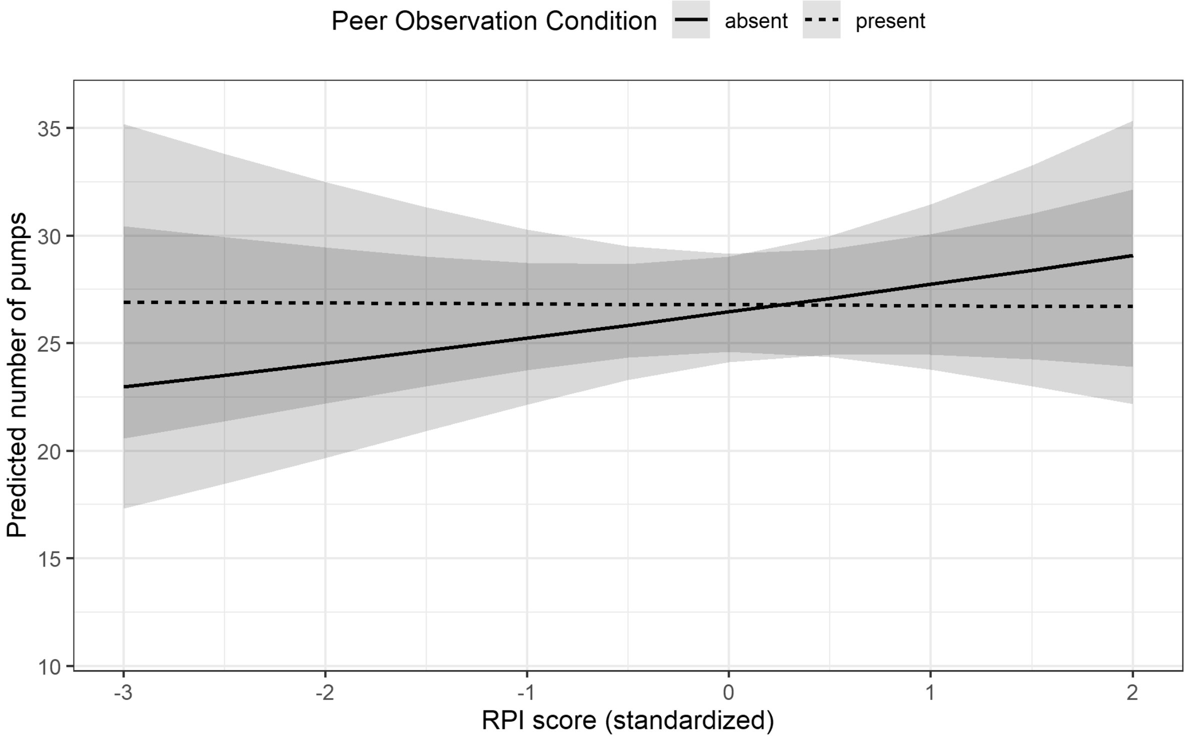


Figure 6. Moderation of resistance to peer influence (RPI) scores on reactivity to peer observation condition in the predicted number of pumps of the Balloon Analogue Risk Task (BART).

The predicted values and 95 % confidence intervals are shown for trial number 16 (i.e., in the middle of the respective condition block) at the mean age of the sample (14 years) and are averaged across gender.

4. Discussion

In this study, an experimental decision-making task, the Balloon Analogue Risk Task (BART), was used to investigate risky choices of pre to late adolescents when virtual peer observation was absent and present during task conduction. Models on adolescent development posit that peer presence has a heightening effect on risk-taking behavior but a growing number of findings on this behalf are rather mixed. It has been suggested that conflicting findings could be due to moderating effects. Likewise, flexible and dynamic processes behind peers affecting adolescent risky decisions remain unclear. Therefore, the study investigated age differences in risk adjustment to peer observation and took into account processes, like learning or reactivity to previous positive and negative outcomes, in explaining these differences. In doing so, the study aimed at adding to the developmental literature about what processes are thought to be influenced by social situations in adolescent risky decision-making. The study further investigated the influences of gender and individual differences in resistance to peer influence on this behalf.

Peer observation did not generally influence risky choices in the BART from pre to late adolescence but moderated age differences in learning from previous experiences in the task. All adolescents adjusted risky choices to previous positive and negative outcomes and across the task, but older adolescents were more successful as they engaged in more risks and thus, were overall more adaptive in their choices. This was similarly true for males that engaged in more risky choices compared to female adolescents on the level of the mean. Thereby, age differences in learning were specifically the case when adolescents were observed by peers. Heightened risky choices when observed, as suggested in accounts of reward-sensitivity in youth, hold only for adolescents with low scores in self-reported resistance to peer influence. However, peer observation did not alter reactivity to positive and negative outcomes during the task.

Age Differences and Adjustment of Risky Choice to Peer Observation. Generally speaking, adolescents showed to be quite adaptive in their risky choices. The study replicated findings with all adolescents reducing risk in reaction to previous negative outcomes (Humphreys et al., 2016; Kessler et al., 2017) and increasing risk with the number of previously sampled trials, i.e. showing learning (Éltető et al., 2019; Lejuez et al., 2002). Older adolescents generally engaged in a higher number of risk decisions than younger adolescents that has been shown in previous studies including the BART (Humphreys et al., 2016; Lauriola et al., 2014; but see, Éltető et al., 2019; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Qu, Galvan, Fuligni, Lieberman, & Telzer, 2015), suggesting them to show overall a better performance in their risky choices. However, age differences were not informed by differences in learning or reactivity to previous negative outcomes when peer observation was absent in the present study, in line with a recent investigation in an adolescent sample (128 pumps max.; aged 7-30 years; Éltetö et al., 2019).

Peer observation had no influence on risky choices on the level of the mean and did not influence reactivity to successful cash-ins and balloon bursts of previous trials. Furthermore, younger and older adolescents did not differ in adjusting risky choices to peer observation. In contrast, social neurodevelopmental imbalance models posit peer presence to fuel an adolescent's hypersensitivity to rewards and consequently risk-taking (Steinberg, 2010; Shulman et al., 2016). Indeed, prior behavioral and neuroimaging studies indicated that only adolescents increased risky decisions when with peers and showed effects on reward processing, at least when comparing adolescents with emerging adults (Chein et al., 2011; Gardner & Steinberg, 2005; Smith, Chein & Steinberg, 2014; Smith et al., 2015). However, risk-heightening effects of peer presence could be found in some task-settings, like simulated driving (Chein et al., 2011; Gardner & Steinberg, 2005) and gambling (Smith et al., 2015), while some studies showed no or opposite effects in similar (Somerville et al., 2018) and other settings, including the BART (Kessler et al., 2017; Reynolds et al., 2014). If at all, adolescents showed more cautious behavior when observed in the BART following trials that resulted in a successful cash-in (Kessler et al., 2017).

Further contributing to conflicting results concerning heightened risk-taking and reward-sensitivity, many previous studies did not compare adolescents with younger age, why it is not clear whether peer effects are adolescent-specific (Defoe et al., 2015, 2019). Even though we could not depict a possible rise until late adolescence and subsequent fall or plateau of risk-taking until adulthood with the age range used in this study, we showed that outcome sensitivity was age invariant from pre to late adolescence, also in respect to peer observation conditions. Consequently, the results of the present study incorporated in the body of findings that show adolescents do not always engage in more risks in reaction to possible rewards (see Kray, Schmitt, Lorenz, & Ferdinand, 2018 for a similar conclusion) or when peers are present (e.g., Defoe et al., 2019). In sum, mixed findings may derive from the fact that many studies focused on reward-processing and risk-heightening effects to investigate peer influences in adolescence. However, the very same neural reward-processing network that has been associated with heightened risky decision-making could also be linked to deliberative and safe decisions (Telzer, Ichien, & Qu, 2015).

In this sense, we found linear age trends in learning for trials in which peer observation was present. Rather older than younger adolescents engaged in more risky decisions with a higher number of experienced trials under peer observation. As such, younger adolescents did not show more risk when observed but were more cautious in adjusting their risk to previously experienced trials than older adolescents. This was reflected in age differences in risky decisions being most pronounced at the end of the block of trials in the peer observation present condition. In sum, peer observation did not affect risky choices but moderated age differences in the general integration of previous experiences during the BART. A recent study support these findings by showing that peer presence enhanced late adolescent's (age 18-23 years) outcome sensitivity more generally, as they showed better learning from both positive and negative experiences when peers were present in a gambling task (Silva et al., 2016). In this study, adolescents did not learn better or worse dependent on being observed or not. If at all, peer observation distracted integration of previous outcomes to a higher extent in young, while more experienced adolescents engaged in more risky decisions irrespective of peer observation and showed better task performance. Though it has been suggested that peer presence rather influences reward sensitivity than distracting from the task at hand in adolescents (ages 15-17 years, Smith et al., 2018) the present findings suggest that peer observation might differentially influence the integration of previous experiences when engaging in risky choices from pre to late adolescence.

Several findings indicate that peers can also have positive effects on adolescents, as they were shown to increase exploration, learning, and prosocial behavior (Van Hoorn et al., 2016). Such findings nurture recent trends to place adolescent risk behavior in a developmental context (Crone & Dahl, 2012; Romer et al., 2017). That is, heightened flexibility to goals and (social) situations when taking decisions would be quite adaptive for individuals that live in an ever-changing environment. This applies to the developmental stage of adolescence in which individuals begin to experience a growing number of complex settings and situations on their own. As such, with increasing experiences, or age, adolescents may become more distinct about when and how to engage in risks. Possibly, it is therefore that older adolescents relied more on previous experiences when observed than younger ages and overall showed better performance in this study. However, the association between decreased effects of peer influence with increasing age might show to be variable when including social norms that give advice about which risks to be taken (e.g., Braams et al., 2019), and might be further dependent on the underlying task context (e.g., Lloyd & Döring, 2019; Somerville et al., 2019).

The Influence of Individual Resistance to Peer Influence and Gender. It has been suggested that heightened risk-taking during adolescence would only be true for individuals that are specifically prone to take risks, e.g., as they engage in more impulsive decisions since childhood due to problems with cognitive control abilities (Romer et al., 2017). Applied to social situations, it has been suggested that differences in findings concerning risky decisions in adjustment to peer presence could be because only individuals that show low resistance to social influences increase risk when with peers. Accordingly, a previous correlational analysis concerning the RPI measure showed adolescents' probability to engage in risky decisions under peer presence to decrease with increasing self-reported RPI in the BART. That is, male adolescents (age 13-16 years) showed more cautious behavior with increasing resistance (Kessler et al., 2017). However, associations with RPI scores were not implemented into the prediction of actual task behavior why findings are not exactly comparable to those of the present study. While Kessler and colleagues (2017) also observed effects of lower RPI towards heightened risk-taking when observed, our findings mainly suggest that adolescents who describe themselves as being low resistant to peer influence (around 2 SD′s from the mean) engage in more risky decisions when under peer observation than when conducting the task alone. In contrast, adolescents with mid to high resistance to peer influence showed no alterations in risky choices to peer observation conditions. Contributing to the view that not all adolescents engage in more risks, there is evidence that more risky decisions under peer observation would only be true for individuals that have problems in resisting social influences.

Thereby, resistance to peer influence has been shown to increase during adolescence and is thought to predict rather younger and male adolescent’s risk behavior (Paus et al., 2008;

Steinberg & Monahan, 2007; Sumter et al., 2009). Surprisingly, we found no age differences in RPI scores between individuals from pre to late adolescence, and there were no age-related effects in RPI predicting task behavior in this study. Besides, female adolescents have repeatedly reported higher RPI than males, while we did not find such gender differences in RPI scores in our sample from pre to late-adolescence. As such, resistance to peer influences and adaptive risk decisions under peer presence may be more characteristic of normally developing pre to late adolescents than previously suggested. Accordingly, Bell and Baron (2015) incorporate resistance to peer influence into a broader framework that highlights the influence of sociocultural perspectives as well as person-context interactions in understanding resistance in youth. The present study contributes to this view by showing that RPI scores were rather an individual expression for which different contexts might predict variable influences, like lower risk with higher resistance (e.g., Kessler et al., 2017) or higher risk with low resistance as in the actual BART environment (see also Peake et al., 2013), instead of a developmental aspect per se. However, other studies that considered the influence of RPI scores on risky choices did not consider age differences in this influence at all, why it remains a matter of future studies to investigate the association between RPI scores and adjustment of risky choice to peer presence in further task settings and age groups.

Additionally, evolutionary theory suggests heightened tendencies for risk to mostly apply to male adolescents. Accordingly, male adolescents are thought to look out more for exciting and novel situations (sensation seeking, Cross et al., 2011; Romer et al., 2017) and are overrepresented in statistics concerning externalizing behavior already in childhood (e.g., Bjork & Pardini, 2015). We were able to replicate the finding of adult male participants engaging in more risky decisions than female participants in the BART (Cazzell et al., 2012; Lejuez et al., 2002) in an adolescent sample (but see Lejuez et al., 2003 that did not find gender differences [age 13-17 years]). It has been suggested that the 'gender gap' in risk-taking decreases with age during adolescence and varies with the type of risk (Byrnes et al., 1999). Here, gender differences in risky decisions, also in adjustment to peer observation, were age-invariant. However, results indeed suggested that a nonlinear age trend in risky decisions with a peak in middle to late adolescence (around 15 years of age) would mainly be true for male adolescents, even though this effect was statistically not robust. Possibly, different developmental trajectories between the gender would be more prominent when also including a more mature sample. Nonetheless, this observation matches the previously described divergent trajectories in exploration and sensation-seeking between the gender (Romer et al., 2017).

However, we did not find an interaction between adolescents' gender and risky decisions in reaction to peer observation conditions in the BART. A recent study investigated gender differences in the influence of peer presence on risky decisions in the Stoplight task. According to evolutionary theory, male adolescents showed more risky decisions when peers were present, while females did not (Defoe et al., 2019a). It has to be noted that instead of maladaptive behavior, heightened risk-taking in these tasks often serves overall performance and males have previously been shown to rely more on underlying probabilities, thus show adaptive forms of risk-taking in gambling tasks (Byrnes et al., 1999; Van Hoorn et al., 2017). While both the BART and the Stoplight task depict risky decision-making in uncertain situations when with peers, it may be that taking risks to increase monetary rewards during the BART had nonetheless a higher value in male adolescents than adjusting risk tendencies to peer observation that did not give specific information about social norms.

In this sense, rewarding aspects of risk-behavior are domain-specific and it has been suggested that male and female adolescents would engage in different types of risk-taking, e.g., rather in the social or monetary domain. Accordingly, in a comparison between delaying monetary and social rewards, males showed differences in processing positive and negative outcomes from female participants (age 13-18 years; Greimel et al., 2018). Males were more indifferent when anticipating negative social but were more sensitive to receipt of positive monetary outcomes than females. This may be why we found gender differences only on the level of the mean, with male adolescents showing overall better performance, but no gender differences in the effect of peer observation condition.

Limitations and Outlook. While our study design and the good ecological validity of the BART measure allowed us to discuss age differences in the adjustment of risky decisions to peer observation and possible mechanisms and moderator effects, our findings underly certain limitations. First, peer influence on adolescent risky behavior is a trending topic in the developmental literature, as understanding social influence in adolescence is a promising approach to infer about how to reduce negative outcomes of risk behavior that mostly happen in the peer group (e.g., Steinberg, 2008). However, it is for this reason that there is an increasing number of studies that show quite diverse approaches to include peer influences. In this study, we can only conclude about the basal effects of peer observation on risky decision-making, devote to social norms, as we did not invite peers into the lab and the virtual peer gave no advice or feedback about task performance. However, a recent study indicated individuals to show flexible adjustment of risky decisions to active and passive peer influence and that there are diverse age-related differences dependent on the decision-context at hand across adolescence (Somerville et al., 2019). As such, understanding basal processes on the influences of social situations in various task contexts, here concerning the BART environment, is a promising approach to infer about more complex processes based on social norms conveyed by peers.

Second, the present study investigated developmental differences in the effect of peer observation in a broad age range from pre to late adolescence, while many previous studies included only a restricted age group to understand how peers alter risky choices.

Furthermore, when age comparisons were made, these were mostly about differences between adolescents and adults, while little is known about developmental trajectories from pre or early to late adolescence. We showed a small effect, suggesting that social influences might be differentially processed from younger to older ages. Nonetheless, often suggested quadratic age effects in risky decision-making with a peak in mid to late adolescence could not be depicted in this study, as findings from early adults are missing. As such, a peak in risky choices, also concerning differences between peer observation conditions, would suggest developmental changes ways into early adulthood. Finally, longitudinal studies would be best fitted to infer about changes in social sensitivity during risky decision-making across adolescence.

Third, future studies would benefit from including gender differences and pubertal maturation into the prediction of risky choices under uncertainty (see Laube & van den Bos, 2016, for a review), also as male and female adolescents differ in the age of onset of puberty and show differences in sensation-seeking (Cross et al., 2011). However, the grand bulk of studies did not investigate gender differences in the effect of peer presence, or only included male participants to rule them out (Defoe et al., 2015, 2019). While in this study, no gender differences in the effect of peer observation on risk exploration were found, such effects in another task setting (Defoe et al., 2019a) suggest that gender differences might be dependent on further characteristics of task settings used. Therefore, future studies should investigate gender effects on peer influences during risk-taking in other motivationally enriched decision contexts as well, to get to know whether the posited domain specificity of gender differences holds. Finally, researchers are increasingly interested in the contribution of pubertal hormones and timing on risk-taking generally (e.g., Kretsch & Harden, 2014; Lee, Tsai, Lin, & Strong, 2017; Op de Macks et al., 2016), but should be specifically so concerning gender differences in risk-behavior (Laube & van den Bos, 2016).

Conclusion. This study showed that most effects in the BART concerned the general integration of previous risk outcomes, i.e. learning and that more experienced adolescents were also more adaptive in doing so. That is older adolescents engaged in more risky choices than younger ones and were also more successful in adjusting risky choices when being observed or not. Also, male adolescents engaged in more risky choices than females but the study showed no gender differences in sensitivity to peer observation. In sum, adolescents showed to be quite adaptive risk-takers in the BART, while only those individuals with a low resistance to peer influence might be prone to show a heightened tendency for unknown risks when observed by a peer. It has been suggested that behaviors in task contexts under risk uncertainty depict more or less risk exploration that might be highly influenced by learning from experience and more generally, from previous life experience, i.e. age (Romer et al., 2017). Accordingly, the study contribute to recent trends in adolescent risky decision-making that highlight adolescents′ flexibility in choice behavior with peers altering learning and deliberative decision-making differentially in younger than older individuals.

II. General Discussion

The dissertation aimed to determine age-related differences in motivated behavior across adolescent development and more specifically addressed the question of whether adolescents are gamblers at any chance. The first study (*Paper I*) expected that conflicting findings concerning a peak in motivated behavior in youth would be related to the various study designs used to investigate adolescent-specific reactions in brain and behavior. It was of specific interest whether different types of incentives, like primary and secondary ones, would differentially account for age-related changes across adolescence. The second study (*Paper II*) aimed at comparing developmental trajectories between risky decision-making tasks that differed in various characteristics. It was expected that task contexts would depict specific states that might be differentially age-variant and susceptible to individual differences in cognitive and socioemotional functioning during adolescence. Finally, the third study (*Manuscript I*) expected that adolescents engage in more risky decisions when observed by a virtual peer, but the peer effect might differ from pre to late adolescence. Of specific interest was the impact of peer observation on the integration of previous risk experiences during the task, as well as influences of gender and individual resistance to peer influence.

The general discussion is structured into five parts. The first part depicts the contribution of the studies to suggested age differences in brain activity patterns and behavior across adolescence. The second part discusses how different task contexts contribute to divergent findings on adolescent-specific tendencies for rewards, risk, and rationality. In the third part, the discussion depicts the impact of individual differences in cognitive and socioemotional functioning on risky choices during adolescence. The discussion ends with an overall conclusion after discussing the strengths and limitations of the present study and providing future research directions.

II.I Age and Gender Differences in Motivational Influences

In a previous meta-analysis, researchers revealed that adolescents activated a similar incentive-related brain network during risky decision-making as adults do but to a higher extent (see Silverman et al., 2015, for a review). However, *Paper I* showed that only a few neuroscientific findings suggested a heightened activity in reward-related brain regions during adolescence and these were often not paralleled by age-related differences in actual task behavior. Nonetheless, there is evidence of associations between heightened activity in reward-related brain regions and psychological as well as behavioral outcomes in adolescence, like sensation seeking (e.g., Hawes et al., 2017), as well as risk-taking in the real-life and the laboratory (e.g., Braams et al., 2015; Galvan et al., 2007). Accordingly, most findings of heightened motivated behavior in youth applied to risky decision-making in *Paper I,* as did revisions of dual-systems models (Shulman et al., 2016; Smith, Chein, & Steinberg, 2013).

Thus, studies investigating risky decision-making in youth found contradicting findings based on concepts like maturational imbalance and reward-sensitivity but also theories that are specifically about developmental changes in decision-making, such as fuzzy-trace theory (Defoe et al., 2015; van den Bos & Hertwig, 2017). In a meta-analysis, early adolescents (aged 11-13 years) engaged in a higher level of risk behavior than middle to late adolescents (aged 14-19 years) that in turn engaged in more risky decisions than adults (aged 20-65 years). While these findings were in line with theoretical accounts, early adolescents and adolescent stages altogether did not differ from children (aged 5-9 years) in their risky decisions, suggesting no peak in risky choices during adolescence. Building upon this, the second study (*Paper II*) compared several risky decision-making tasks in a broad age range from pre to late adolescence and revealed no general peak in risky choices during mid-adolescence or a linear in- or decrease with age across tasks. Accordingly, Frey and colleagues (2017) suggested that behavioral measures of risk-taking are only sparsely associated with each other and that there might not exist a general risk-taking factor.

Thereupon, some types of risk-taking are thought to be more or less related to adolescent-specific tendencies to engage in motivated behavior, like real-life risks. The dynamic nature and unknown probabilities of risky choices in the BART used in the third study (*Manuscript* I) have commonly been associated with real-life risk behaviors (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Lejuez, Aklin, Zvolensky, & Pedulla, 2003). In the study, adolescents increased the number of risky choices with age and thus, show greater risk exploration but also higher outcomes, while younger adolescents dared but also gained less. In sum, all adolescents showed adaptive behavior in the BART by learning with experience across trials, and reducing risks when previous choices resulted in negative outcomes, irrespective of being observed by a peer or not. Several empirical studies support the finding of adolescents showing learning (Éltető et al., 2019; Lejuez et al., 2002), and behavior in risky decision-making adaptive to previous outcomes (Humphreys et al., 2016; Kessler et al., 2017), suggesting that adolescents are not ubiquitously imprudent in their decisions and adjust their choices to what they previously experienced. However, older adolescents were more successful in doing so according to previous studies that showed increasing risk-taking with age in the BART (Humphreys et al., 2016; Lauriola et al., 2014; but see, Éltető et al., 2019; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Qu, Galvan, Fuligni, Lieberman, & Telzer, 2015).

Yet, age differences in risk-taking were not accounted for by differences in reactivity to previous positive or negative feedback or learning. In conditions of the BART with more restricted ranges of possible pumps per trial, also no differences in risky choices between early and late trials have been found (Lejuez et al., 2002). Thus, age differences in learning have previously been found when including balloon trials that differed in risk probability (aged 3-17 years; Humphreys et al., 2016). The findings posited increases in learning but a decrease in sensitivity to negative feedback from childhood to late adolescence, with adolescents being in the middle of both changes. Another study found some adolescents with reduced neural integration of negative feedback to engage in more risky choices, perhaps as they discount negative relative to positive feedback information in risky choices (McCormick & Telzer, 2017b). Following, blunted sensitivity to negative feedback and age differences in learning might depend on alterations in risk probabilities and the individual risk-taker.

Another influence on adolescent-specific tendencies for risk-taking would be gender differences that have mostly been neglected in previous studies using risky decision-making tasks in adolescence (Defoe et al., 2015). Though the study of *Paper II* did not test gender differences in developmental trajectories of the diverse task contexts used, gender did not predict risky choices above age. Yet, male adolescents engaged in more risky choices than female adolescents when investigating risky behavior on a trial-by-trial basis in the BART. That is, while mean differences in risk propensity were not associated with gender differences above age in *Paper II*, risk adjustment was susceptible to differences between male and female adolescents in *Manuscript I*. Furthermore, the study of *Manuscript I* showed a trend for the age by gender interaction with male adolescents depicting an inverted u-shape in the exploration of unknown risks, while females increased risky choices rather gradually with age. Accordingly, risk exploration and sensation-seeking in adolescence have rather been associated with male choice behavior than with the risk-taking behavior of female adolescents (Cross et al., 2011). Meanwhile, findings suggest a decreasing gender gap in behavior with adolescent development and gender differences in varying risk contexts (Byrnes et al., 1999). Thus, the thesis showed indices for diverse approaches to risks between gender but future studies should further investigate the meaning of gender differences for developmental trajectories in risky decision-making across adolescence.

II.II The Influence of Task Context on Developmental Differences

The influence of incentive type on adolescent reward processing. The review of *Paper I* posited that contradicting findings in the literature concerning the heightened approach to and processing of rewards in adolescence could be due to diverse influences by different types of incentives. The ventral striatum was particularly sensitive to the influence of incentives when consuming or not receiving primary incentives, like sweets, in youth compared to adulthood. Yet, most studies relied on the influence of different amounts of monetary gains or omission of these. The findings seldomly showed age-related differences in brain activity patterns which were moreover dependent on the task setting used and the processing stage examined. Thereby, only a few studies investigated the impact of negative incentives on age differences in brain activity and functionality. The findings suggested that heightened brain activity in cognitive control regions but reduced activity in the amygdala signals a lower sensitivity to negative outcomes in youth. Furthermore, though event-related potentials are specifically suitable to infer about mechanisms in the processing of different kinds of incentives separately for anticipation and reception stages, there are only a few studies that investigated developmental differences in neural underpinnings of incentive processing. These studies posited incentives to mostly impact feedback processing instead of anticipation processes, while processing of positive and negative monetary and cognitive feedback was mostly age-invariant or reduced to the immature cognitive abilities of children but not adolescents.

Neurodevelopmental models conceptualized divergent developmental trajectories between brain systems responsible for cognitive control and socioemotional function and suggested adolescents being hypersensitive to arousing situations. Indeed, there is accumulating evidence that adolescents engage in activity in similar reward-related brain networks as adults when processing different kinds of incentives (see also, Ruff & Fehr, 2014, Secousse et al., 2013, for a review) and engage in reward-related brain activity to a higher extent than adults in risky decision-making tasks (see Silverman et al., 2015, for a review). The findings of *Paper I* were in line with these assumptions but showed that the latter finding might only be true for some but not all types of incentives and processing stages. That is, the review of neuroscientific findings in the first study (*Paper I*) suggested adolescents' brain activity patterns to be most sensitive to salient stimuli, that is, with high incentive values and low probability of receiving them.

As elaborated in the previous section of the discussion, adolescent-specific effects of different kinds of incentives on neuroscientific measures do not always align with findings on the behavioral level. In the reviewed studies (*Paper* I), children and adolescents reported more positive feelings towards the receipt of primary incentives than adults, but sweets and sugary drinks did not modulate actual behavior. In contrast, all age groups showed better performance in the prospect of monetary and cognitive incentives with only some evidence for a heightened approach to receipt of such incentives by adolescents. If at all, the study found age differences in risky decision-making, with adolescents engaging in more risky choices when their outcomes were unknown or under social influence. In sum, there are only a few indices for an adolescent-specific influence of different kinds of incentives on brain activity patterns and behavior and these were dependent on the specific task context used.

The influence of task context on adolescent risky decision-making. The findings of the second study (*Paper II*) showed that risk propensity in the divergent task settings was only lowly associated with one another. Furthermore, the task contexts differed in their predictions about developmental trajectories across adolescence. This is in line with the assumption that risky decision-making is a multifaceted construct (Frey et al., 2017) with different facets predicting diverse developmental trajectories across the lifespan (Defoe et al., 2015; Romer et al., 2017). The meta-analysis of Defoe and colleagues (2015) also investigated whether task moderators could explain the conflicting finding of adolescents engaging in equal levels of risk as children but showing greater risk-taking than adults. In a comparison of task moderators on risky choices between adolescents and adults (ages 20-65) findings were in line with neurodevelopmental imbalance models. Specifically, when positive and negative feedback was provided immediately after decisions, adolescents engaged in more risk-taking than adults. Contrasting early adolescents (aged 11-13 years) with children (aged 5-10 years), none of the investigated task moderators altered the finding of equal levels of risk between the age groups (Defoe et al., 2015). However, contrasting all adolescents (ages 11-19) with the child group, findings depended on task characteristics. In line with fuzzy-trace theory, when task contexts allowed basing choices on qualitative characteristics, i.e. when the task provided the opportunity for a "no risk" or safe option, adolescents decided less for options that implied some risk than children (Defoe et al., 2019).

Yet, when comparing adolescents with adults the meta-analysis did not differentiate between early and middle to late adolescents, and the included studies were generally limited in age groups used to infer about developmental changes. Furthermore, most studies did not directly compare diverse task settings and seldomly included loss gambles that led to some moderators not being tested in specific age comparisons (Defoe et al., 2015). In the study of *Paper II,* the various task settings obtained choice behavior between risky and safe options with immediately provided rewards and losses. The developmental stages ranging from pre to late adolescence showed overall similar patterns to adults' engagement in risky decision-making. Across age, adolescents showed fewer risky choices when probabilities were unknown than when they were known (e.g., Hertwig et al., 2004) but losses loomed larger than gains in described task settings (Tversky & Kahneman, 1992). The following sections will further discuss developmental changes concerning task contexts that differed in gain versus loss gambles and known versus unknown risk probabilities.

Developmental differences in described gain versus loss gambles. Developmental differences in the study of *Paper II* showed that there was no peak in choices under risk when adolescents were in the prospect of gains compared to losses, as the hypothesized reward-sensitivity in youth would suggest. Moreover, choices under risk were age-invariant in the gain domain. Framing biases between gain and loss gambles usually imply adults to prefer sure gains and risky losses (Tversky & Kahnemann, 1992). Adolescents in contrast have shown reversed framing effects, i.e. preferring sure losses and risky gains (e.g., Reyna et al., 2011). In accordance, previous findings showed that adolescents have a higher tendency for risky choices when gambling to maximize wins than to minimize losses (van den Bos & Hertwig, 2017) or at least an increase in risk propensity in the gain domain (Levin et al., 2014). Reyna and colleagues (2018) even replicated findings of reversed framing that has previously been suggested to underly adolescent decision-making in adult risk-taking. Furthermore, reversed framing, i.e. verbatim-based risk preference was suggested to depict developmentally inappropriate decision patterns and was associated with criminal and non-criminal risk-taking in adults. The covariation between laboratory and real-life risk tendencies was reflected in brain activity patterns by also showing neuroscientific evidence for the difference in the cognitive effort between decision strategies that were higher for developmentally appropriate framing biases compared to the age-inappropriate reversed framing patterns (Reyna et al., 2018).

Conversely, most of the previous findings that revealed a reversed framing effect in adolescence were related to task contexts that implicated more salient incentives than in the gain and loss domain of the Treasure Hunting Task (THT) of this study (2€, 3€, or 5€). Thereby, formal models also suggest outcome magnitude and probability altering the reference point of the decision-maker, why high gains with lower probability often lead to risk-seeking behavior and reversed framing in adults (Tversky & Kahnemann, 1992). At least, greater reward sensitivity in choices under risk in some studies would be because high wins stood more out from lower wins as outcome values were more variable than in the THT ($5, $20, or $150, Reyna et al., 2011; 3€-32€, aged 8-22 years, van den Bos & Hertwig, 2017). Supporting the notion of reverse framing effects in adolescence being dependent on outcome probabilities and magnitudes, one study showed adolescents to engage in more risky choices in the loss than in the gain domain concerning small to medium incentives ($5 and $20, aged 14-17 years, Reyna et al., 2011) but they showed greater sensitivity to gains than losses when incentives were high ($150, Reyna et al., 2011).

Furthermore, White and colleagues (2018) investigated whether adolescents (aged 13-17 years) and young adults (aged 18-24 years) differ in their framing biases in gain and loss gambles using an online risk-taking dilemma. Testing hypotheses drawn by fuzzy-trace theory, the results revealed that adolescents relied on both intuitive (gist) and quantitative (verbatim) representations of risky choices with more risk-taking but a lower framing effect than adults. Adults in turn showed differences in their framing bias even between low- and high-risk conditions, which means they relied more on categorical (gist) representations of risky choices than adolescents (White, Gummerum, & Hanoch, 2018). In a prospective publication of our study group concerning the THT (Kray, Kreis, & Lorenz, 2020), results revealed no age differences in the framing effect from pre to late adolescence but suggest variability in this effect depending on the advantageousness of the risky versus safe choice. When information about expected values between choice options did not differ, framing effects were stronger, especially compared to trials in which risk-taking was advantageous. Interestingly, mid-adolescents (12-14 year-olds) differentiated most between advantageousness of risk decisions in the framing effect. The findings depicted greater description-based information integration (verbatim) in reactivity to risky choices in the gain and loss domain with age. But when description did not yield information about advantageousness of risk and safe choices, especially middle adolescents based their decisions on valence domain, i.e. preferred safe gains but risky losses. In conclusion, reverse framing effects in adolescence might specifically be the case when task contexts provide highly salient or categorical choice options, while adolescents increasingly prefer sure gains and risky losses with age.

Developmental differences in choices under risk and uncertainty. According to findings of a greater tendency to explore unknown risk situations in youth (e.g., Romer et al., 2017), mid adolescents were more tolerant to risk uncertainty than younger and older ages, which is in line with previous empirical findings (Blankenstein et al., 2016; aged 12-17 years, Tymula et al., 2012; van den Bos & Hertwig, 2017). On the contrary, adults have repeatedly shown a reversed pattern of the description-experience gap with higher risk propensity under risk than under uncertainty (Wulff, 2018). This has been explained by adults relying on verbatim, i.e. descriptive information when information about outcomes and probabilities are provided which is thought to increase choices for risky options (Reyna & Rivers, 2008). When no information is provided, adults would rely on gist-based processes that render them more risk-averse as they would then prefer rather no risk than some risk. In this sense, a recent study that differentiated between developmental differences in described-, ambiguous, and uncertain task conditions posited that a developmental decline in risky choices with known outcome probabilities in adolescence reflected predictions by fuzzy-trace theory. According to developmental perspectives of the fuzzy-trace theory, adolescents would rely less on gist why they would be more prone to engage in unknown risks to sample outcomes of choice options as they only have a few previous experiences with such decision situations (Defoe et al., 2019; Romer et al., 2017). However, imbalance models might have better depicted the mid-adolescent peak in the tendency to explore risks for which outcome probabilities are ambiguous or uncertain (van den Bos & Hertwig, 2017).

It is therefore that the findings of *Paper II* contributed to such assumptions by showing that experience-based task contexts trigger risk exploration specifically in mid-adolescence, while adolescents become gradually more risk-averse in described settings, especially when gambling to minimize losses. Such developmental processes have been explained by qualitative outcome dimensions, e.g., a sure option to lose only a relatively low amount, becoming more important than quantitative dimensions, e.g., the possibility to lose nothing or a high amount, during adolescence (Reyna & Farley, 2006). Yet, future developmental studies would be well advised to differ between both positive and negative incentive valence (see also Defoe et al., 2015), as well as various sets of values and probabilities, to further infer about age differences in the subjective representation of risk in adolescent choice behavior. Specifically, as in the studies of this dissertation, all choices were attributable to qualitative dimensions, i.e. included a safe or “no risk “ option that might facilitate gist-based processes and decisions against risk in adolescence (Defoe et al., 2015, 2019).

Beyond greater risk-taking in experience- than description-based measures, these differences were mostly driven by adolescents greater risk-taking in the Stoplight task than the BART in *Paper II*: Though both task contexts imply experience-based choices the static risk probabilities in simulated driving allow to rely more on previous experiences, as they can be transferred to future decisions that underlie the same risk probabilities. In dynamic choices in turn, risk levels change with each decision in each trial, increasing risk uncertainty and leading to generally risk-averse behavior when referring to the maximal earnings point in the BART, also in adolescents (e.g., Ashenhurst, Bujarski, Jentsch, & Ray, 2014; Kessler et al., 2017; Lejuez et al., 2002; Mamerow, Frey, & Mata, 2016; Mata, Hau, Papassotiropoulos, & Hertwig, 2012). Other influential differences between the task contexts are the induced time pressure and the obvious exceeding of social norms when crossing red traffic lights in the

Stoplight task in contrast to risk-taking in the BART that can lead to omission of monetary gains and a balloon to burst. In the meta-analysis of Defoe and colleagues (2015), at least dynamic versus static and time pressure versus no time pressure were no significant moderators in explaining age differences in risky decision-making across adolescence. Accordingly, the effect of greater risk-taking in the Stoplight task than in the BART was age-invariant in the study of *Paper II.* As time pressure and dynamic choices have both been suggested to increase arousability in adolescence (Defoe et al., 2015), time pressure might have more reliably done so. However, future studies should consider and dissect the influence of further characteristics, such as whether known social norms are exceeded or whether risk-taking implies potential risks for others, on choice behavior in adolescence.

Altogether, changes from quantitative and qualitative representations in adolescence to mostly qualitative representations of risky choices in adulthood might account for increasing risk-aversion with age in described risky decision-making, as shown in the studies on the THT (*Paper II*; Kray et al., 2020). In contrast, a greater tendency to approach risks during adolescence might apply to choice behavior when highly salient, improbable, or unknown outcomes are at stake. The previous findings described above suggested that the inclusion of a more mature sample of emerging adults and more distinct or salient incentives in the second study (*Paper* II) would have revealed more pronounced developmental changes, e.g. in sensitivity to valence domain and to known versus unknown risk probabilities across adolescence.

Age differences in adjustment of risky choices to peer observation. The review of findings on motivated behavior in *Paper I* suggest that some of the most salient cues in adolescents' risky-decision making would be social ones (see also., Crone & Dahl, 2012; Defoe et al., 2019; Shulman et al., 2016). Surprisingly, the results of the third study

(*Manuscript I*) showed no effect of a social manipulation on choice behavior in a dynamic and experience-based decision-making task. Moreover, the effect of peer observation was age-invariant from pre to late adolescence, suggesting that early and late adolescent developmental stages do not differ in their susceptibility to peer observation during risky decision-making. This stands in contrast to the hypothesized social sensitivity in youth (e.g., Blakemore & Mills, 2014) that has been associated with higher reward-related brain activity and thus, heightened risk-taking in adolescence (e.g., Chein et al., 2011). Against predictions of evolutionary theories (Wilson & Daly, 1985) and the findings of a recent study on the Stoplight task (Defoe, Dubas, & Romer, 2019), male adolescents did not engage in more risky choices than females when observed by a peer. Contradicting findings could be since studies differed in the type of social influence, risky decision-making tasks, and age groups used to infer how peers influence risky choices during this period. In this sense, previous examinations on the influence of peers also show contradicting results with peer presence sometimes increasing risky choices (e.g., Smith et al., 2014; Van Hoorn, Crone, & Van Leijenhorst, 2017) but sometimes showing mixed-effects (e.g., Haddad et al., 2014; Lloyd & Döring, 2019; Somerville et al., 2019), or triggering even more cautious behavior (e.g. Kessler et al., 2017), suggesting that peers do not ubiquitously provoke more risk-taking in adolescence. Furthermore, gender differences were seldomly reported in studies about the development of risky decision-making in adolescence and have recently been shown for the peer effect in only one specific task context, i.e. simulated driving (Defoe, Dubas, Dalmaijer, et al., 2019).

Recently, several studies investigated the interaction between different types of peer influence and the characteristics of the decision-making task. Lloyd and Döring (2019) found a risk enhancing effect in adolescents (aged 12-15 years) when decisions were made in groups and choices were under ambiguity but not under risk, suggesting that the influence of peers mainly extends to dynamic contexts. While the BART shares the characteristic of a dynamic task context, peers were not actively involved in the deliberations that preceded decisions in the study of *Manuscript I*, suggesting that the lack of the peer effect in this study might be due to virtual peers only passively observing the decision-making process. However, Somerville and colleagues (2019) aimed at dissecting the interaction between peer presence and the type of choice further, while also including a broad age range (13-25 year-olds) to infer about potential age differences in this interaction. The study showed that observation by a peer heightened risky choices in the youngest participants for the 'cold' context of the Columbia Card Task, but for the 'hot' condition in middle to late adolescents, while other ages and contexts rather decreased risk under peer observation. As such, peer observation is not insufficient to alter risky choices in youth but its effect is highly dependent on the specific study design used.

Though peer observation did not influence risky choice per se in the third study of this thesis (*Manuscript I)*, the social condition modulated the general integration of previous choice outcomes with age. That is, older adolescents increased risky choices across the task, i.e. showed learning to a higher extent than younger adolescents when peer observation was present. An interaction of learning with age was not observable when peer observation was absent. Yet, peer observation did not modulate reactivity to previous gains or gain omission, and reactivity to previous positive or negative outcomes was not age-variant. Such findings suggest peer observation to modulate learning from positive as well as negative feedback in the BART, instead of influencing the value of positive or negative outcomes. In contrast, a recent neuroscientific study investigating the influence of a virtual peer observing gambling and a response inhibition task in adolescence (ages 15-17 years, Smith et al., 2018) found social influence to heighten risky decision-making and related reward-sensitivity in the brain but not behavioral response inhibition and control-related brain activity. Though the findings suggested peers to rather influence reward processing than distracting from task conduction, the study did not test age differences in such effects.

Thus, the BART leaves the adolescent in complete uncertainty about at which point balloons are more likely to burst, while in choices under ambiguity at least some information about risk probability and outcomes are given. In this sense, previous studies using the BART did find an effect of increased risk-taking in adolescents when peers encouraged risky choices but not when peers were only observing tsk conduction (Harakeh & de Boer, 2019; Reynolds et al.,2014). It might be that risk heightening effects of peer observation rather occur under ambiguity than uncertainty and rather concerning static choices than dynamic ones, as uncertain and dynamic settings further reduce the predictability of the respective choice outcomes. Correspondingly, one study even found a risk decreasing effect of peer observation following successful trials in a modified version of the BART (Kessler et al., 2017), suggesting more risk-aversion when peers observed dynamic choices under uncertainty.

In a study using the BART but devote of social influence, McCormick and Telzer (2017a) revealed adolescents (aged 8-17 years) to show learning throughout the task with older adolescents showing the highest learning rates. Thereby, age-related changes in brain activity and interregional connectivity between reward- and control-related brain regions explained the connection between age and increases in flexible learning. Similarly, another study that investigated the effect of peer observation on how late adolescents (aged 18-22 years) learned which choice options led to long-term gains and losses in the Iowa Gambling Task (Silva et al., 2016). Comparable to the finding of greater learning in older than younger adolescents when peers were present in the study of *Manuscript I*, late adolescents that conducted the gambling task under peer presence showed more exploratory behavior, showed better task performance, and learned faster from both positive and negative outcomes than those that were alone (Silva et al., 2016).

In a recent working paper, Tymula and Wang (2020) differentiated between gain, loss, and mixed gambles in the effect of peer observation on risky choice in adolescence (aged 12-24 years). In line with findings of Silva and colleagues (2016) and similar to the greater learning for older than younger adolescents in the present study, older adolescents (aged 18-24) engaged in more risky choices under peer observation and the effect was independent of the valence domain, i.e. from whether emerging adults were in the gain, loss, or mixed condition. More specifically, they also did not find evidence for adolescents being less sensitive to losses versus gains under observation but their relative weighting of losses to gains, i.e. loss aversion increased (Wang & Tymula, 2020). This is in line with the finding of *Manuscript I* that showed peer observation to influence the integration of positive and negative outcomes but not the reactivity to gain omission over gains and further revealed a reduction of learning in rather younger than older adolescents in the social condition.

However, the study of *Manuscript I* did not include a subsample of emerging adults, why it could be that the findings did not depict a quadratic age trend with risk heightening effects, i.e. increases in learning when peer observation was present than absent that would be most prevalent in middle to late adolescence. Furthermore, given the previously described findings, it could be argued that learning from positive and negative experiences in risky choice would be further enhanced in older than younger adolescents when peers were actively involved in such deliberations instead of passively observing task conduction. Beyond heightened risk-taking in the presence of peers in adolescence, researchers suggested peer presence and related brain activity patterns to also imply positive effects (for a review, see Telzer, 2016) with peers in the lab facilitating learning and adaptive prosocial development (for a review, see van Hoorn et al., 2016). Likewise, peers do not only provoke heightened engagement in maladaptive but also the exploration of adaptive risk-behaviors (Duell & Steinberg, 2019), highlighting the two facets of adolescent development as a period of risk and opportunity.

II.III Individual Differences in Cognitive and Socioemotional Functioning

The study of *Paper II* revealed that not all risky decision-making tasks were susceptible to individual differences in socioemotional functioning, as measured by individual dispositions in approach to rewards, impulsivity, venturesomeness, and empathy, as well as in cognitive abilities, like fluid intelligence. This finding further supports the notion of how variable task contexts are in eliciting socioemotional arousal and the allocation of cognition in youth. Thereby, it has to be noted that the risky decision-making tasks used in the second and third studies of the thesis (*Paper II* and *Manuscript* I) were adapted to be more game-like and thus, aimed at being particularly exciting and more child-friendly than previous versions.

Individual Differences in described risky decision-making. Concerning choices under risk, adolescent risk propensity was predicted by cognitive functioning above age and gender in gambles to minimize losses (THT Loss) but the gain domain (THT Gain) was not susceptible to individual differences in fluid intelligence. Though somewhat surprising at first glance, the processing of positive versus negative information could have differentially allocated cognitive resources. As such, the integration of information about risk outcomes and probabilities has previously been shown to have a more protracted development in the loss than in the gain domain in a developmental study (aged 5-7 and 8-11 years, Levin et al., 2007). Therefore, the THT Loss might still have allocated more cognitive resources in pre to late adolescents and thus, was associated with a measure of fluid intelligence, in comparison to the THT Gain. Nonetheless, adolescents decreased choices under risk with age that could be completely accounted for by increases in cognitive abilities in the THT Loss.

When accounting for the sensitivity to expected values in a previous version of the THT, the Cups task, risky choices across the valence domains could be accounted for by another cognitive measure, namely numeracy (aged 8-17 years, Levin et al., 2014). In a more thorough investigation of the influence of working memory on age differences in the THT by our study group (Kray et al., 2020), working memory accounted for age differences in the sensitivity to expected values across valence domains, i.e. predicted more adaptive choice behavior with increasing cognitive abilities. Yet, working memory was not associated with the framing effect in youth. As such, gain and loss gambles might allocate fluid intelligence differentially but the sensitivity to incentive valence in described risky decision-making is not associated with cognitive functioning in pre to late adolescents.

Consequently, it could be argued that cognitive functioning explains increases in adaptive choices with age but socioemotional functioning would account for sensitivity to gains and losses in adolescence. This would also reflect assumptions by neurodevelopmental models that suggest cognitive control and socioemotional functioning to differentially influence motivated behavior in youth. Beyond developmental differences and cognitive functioning, adolescents with higher self-reported venturesomeness were more likely to show heightened risky choices in the THT Loss. According to the THT Loss being a task context that reflects tendencies to engage in risks under described potential losses, venturesomeness depicts adolescents’ motivation to explore behaviors for which individuals are fully aware of potential negative consequences (e.g., bungee jumping). Consequently, the findings on the association between risky choices in the loss domain of the THT and venturesomeness suggest that some individuals are more prone to explore risks under known loss probabilities, just like in real life where socially accepted forms of risk-taking might not be associated with protracted cognitive abilities or maladaptive outcomes (Duell & Steinberg, 2019).

Furthermore, when gambling to maximize wins (THT Gain) risky choices were not associated with individual differences in socioemotional functioning. Yet, it would be intuitive to imply that adolescents with a greater tendency to approach rewarding situations, as measured with the Behavioral Approach System (BAS, Carver & White, 1994) or sensation-seeking, would engage in more risks to maximize wins in the THT Gain. Based on neurodevelopmental models, it could be further suggested that positive rewards would trigger more acting without thinking, i.e. impulsivity in risky choices and thus, more risk-taking in adolescence. Yet, that individual reward-sensitivity and impulsivity did not predict more risk-taking in the THT Gain in the study of *Paper II* is in line with previous findings. That is, a recent study found also no associations between individual novelty- or thrill-seeking tendencies and risky choices in the gain domain of a description-based task context (van den Bos & Hertwig, 2017). Concerning impulsive tendencies, a prospect study about risky choices in the THT of our study group revealed no associations between age, impulsivity, and adaptive decision-making or the framing effect and no mediation of impulsivity on age differences in such choice behavior (Kray et al., 2020). Against assumptions of models on adolescent development, neither individual dispositions to act without thinking nor to engage in rewarding situations predicted risky choices in gambles to maximize gains or reactivity to incentive valence above or with development.

Interestingly, Levin and colleagues (2014) revealed that surgency, a measure that also reflects behavioral approach tendencies and sensation-seeking similar to the BAS, was associated with more adaptive decision-making of children and adolescents (ages 8-17 years). In a similar sense, BAS scores accounted for a reduction in the reactivity of a control-related brain region (dorsolateral prefrontal cortex) that previously predicted fewer risk decisions in a gambling task (but see Qu et al., 2015), suggesting the association to depict strengthened connectivity between reward processing and control regions (ages 11-24 years, Blankenstein et al., 2018). As a conclusion, dispositions to look out and engage in rewarding situations can also improve the adaptiveness of risky choices to increase outcomes and might not depict acting without thinking. Yet, reward-seeking behavior did not account for age differences in described risky decision-making (Levin et al., 2014), suggesting that reward-sensitivity might be a characteristic of some individuals above developmental changes and cognitive abilities.

Individual Differences in experience-based risky decision-making. The two experienced-based measures of risk-taking investigated in *Paper II* were differentially associated with cognitive and socioemotional functioning than the description-based measures. Thereby, neither the Stoplight task nor the BART was associated with individual differences in fluid intelligence, suggesting that experience-based decision-making would be rather on the socioemotional side of motivated behavior. At least concerning the Stoplight task, a recent study showed that similar to the lack of association between risky choices and fluid intelligence in the study of *Paper II*, self-regulative capacity did not predict risk-taking (Botdorf, Rosenbaum, Patrianakos, Steinberg, & Chein, 2017). More specifically, Botdorf and colleagues (2017) could show that when differentiating between cognitive and emotional self-regulatory abilities, only the capacity to regulate emotional interference predicted risky choices in the Stoplight task. That is adolescents with greater problems in cognitive control performance under arousal engaged in more risky decisions (Botdorf et al., 2017).

Accordingly, heightened choices to overrun an intersection at a yellow light instead of stopping in the Stoplight task were predicted by individual differences in impulsivity and empathy above age, gender, and fluid intelligence. This finding stands in contrast to previous studies using simulated driving tasks that showed risky choices to be associated with sensation-seeking but not impulsivity (Chein et al., 2011; Steinberg et al., 2008), as measured by the Barratt Impulsiveness Scale (BIS-11, Barratt, 1959). Thus, previous studies were based on more restricted age ranges in the adolescent period and differences between the impulsivity measures likely confounded findings between studies. For example, the BIS-11 includes items that might not be appropriate to measure self-reported impulsivity in youth, such as ‘I spend more money than I earn’. Given that the sample of the second study (*Paper*

II) incorporated pre to early adolescents, the German adaption of the Impulsiveness Questionnaire I6 (IVE; Stadler & Janke, 2003) was used for which the impulsivity measure is adapted for younger ages and showed sufficient validity across age groups.

Following risk propensity being predicted by emotional over cognitive self-regulation (Botdorf et al., 2017), it is intuitive that individual differences in impulsive and emotional drives, such as acting without thinking and empathy, account for greater risk-taking in the Stoplight task in adolescence. Furthermore, risky choices in simulated driving have repeatedly been shown to be influenced by social situations, such as peer presence (e.g., Chein et al., 2011) and social exclusion (e.g., Peake et al., 2013). It might be for the induced time pressure to reach a goal as fast as possible while deciding to risk accidents, or the obvious exceeding of social norms when risking to overrun red traffic lights, that might lead to robust findings of heightened risky decisions and associations with impulsivity and social sensitivity in youth concerning the Stoplight task. Yet, the study of *Paper II* was first to show that risky decision-making in the Stoplight indeed varies with individual empathic functioning in adolescence while measures of emotional and social regulatory capacity seem fruitful in understanding how adolescents cope with arousing situations (Botdorf et al., 2017).

Even though the BART shares characteristics with the Stoplight task, such as risk probabilities that can only be inferred with experience, the BART was not associated with any of the individual differences measures. On the one hand, previous studies found risk propensity in the BART to be associated with individual differences in socioemotional functioning (BAS Drive, Braams et al., 2015; sensation-seeking and impulsivity, Lauriola et al., 2014) but these associations increased across the lifespan. As such, in developmental studies during adolescence, these associations might not yet be given. On the other hand, the BART differed from all the other task settings used in the study of *Paper II* as it reflects dynamic instead of static choice options. That is, while in most static task settings adolescents decide to engage in risks or not, the dynamically increasing gains but also risks with each decision to pump balloons in the BART reflect decisions about when to stop engaging in risks to maximize outcomes. The dynamic task property increases uncertainty as adolescents do not only have to learn about outcome probabilities but also keep track of previous decisions to infer about how much risk to take. Eventually, differences in the dynamics of task contexts might account for diverse associations between risky choices with cognitive and socioemotional functioning between the experienced-based risk measures (BART and Stoplight task) in the study of *Paper II*.

Individual differences in susceptibility to social influence. Hence, when investigating the influence of virtual peer observation on consecutive risky choices in the study of *Manuscript I* the findings revealed that RPI scores moderated adolescents' adjustment of risk-taking to peer observation. According to the assumption that not all adolescents might show heightened risk-taking in social situations, only individuals that reported a low RPI increased risky choices in the BART when observed. Several studies investigated how risk-taking under peer presence was correlated with RPI scores. In the study of Peake and colleagues (2013), some adolescents underwent a social exclusion situation before conducting the Stoplight task. In line with the study on the influence of peer observation in the BART, results showed more risky choices when previously having been socially excluded by individuals with low scores in RPI. Interestingly, this association was reflected in higher levels of activity in the right temporoparietal junction suggesting greater effort in mentalizing in individuals with low RPI that have been socially excluded. Similarly, reward-related brain activity in response to peer presence was correlated with self-reported RPI in risky choices during the Stoplight task even after controlling for age (Chein et al., 2011). That is, the perception of individuals' RPI matched neural and behavioral responses to social situations.

In contrast, a study using a variant of the BART (Kessler et al., 2017), found associations between risky choices and RPI scores to be rather in the direction of individuals with high RPI showing more cautious behavior when observed by peers. Thereby, RPI was not associated with neural underpinnings in terms of ERP's as measures of reward sensitivity when peer observation was present. Differences in associations between RPI and risky choices in adjustment to peer observation between studies using the BART may depend on the specific risk characteristics that were sometimes altered in previous studies to adapt task environments for neuroscientific measures. Thus, RPI was not only correlated with task behavior but moderated risky choices on a trial-by-trial basis in this study, highlighting the robustness of individual RPI influencing social sensitivity in task behavior.

Thus, RPI has previously been suggested to increase with age and female adolescents were thought to show greater resistance than males (Paus et al., 2008; Steinberg & Monahan, 2007; Sumter et al., 2009). In the study of *Manuscript I,* there were no age differences in RPI scores from pre to late adolescence and females did not differ in their self-reported RPI from males. Furthermore, the moderation of risky choices in adjustment to peer observation by RPI was age-invariant, suggesting heightened risk-taking under peer observation with low RPI scores irrespective of age. In a review, Bell and Baron (2015) propose a broader framework that suggests understanding resistance to peer influence in terms of sociocultural perspectives and person-context interactions that might ultimately form individual resistance to peer influence with experience. Given that the direction of the associations between RPI scores and risky choice behavior showed slight variances between task contexts in previous studies (e.g. Kessler et al., 2017), the influence of RPI scores on risky choices under peer presence might indeed depend on further characteristics of the given task context. Eventually, age and gender differences in RPI might be more pronounced in studies that also included emerging adults that already gained more life experience and adjusted RPI accordingly.

To sum up, the findings of the studies of *Paper II* and *Manuscript I* suggested that predictions of cognitive and socioemotional functioning on risky choices in youth depend on the task context. Influences of individual cognitive functioning could only be shown in described risk choices. Sensation seeking tendencies (BAS, venturesomeness, novelty-seeking) increased choices under risk in some studies and implied deliberation. Whereas self-reported acting without thinking (impulsivity), as well as socioemotional sensitivity (empathy and RPI), predicted more risk-taking in task contexts that allow less for consideration of potential consequences in adolescence. Thereby, predictions by individual differences were mostly independent of developmental differences.

In this sense, recent longitudinal studies identified groups of adolescents with heterogeneous tendencies for acting without thinking, preferring immediate smaller over delayed higher rewards (delay-discounting; ages 11-18 years, Khurana et al., 2018) and sensation-seeking (ages 14-28 years, Yoneda, Ames, & Leadbeater, 2019). The groups of adolescents that revealed a high increase in acting without thinking and stable rates of delay discounting across development were at risk for substance use disorder (Khurana et al., 2018) and high impulsive and sensation-seeking adolescents showed less adaptive outcomes in young adulthood (Yoneda et al., 2019). In contrast, sensation-seeking was rising during adolescence but was not associated with weak cognitive control or maladaptive outcomes (Khurana et al., 2018), with moderate levels of sensation-seeking even predicting the best outcomes, as measured by educational archievements and finances in young adulthood (Yoneda et al., 2019). This is in line with a recently emerged developmental model, that suggests imbalances between heightened reward-sensitivity and protracted cognitive control to be a characteristic of a sub-group of adolescents with low cognitive abilities but adaptive exploration tendencies for normally developing adolescents (Romer et al., 2017).

III Synopsis

The present thesis investigated fundamental moderators on adolescent motivated behavior and risky decision-making that are of high importance in understanding recent developments in studying adaptive and maladaptive outcomes in youth. Another essential point is identifying individual dispositions that will not only contribute to and clarify developmental models but might also have practical implications in promoting adolescent health.

Considering first reward sensitivity and heightened motivated behavior in youth, the findings of the review on the influence of different kinds of incentives on adolescent goal-directed behavior, learning, and decision-making revealed that only a few motivationally enriched situations are age variant across adolescence. In contrast to the universal peak in reward-sensitivity and motivated behavior as posited by neurodevelopmental imbalance models, neuroscientific evidence suggested adolescents engage in activity in similar reward- and control-related brain networks as adults but only to a higher extent in the prospect of highly salient incentives. Thereby, risky decision-making is a promising approach to study the influence of socioemotional and cognitive functioning on adolescent behavior. On the one hand, an understanding of risk-taking during adolescence and its underlying developmental trajectories is important given the potential for maladaptive outcomes of risk behaviors in youth with long-lasting consequences later in life. On the other hand, as also the review of *Paper I* revealed that risky choices showed a peak during adolescence, while adolescent-specific effects have shown to be dependent on the characteristics of the task context (Defoe et al., 2015). The findings further highlighted that developmental studies would benefit from models on decision-making and learning to infer about what drives adolescent-specific tendencies for risk-taking and sensation-seeking (e.g., Van Duijvenvoorde, Blankenstein, et al., 2016).

As such, the third study revealed that when risk probabilities are unknown and can only be experienced, all adolescents are adaptive in their risky choices as they show learning and reduce risk in reaction to previous negative outcomes. Thereby, adolescents increased risk but also outcomes with age. Furthermore, male adolescents engaged in more risky choices than female adolescents in a dynamic and experiences-based task context according to evolutionary theories (Wilson & Daly, 1985) but divergent developmental trends between the gender were not robust. Across task contexts, the findings of the second study did not suggest that risky decision-making generally peaks in adolescence, as did a meta-analysis that showed decreases in risky choices with age but no differences between children and adolescents (Defoe et al., 2015). Different types of risky decision-making tasks are thought to represent specific states that can be used to infer about when adolescents engage in risky choices and what are the characteristics of the risk situations that causes such behavior (Frey et al., 2017). Hence, task context and individual differences in cognitive control and socioemotional functioning are important moderators on development in risky decision-making (Defoe et al., 2019).

Building upon this the dissertation project unveils developmental differences in risk-taking during adolescence based on commonly assessed task characteristics in the decision-making and learning literature (e.g., Van Duijvenvoorde, Blankenstein, et al., 2016). First, adolescents did not engage in more risky choices to maximize wins than to minimize losses and did not increase risky choices in the gain domain, as suggested by heightened reward-sensitivity in imbalance models but also by reversed framing effects in fuzzy-trace theory (e.g., Reyna et al., 2015). Adolescents preferring sure losses but risky gains might specifically be the case when highly salient incentives are at stake, as also formal models on risky decision-making posit that high gains with low probability increase risk-seeking behavior (Tversky & Kahneman, 1992). Hence, reversed framing, or reward sensitivity in adolescence, respectively, might rather apply to task contexts in which choice options are highly distinctive, i.e. show great variance in outcome magnitudes and probabilities (e.g., Reyna et al., 2011). Nonetheless, loss-aversion increased with age in the loss domain replicating assumptions by the fuzzy-trace theory which suggests that across adolescence qualitative characteristics of choice options, i.e. a sure loss, become more influential than quantitative dimensions, i.e. losing nothing or a higher amount (Reyna & Farley, 2006).

Second, middle adolescents showed the highest tolerance for the unknown when engaging in risks, while adults usually engage in more risks when their probabilities are known than unknown. While this developmental phenomenon could again be explained by fuzzy-trace theory and linear increases in gist-based decisions with development, imbalance models seem to better depict the mid-adolescent peak in sensation-seeking or risk exploration when risk probabilities are unknown (see also, van den Bos & Hertwig, 2017). Adolescents further engaged in more risky choices in experience-based measures that implied time pressure and static choices instead of monetary gains and dynamic risk probabilities, without age differences herein. As time pressure and dynamic choices have both been suggested to increase arousability in adolescence (Defoe et al., 2015), time pressure might have more reliably done so.

Third, peer observation had overall no effect on adolescent risky decision-making. Furthermore, there were no age differences in this effect and peer observation did not alter the value of previous positive and negative risk outcomes. This stands in contrast to social variants of neurodevelopmental models and suggested social sensitivity in youth that implies heightened risk-taking, as well as a heightened reward- or blunted sensitivity to negative outcomes when in the presence of peers (for a review, see Ciranka and van den Bos, 2019). Conflicting findings could be accounted for by the specific task setting used in this study that not only leaves the adolescent uncertain about risk probabilities but these moreover changed dynamically with previous decisions. Experienced-based task settings with more static or assessable risk probabilities also more robustly showed risk heightening effects of peer presence in previous studies (e.g., Chein et al., 2011). Nonetheless, peer observation moderated learning from both positive and negative feedback with age such that older adolescents learned from experience rather irrespective of peer observation condition than younger adolescents. Previous findings suggested that peer presence facilitates learning in late adolescents (e.g., Silva, Shulman, Chein, & Steinberg, 2016) instead of distracting from performance (e.g., Smith et al., 2018) but it has been discussed this might differentially be the case for younger adolescents.

Finally, the diverse task contexts used in the studies of the dissertation were differentially susceptible to individual differences in cognitive and socioemotional functioning. Age-related decreases in risky choices of loss but not gain gambles were accounted for by increases in fluid intelligence. Eventually, as risky choices under losses allocate more cognitive resources than gain gambles (e.g., Levin et al., 2007). Individual RPI modulated risky choices under peer observation with only low-scoring adolescents heightening risk under peer observation, similar to previous correlational analyses (e.g., Chein et al., 2011; Peake et al., 2013). Altogether, predictions of risky choice by individual differences in socioemotional functioning depicted that such differences exist rather independent from developmental differences but are differentially associated with risk-taking dependant on characteristics of the risk situation. In line with the Lifespan Wisdom Model (Romer et al., 2017) the findings of the dissertation suggest that there might exist adaptive, i.e. risk exploration, sensation-seeking, and approach behavior, as well as maladaptive forms in individual behavioral tendencies in risk situations, i.e. impulsivity and drive for immediate rewards, that moderate developmental trajectories across adolescence.

IV Strengths, Limitations, and Outlook

First, the empirical studies of the dissertation were based on cross-sectional data including a broad age range from pre to late adolescence (aged 9-18 years) and incorporating several risky decision-making tasks with various characteristics of the task context, such as description- versus experience-based risk probabilities, outcome types, and social influence. In contrast, many previous studies inferred about development in risky choice in adolescence mostly based on one adolescent sub-group and an adult sub-group and one distinct task context. Beneath the advantage of studying the development of risky decision-making also in younger ages, the studies of the dissertation would have benefited from including a more mature sample, as most developmental models posited nonlinear age trends across late adolescence. However, as the study was conceptualized as a longitudinal study, future investigations will be likely able to depict such age trends whereas the studies of the dissertation will have had built a base for even more profound hypotheses on the longitudinal change in risky decision-making.

Secondly and related to the first caveat, the studies made predictions about developmental differences based on the age of the adolescents, while development in risky decision-making during adolescence is likely bound to the individual pubertal stage (see Laube & van den Bos, 2016, for a review). However, trajectories of age and pubertal development, are highly intervened given multicollinearity. Thereby, most studies in the developmental literature are about age differences making it still difficult to compare the own findings to others when only including the pubertal stage. Nonetheless, especially the longitudinal data will be suited to infer about differential influences of change in age and pubertal stage on risky decision-making.

Following this, there is increasing interest in understanding how developmental trajectories in risk behavior differ between males and females based on their diverse biological maturation and pubertal onset (for a review, see Laube & van den Bos, 2016). The dissertation did report gender differences in risky decision-making and for example, investigated the role of gender in the adjustment of risky choices to social influence, while most previous studies about adolescent risky decision-making did not (Defoe et al., 2015). However, the dissertation mostly did not consider divergent developmental trajectories between gender. Future studies should further overcome this gap in the literature, especially as adolescence has been thought to be a period in which gender differences in behavior are most prevalent to then decline with age (Byrnes et al., 1999), or puberty, respectively.

Third, though the dissertation is to our knowledge the first to investigate four task contexts that are well-established in the adolescent literature simultaneously in a sample of a broad age range from pre to late adolescence, the diverse settings were also not completely comparable based on distinct characteristics. The comparisons made, e.g., gain versus loss domain and described- versus experiences risk probabilities, are some of the most prevailing influences on risky decision-making. Thus, the experience-based measures used in this study, for example, differed from one another in further characteristics, such as static versus dynamic risk probabilities, and monetary gains versus time loss, that might have further contributed to the variance in developmental trajectories and susceptibility to individual differences between contexts. Future studies should investigate different types of arousing contexts with further variation in incentive type and magnitude and the processes that underlie developmental differences in reaction to these, to infer the negative and positive consequences of, as well as maladaptive and adaptive tendencies in, adolescent motivated behavior.

Relating to the task contexts used in the dissertation, the game-like settings were designed to be more arousing and appealing than previous versions, also for younger ages, and have proven useful in creating differentially arousing task contexts to study reactions in choice behavior to these. However, the association between experimental and real-life risk propensities remains a matter of debate (e.g. Frey et al., 2017). Though most of the task contexts used have shown to be associated with, e.g., adolescent alcohol and cigarette consumption, theories on risk-taking suggest considering person-environment interactions to understand initiation and maintenance of risk behaviors. That is, the adolescents' peer and family environment but also differences in socioeconomic status and thus, previous risk experiences, are important influences on development in risk behavior. Though the dissertation did not relate to associations with real-life risk behaviors, experimental task contexts allowed to infer about choice behavior in situations that are new for all individuals, irrespective of their life experiences. It is therefore that experimental risk-taking is still suitable to investigate the basal processes that underly risky choices in adolescence and specifically, developmental differences in these.

Finally, neuroscience studies and, in general, studies on risky decision-making could be thoroughly improved when they would be used with better conceptualizations about what processes are relevant in adolescent decision-making (van Duijvenvoorde et al., 2016). There is an increasing number of research groups that highlight the benefit of incorporating formal models into studies on adolescent decision-making. Such analyses can be combined with neuroscientific measures and specifically, ERP's to detect neural signals associated with specific mechanisms (van Duijvenvoorde et al., 2016). Though the dissertation gave insights into the development of important formal processes in adolescent risky decision-making, there are even more contextual influences to focus on (van Duijvenvoorde, Blankenstein, et al., 2016), specifically, concerning social influences (Ciranka & van den Bos, 2019) and sophisticated methods to model them (e,g. Bolenz, Reiter, & Eppinger, 2017).

V Conclusion

Despite the intuitive account of dual-systems and imbalance models and the valuable insights that derived from hypothesis drawn based on these assumptions, the current dissertation but also recent developments in the adolescent literature concludes that neurodevelopmental models might not be sufficient to explain the complex changes and interactions in a multitude of behaviors during adolescence (e.g., Pfeifer & Allen, 2012, 2016; Strang et al., 2013; van den Bos & Eppinger, 2016; Van Duijvenvoorde et al., 2016).

Concerning the suggested peak in motivated behavior during adolescence, not all of the relatively few adolescent-specific brain activity patterns in reaction to incentives were aligned with actual effects in task behavior. The focus on neurodevelopmental models in explaining adolescent behavior even implied some caveats. As a consequence, most studies in the adolescent literature relied on investigating the effects of positive incentives in terms of testing reward-sensitivity in youth. As such, it is not sufficient to just combine brain imaging with behavior without specific knowledge about what it is that drives adolescent-specific tendencies for sensation-seeking and risk-taking (van Duijvenvoorde et al., 2016). The dissertation applied this idea by not only asking whether there are adolescent-specific effects in incentive processing, motivated behavior, and risky decision-making but by also inferring about when adolescents engage in risky choices, what are the characteristics that lead them to adaptive and maladaptive decisions and who is willing to take the risks.

With its approach, the thesis contributes to the view that adolescents are not ever imprudent in their behavior. That is, adolescents do not show hypersensitivity to all rewards but are in favor to explore salient situations that promote high or seldom outcomes or leave the adolescent in uncertainty about them and associated risks. Applied to risky situations in real life that sometimes share these characteristics, one would indeed suggest adolescents being imprudent and reckless in risk situations. However, pre to late adolescents showed to be adaptive in exploring risks, integrated contextual information when available, learned about both positive and negative outcomes, and showed increased efficiency in evaluating risks against outcomes with age. Even under social influences, most adolescents were not triggered to heighten risky choices. As such, researchers increasingly highlight the adaptive changes that occur in adolescence (e.g., McCormick & Telzer, 2017a; Telzer, 2016) and the resulting window of opportunity in contrast to the view of adolescence being a period of ‘storm and stress’, and even did so some years ago (Crone & Dahl, 2012).

Generally speaking, the findings on age differences in adolescent risky decision-making of this dissertation are in line with more recent developmental perspectives that distinguish between different facets of risk-taking behavior (Romer et al., 2017; Shulman et al., 2016). The dissertation could show that pre to late adolescents indeed peak or at least increase in their tendencies to explore unknown risks. Sensation-seeking tendencies, and individual differences therein, like venturesomeness in this study, as well as a heightened approach to rewards in previous studies (e.g., Blankenstein et al., 2018), increased risk but also outcomes. Therefore, exploration tendencies in adolescence might be an adaptive form of risk and reward sensitivity that is not characterized by an absence of cognitive control. In turn, impulsive choices under risk decreased during adolescence in the dissertation, as well as in an extensive meta-analysis about risky decision-making in adolescence (Defoe et al., 2015), highlighting increased engagement in deliberative decision-making. However, reduced control but heightened socioemotional arousability might result in acting without thinking in a sub-group of adolescents (Khurana et al., 2018; Romer et al., 2017; Yoneda et al., 2019), i.e. with a low resistance to peer influence, high impulsivity, and empathy in the thesis, that indeed might be gamblers at any chance but even before and likely after the adolescent period. Eventually, future studies will shed light on the inter- and intraindividual changes in the depicted divergent behavioral approaches to risk and rationality across adolescence.

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