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Computational Mechanisms of Social Influence During Adolescence

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Für Papa †

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Abstract

Adolescents are known for their propensity to take risks. They binge-drink (Spear, 2018), use drugs (Defoe et al., 2019), drive risky (Romer et al., 2014) and get into trouble with the law (Viner et al., 2011) more often than people in other developmental stages (Steinberg, 2018). However, a recent meta-analysis on adolescent risk-taking behaviour in controlled laboratory settings showed no evidence of an adolescent risk-taking peak (Defoe et al., 2015). Past research identified two major reasons for the discrepancy between adolescents' real-life and laboratory risk-taking. First, adolescents are especially attentive to social signals (Blakemore & Mills 2014), and most adolescent risk-taking behaviour in real-life occurs in some kind of social context. Second, adolescents seem to be less inhibited by uncertainty than people in other developmental stages (Tymula et al., 2012; van den Bos & Hertwig, 2017). The risks that adolescents take in real-life are subject to much greater uncertainties than those portrayed in many laboratory experiments. In my dissertation, I investigate how adolescents' sensitivity to social signals and their uncertainties contribute to their propensity to take risks. Chapter 1 gives a broader literature overview that ends in pointing out how understanding the intersection between social susceptibility and uncertainty is crucial to understanding adolescent risk-taking. Chapter 2 points out that the developmental processes underlying adolescents' social sensitivity remain poorly understood, despite extensive research and theorisation. I emphasise that while many theories assume different mechanisms behind adolescent social susceptibility, they are all consistent with a broad range of evidence from laboratory experiments. I thus propose a formal framework depicting these theories in mathematical equations that make precise predictions that can be evaluated against one another and show that doing so synthesises seemingly disparate results. Chapter 3 introduces a novel experimental paradigm that allows to manipulate uncertainties and proposes a model that understands social influence as a learning process wherein social information is more impactful when people are more uncertain. This chapter shows that developmental differences in peoples' uncertainties can partially explain developmental differences in social impact during risk-taking. Chapter 4 shows how social norms contribute to real-life risk-taking in the general population and provide evidence that adolescents overestimate the normative character of many risky behaviours. Chapter 5 points out that people in different developmental stages live in different environments that expose them to different risks. Using agent-based modelling, I show that an adolescent-peak in risky behaviour can, in combination with a tendency for exploration, be emergent form transitioning from a relatively safe childhood into a risky adult environment. Chapter 6 provides a summary and conclusion of the preceding chapters and points to future research questions that my dissertation opens up.

Zusammenfassung

Jugendliche sind bekannt für ihre Neigung Risiken einzugehen. Sie trinken zu viel Alkohol, konsumieren illegale Drogen, fahren oft zu schnell und geraten generell öfter in Konflikt mit dem Gesetz als Menschen in anderen entwicklungspsychologischen Stadien. Eine jüngste Metaanalytische Studie weist jedoch darauf hin, dass Jugendliche unter kontrollierten Laborbedingungen in ihrer Risikobereitschaft nicht herausstechen. Die Wissenschaft hat zwei Gründe für das Auseinanderklaffen jugendlicher Risikobereitschaft im Labor im Vergleich zur echten Welt identifiziert. Erstens, Jugendliche legen einen großen Wert auf soziale Signale und ein Großteil der Risiken, welche Jugendliche im echten Leben eingehen, steht im Zusammenhang mit sozialen Faktoren. Zweitens, Jugendliche lassen sich weniger von Ungewissheiten abschrecken als Menschen in anderen Entwicklungsstadien, aber Risiken die in Laborbedingungen simuliert werden, sind sehr viel weniger Ungewiss als die Risiken des echten Lebens. In meiner Dissertation untersuche ich daher, wie jugendliches Risikoverhalten von sozialer Information und Ungewissheit beeinflusst wird. Kapitel 1 gibt einen Überblick über die aktuelle Literatur und arbeitet heraus, warum es im Hinblick auf das Risikoverhalten Jugendlicher notwendig ist, auch die Schnittmenge zwischen sozialem Einfluss und Ungewissheit besser zu verstehen. Kapitel 2 hebt hervor, dass die entwicklungspsychologischen Prozesse welche dazu führen, dass Jugendliche größeres Risikoverhalten im sozialen Kontext zeigen trotz Fortschrittes in der Theoriebildung bislang nicht gut verstanden sind. Ich zeige im Kapitel, dass unterschiedliche Theorien zwar verschiedene Gründe für die soziale Anfälligkeit Jugendlicher benennen, empirische Forschungsergebnisse jedoch in der Regel mit mehreren Theorien konsistent sind. Daher erarbeite ich im Kapitel in ein mathematisches Rahmenwerk, worin verschiedene Theorien präzise, aber unterscheidbare, Vorhersagen machen die nun miteinander verglichen werden können. Ich zeige wie ein solches Verfahren das Potential hat, scheinbar widersprüchliche Ergebnisse zusammenzuführen. Kapitel 3 stellt ein neues Paradigma welches es möglich macht Ungewissheiten und soziale Information experimentell zu manipulieren, und ein mathematisches Modell worin sozialer Einfluss von individuellen Ungewissheiten abhängig ist, vor. Der empirische Teil dieses Kapitels zeigt, dass entwicklungspsychologische Unterschiede beim Nutzen sozialer Informationen auf entwicklungspsychologische Unterschiede in der subjektiven Erfahrung von Ungewissheit zurückzuführen sind. Kapitel 4 zeigt, dass soziale Normen einen großen Einfluss auf Risikoverhalten haben und liefert Hinweise darauf, dass Jugendliche den normativen Charakter einiger Risiken überschätzen. Kapitel 5 weist darauf hin, dass sich Menschen in verschiedenen Entwicklungsstadien in unterschiedlichen Umwelten bewegen, in welchen sie unterschiedlichen Risiken ausgesetzt sind. Mit Agenten-basierter Modellierung zeige ich, dass ein Anstieg im Risikoverhalten aus einer Kombination zwischen explorativem Verhalten und dem Übergang von der relativ risikoarmen Umgebung der Kindheit zu der risikoreicheren Umgebung des Erwachsenenalters entstehen kann. Kapitel 6 fasst die Studien der vorherigen Kapitel kritisch zusammen und zeigt auf, wo meine Dissertation Anhaltspunkte für zukünftige Forschungsvorhaben gibt.

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Introduction

"How I admire your arrogance and rage and misery. How pure and righteous they are and how passionately storm-drenched was your adolescence. How filled with true feeling, fury, despair, joy, anxiety, shame, pride and above all, supremely above all, how overpowered it was by love. My eyes fill with tears just to think of you. Of me. I am perhaps happier now than I have ever been and yet I cannot but recognise that I would trade all that I am to be you, the eternally unhappy, nervous, wild, wondering and despairing 16-year-old Stephen: angry, angst-ridden and awkward but alive. Because you know how to feel, and knowing how to feel is more important than how you feel. Deadness of soul is the only unpardonable crime, and if there is one thing happiness can do it is mask deadness of soul."

– Stephen Fry's letter to himself: Dearest absurd child (2009)1.

On their way to adulthood, humans are on a quest to become independent and competent decision-makers, but their path is not an easy one. Despite the fact that adolescents are physically amongst the healthiest individuals in most societies (Barch et al., 2017), mortality, which steadily declines throughout the childhood period, is on the rise again between the age of 12 until people are in their mid-twenties, in both western and non-western cultures (Viner et al., 2011). Criminal records mirror the rising trend in mortality and show that especially male adolescents (Moffitt, 2018) break the law more often than children and older adults (Shulman et al., 2013). But there is another, more uplifting, side to adolescent behaviour. Through the course of their lives, people will never again be as eager to gain novel experiences as they were in their adolescence. As a consequence of their drive to seek novelty (Romer & Hennessy, 2007), adolescents have brought unparalleled achievements to society, be it by inventing new music genres or art forms, founding software companies, speaking up against injustice or starting a political movement. Thus, there is, without a doubt, something remarkable about adolescents in our society. However, up until the twentieth century, there was an active debate about whether adolescence even exists as a unique developmental period. The question asked by many scholars was whether adolescence constitutes a biological peculiarity that has a clear "before" and a clear "after"? The answer is yes, and no.

[1] https://www.theguardian.com/media/2009/apr/30/stephen-fry-letter-gay-rights

On the one hand Aristotle and Shakespeare (Blakemore & Robbins, 2012) already famously remarked upon the recklessness of their teenage contemporaries and Victorian writers lamented that *"[...] it must be confessed that an irreverent, unruly spirit has come to be prevalent, an outrageous evil among the young people [...]"* (Burton, 1863). On the other hand a unifying concept of "adolescence" as a distinct developmental period between child and adulthood, only became prominent after Stanley Halls' pioneering work “Über den Begriff der Jugend” in the early 20th century (Hall, 1904), was still subject of active debate in the 1960ies (Demos & Demos, 1969) and continues to have a loose end today. That is, most researchers might consent to a clear “before": adolescence starts with the hormonal changes that begin with puberty. However, there is no clear "after". Adolescence is over when people have found and taken on an adult role in society (Blakemore, 2019; Monahan et al., 2009; Somerville, 2013), but there is no strict definition as to what it means to be an adult. In other words, while the beginning of adolescence can precisely be defined biologically, its' end is uncertain and defined by culture.

The beginning of adolescence: hormonal and neural development

Puberty, and therefore adolescence begins with changes in the brain which start to occur when children are asleep (Crone & Dahl, 2012). At some point in ontogeny, on average when children are between 9 and 10 years old (van Duijvenvoorde & Crone, 2013), the brain region responsible for hormonal regulation, the hypothalamus, begins to secret the Gonadotropin-releasing hormone (GnRH) in a pulsatile fashion. GnRH sets in motion the bodies homeostatic control system for sex hormones, the hypothalamic-pituitary-gonadal (HPG) axis, which has been silent since shortly after birth. As the HPG axis re-awakens, the pituitary gland releases the follicle-stimulating hormone (FSH) and the luteinizing hormone (LH) which in turn stimulate the ovaries or testis to produce oestrogen and testosterone. The latter set in motion the maturation of the secondary sex organs. At roughly the same time, the pituitary gland releases the growth hormone (GH), which causes physical growth in young people to take-off. These pronounced hormonal changes of puberty are correlated with many neurodevelopmental changes, affecting single nerve cells, neurotransmitter levels and synapses, brain structure, brain function and the connectivity between different brain areas (Dahl et al., 2018; Davidow et al., 2016; Mills, Lalonde, et al., 2014; Pfeifer et al., 2011; Telzer, 2016; van den Bos et al., 2015).

There are several heuristic models about how these vast neurodevelopmental changes act together and impact adolescent behaviour. One important "dual systems" approach rests on the finding that around the onset of puberty, those brain-regions responsible for processing rewards, like the nucleus accumbens and striatum (Telzer, 2016; Telzer et al., 2020), are almost mature (Shulman et al., 2016). The part of the brain important for deliberate cognition and impulse control, however lags behind. More precisely, the prefrontal cortex (PFC), a brain region known to be involved in logical reasoning

(Dumontheil, 2014), inhibition (Ernst et al., 2005) and cognitive control (Koechlin et al., 2003) matures well into young adulthood (Casey et al., 2008; Casey et al., 2011; Hartley & Somerville, 2015). Because of the imbalance between mature reward processing and immature cognitive control, some theorize that adolescents are left with a situation that can be compared with having to drive a car that has "all gas, but no breaks" (Payne, 2012) – adolescents may feel and pursue rewards without the decelerating intervention of their PFC (Albert & Steinberg, 2011). As a consequence of this maturational imbalance, adolescents may be especially motivated to take a risk.

Another well-known model focusses on adolescents' developing "social brain" (Blakemore, 2008; Lockwood et al., 2020). Brain regions like the temporal poles, involved in social emotions such as feeling rejected by or superior to others (Olson et al., 2007), are still maturing during adolescence (Mills, Goddings, et al., 2014). Moreover, the temporal-parietal junction as well as the medial prefrontal cortex (Blakemore, 2008) crucially involved in perspective-taking (Singer & Tusche, 2014) also undergo pronounced changes across adolescence (Burnett et al., 2011; Mills, Lalonde, et al., 2014; van den Bos et al., 2011). These changes in orchestration presumably help adolescents to better navigate the increasingly complex social world they find themselves in (Blakemore & Mills, 2014).

In sum, adolescents' brains are "unfinished" and brain regions responsible for reward (Shulman et al., 2016) and sociocultural (Blakemore & Mills, 2014) processing undergo the most prominent changes across adolescence. These maturational changes in reward and social processing brain areas seem correlated with an increased propensity to take risks and increased attention to social surroundings during adolescence.

Risk-taking during adolescence

Their imbalance between reward processing and cognitive control presumably leads adolescents to take risks that can have detrimental consequences for them. For example, in West-Berlin between 1989 and 1995, 41 teenagers were involved in severe accidents, 18 of which fatal, as the consequence of "train surfing". Here, young people climb on the roof of a driving train and try to remain there as long as they can (Strauch et al., 1998) in order to get some "kick" or approval by their peers. Other risky decisions adolescents take may not carry immediate risks of injury or death but still have the potential to stick with them for a long time, sometimes even for the rest of their lives. For instance, adolescents are known to experiment with alcohol (Centers for Disease Control and Prevention (CDC), 2012) and other drugs (Defoe, Khurana, et al., 2019), which has severe long-term effects on the brain and behaviour of individuals (Crone & Dahl, 2012; Spear, 2018). Moreover drug and alcohol use during adolescence is related to mental illness in adulthood such as addiction (Hansen & Graham, 1991), but also depression and anxiety disorders (Hauser et al., 2018).

That adolescents take more risks than children and adults implies that the development of decision-making does not proceed from worse to better, as it was assumed in classic theories of human development (Bjorklund, 2018). Much rather, it suggests that decision-making undergoes a non-linear developmental trajectory with a marked increase in maladaptive risk-taking and impulsivity during adolescence. The result is a narrative about reckless and impulsive adolescents, which has long dominated the scientific debate (Demos & Demos, 1969; Gullone et al., 2000; Hall, 1904; Resnick et al., 1997; Steinberg et al., 2018; Wills et al., 1994). However, one issue with real-life data such as police or hospital records on which this narrative is based is that these records do not control for age-related differences in risk-exposure (Defoe, Semon Dubas, et al., 2019). Adolescents experience less supervision by their parents and are more independent than children (Baumrind, 1987). As a consequence, they have more opportunities to take risks (Romer et al., 2017). If we want to judge whether their higher propensity to take risks rests in the general nature or biology of adolescence, the question that should be asked is whether adolescents would take more risks than children and adults if everybody had the same risk-taking opportunities (Willoughby et al., 2013). Exposing children, adolescents and adults to the same boundary conditions can be achieved in laboratory experiments.

In the laboratory, risk-taking is often defined as making a decision for which the outcome is uncertain and negative consequences could occur (Hertwig et al., 2019; Rosenbaum et al., 2018; Rosenbaum & Hartley, 2019; van Duijvenvoorde & Crone, 2013). Experiments using this minimal definition often require choosing between different options where some options' outcomes have a higher variance than others. High variance outcomes are more uncertain and will be harder to predict (Bach & Dolan, 2012), therefore choosing high over low variance is an index of risk-taking (Chung et al., 2015; Frey et al., 2017; Hertwig et al., 2019; Niv et al., 2012). A recent meta-analysis on the development of risk-taking in laboratory experiments revealed that while adolescents take more risks than adults, younger children take even more risks than adolescents (Defoe et al., 2014; Defoe, Semon Dubas, et al., 2019), which is in contrast to earlier conceptions of adolescents as exceptional risk-takers.

It was also argued that adolescents' risk-taking is more related to their propensity to act without thinking, in other words their impulsivity (Casey et al., 2008; Khurana et al., 2018; Rivers et al., 2008; Rosenbaum & Hartley, 2019; van den Bos et al., 2015). Experimental paradigms investigating impulsivity are often in the tradition of the famous marshmallow experiment (Mischel et al., 2011). In the marshmallow experiment, children were presented with a small reward, one marshmallow, which they could obtain right away but if they can resist the temptation, control their impulse and wait for some time, they would get two marshmallows instead. Studies using age-appropriate rewards like money find that as they progress through adolescence, individuals steadily become better at controlling their impulses (Laube et al., 2017; Laube & van den Bos, 2016; Rosenbaum & Hartley, 2019; van den Bos et al., 2015). Again, it seems as if adolescence is not marked with a sudden, hormone driven increase in irrational behaviour (Laube et al., 2017).

In sum, actuarial data suggests in line with dual systems-models of adolescent brain development (Shulman et al., 2016), that adolescents are exceptional risk-takers (Steinberg et al., 2018). However, there is compelling evidence from laboratory studies that risk-taking and impulsivity decreases linearly across adolescence (Defoe et al., 2015). Therefore, other factors which are hard to isolate experimentally may mediate adolescents' propensity to take risks in the real world.

Uncertainty and adolescent risk-taking

How uncertainty impacts human decision-making has received a lot of attention in the literature, dating back to the observations made by Daniel Bernoulli in 1713. Because most people were not willing to pay a fee that was lower than the expected return of a bet on a long sequence of heads in sequence of coin flips, Bernoulli concluded that people are risk-averse when there is uncertainty about whether a beneficial outcome will occur (Bernoulli, 1954). For the first time in their lives, adolescents learn to make most decisions without their care-takers guidance (Blakemore, 2019), leaving them with considerable uncertainty about whether taking a risk will be worth it or not. Therefore understanding adolescent risk-taking benefits from understanding how adolescents approach uncertainty (Somerville et al. 2017; van Duijvenvoorde & Crone, 2013; van den Bos et al., 2019). Unfortunately, the uncertainties that adolescents face in their everyday lives are much more substantial than the uncertainties that experiments in Bernoulli's tradition can portray.

Risks that adolescents take, like binge drinking at a party or daring to ask a crush for a first date, comprise a broad range of possible outcomes and the range of outcomes is hard to imagine and their probabilities are usually unknown (Rosenbaum & Hartley, 2019; Hertwig et al., 2004; Hertwig & Erev, 2009). Because of these unknowns in real-life, people often base their risky decisions on a gut-feeling (Mousavi & Gigerenzer, 2014). Such gut feelings however are built on experiences that adolescents are often yet to make (Hartley & Somerville, 2015; Rivers et al., 2008) and adolescents learn differently from experience than adults (Davidow et al. 2018; Hartley & Somerville, 2015; Jepma et al. 2020; van den Bos et al., 2012). Therefore, experience-based experiments involving substantial uncertainties might provide better insights into adolescents' propensity to take risks in the real world (van den Bos & Hertwig, 2017). Evidence from experimental research suggests that when outcome probabilities are uncertain, adolescents are particularly optimistic (Tymula et al., 2012). In another experiment, subjects have been left uncertain about outcomes of different monetary lotteries but were given the chance to reduce their uncertainties by sampling the outcomes before committing to a decision. Here, adolescents were satisfied with far less information than younger or older participants before making a consequential choice. In other words, adolescents tolerated uncertainty more than other age-groups (van den Bos & Hertwig, 2017). The Iowa-gambling-task (Bechara et al., 2005) is another experiment that is used to study how adolescents make decisions under uncertainty. In the Iowa-gambling-task, subjects win money by drawing cards from one of four different card decks. Each deck holds cards that will either reward or penalize them. Some decks are "risky decks", and other decks are "safe decks", because some decks will tend to reward the player more predictably than other decks. When adolescents play the Iowa-gambling-task, they more often choose risky decks than adults (Cassotti et al., 2014). Adolescents also take more risks than adults in the Ballon-analogue-risk-taking task (Lejuez, 2003) which requires them to pump up a virtual ball to get additional rewards with every pump but without overshooting a threshold, which is unknown to them and after which a massive loss is incurred (Braams et al., 2015).

In sum, laboratory evidence suggests that risk-taking peaks during adolescence when paradigms involve uncertainty and people have to decide on the ground of experience-based beliefs.

Social cognition and behaviour during adolescence.

As humans enter their adolescence, their social environment and goals change drastically (Blakemore & Mills, 2014; Crone & Dahl, 2012; Telzer et al., 2018; Worthman & Trang, 2018). Adolescents transition into new schools, begin to identify more with their peers than with their parents and become interested in forming romantic relationships. Therefore, adolescence is often thought of as the developmental period of social re-orientation (Nelson et al., 2016). How others evaluate them becomes very important for adolescents and as a consequence they become obsessed with what others may think about them (Elkind, 1967) and react with stronger emotions when they feel rejected, than people in other developmental stages (Will et al., 2016). For example, researchers asked adolescents to play a virtual ball tossing game called cyberball (Will et al., 2016). During cyberball, three players pass a ball between each other but after some time others stop passing the ball to adolescent participants. Adolescents' resulting negative affect is stronger than the negative affect of children or adults experiencing the same exclusion (Crone & Konijn, 2018). Another study, mimicking today's social media platforms, measured how adolescents reacted when others rated their profile pictures. Adolescents differed from children and adults in two ways. First, when asked which ratings they would expect, adolescents generally anticipated to receive worse ratings. Second, when adolescents received a lousy rating, their emotional reaction, like in the cyberball experiments, was more severe than the reaction of younger or older individuals (Guyer et al., 2009). In general it seems as if when they think they are being watched, adolescents become more nervous than adults or children - neural markers of arousal rise when adolescents feel observed (Breiner et al., 2018; Somerville et al., 2013). This suggests that adolescents' social cognition differs from that of people in other developmental stages. In line with this notion, adolescents also process very basic social stimuli, like pictures of faces differently from children or adults, as shown by increased neural responses in brain areas specialized for face processing (Scherf et al., 2012).

Adolescents' pronounced social attention has direct effects on their decision-making capacities, as evidenced by a study using a social response inhibition task (Lee et al., 2018). In this task, subjects were asked to press a button when they saw a neutral face, and not to press the button when they saw a smiling face, which occurred very rarely. Here, adolescents failed to inhibit pressing the button in response to a happy face and performed worse than children or adults. The same subjects also performed a control task where non-social stimuli were used. In the control task, children most often pressed the button when they should not have. Adults made least mistakes and adolescents were in the middle. Thus, evidence suggests that adolescents indeed react to social information differently as compared to people in other developmental stages. Because of their apparent self-control failures in social contexts (Botdorf et al., 2017), it was proposed that their peculiar social cognition directly relates to the alleged adolescent peak in risk-taking and impulsive behaviours (Albert et al., 2013; Blakemore, 2008; Shulman et al., 2016).

If adolescents pay more attention to social signals than people in other developmental stages and if it is also more important for them to be liked, then their behaviour is likely strongly motivated by social information (Blakemore & Mills, 2014). As a result it should not be too surprising that, adolescents taste in music (Berns et al., 2010), sport (Lubans et al., 2011), fashion (Chittenden, 2010) and even attitudes towards academic achievement (Yeager et al., 2018) are strongly correlated with that of their friends. Understanding how important social information is to adolescents, adds another crucial dimension to the understanding of adolescents' propensity to take risks (Albert et al., 2013; Blakemore & Robbins, 2012; Steinberg, 2008). Most risky behaviours during adolescence are connected to a social context (Albert et al., 2013). This is true for complex risk-taking behaviours in real life such as drug-use (Clark & Lohéac, 2007; Defoe, Khurana, et al., 2019; Spear, 2000), petty crime (Moffitt, 2018) or risky driving (Romer et al., 2014). But also in the laboratory, adolescents are more likely to risk a crash in driving simulations (Albert et al., 2013), when they are with others. Adolescents' risk-taking even seems elevated by a social context in comparatively simple experiments requiring decisions between monetary lotteries (Smith et al., 2014). After receiving advice about which lotteries to choose, adolescents change their behaviour more than adults or children (Engelmann et al., 2012), the same is true for advice from their peers (Braams et al., 2019). Moreover a recent study found that simply asking adolescents to take the perspective of others, has a pronounced impact on the risky decisions adolescents, but not adults, make for themselves (Reiter et al., 2019).

Taken together, there is an almost unanimous consensus in the literature that adolescents indeed process and respond to social information differently than members of other age groups.

Uncertainty and social influence

That people use social information to a greater extent when they are more uncertain of what to do is one of the central assumptions in cultural evolutionary theory (Hills et al., 2015; Molleman et al., 2014; Morgan & Laland, 2012). And indeed, plenty experiments show that the more uncertain humans or other animals are about the state of the world, the more likely they are to copy others' behaviour (Coskun et al., 2020; FeldmanHall & Shenhav, 2019; Melamed et al., 2019; Moutoussis et al., 2016; Toelch et al., 2013; Toyokawa et al., 2019; Tump et al., 2020). While copying others when one feels uncertain is an efficient heuristic that saves limited cognitive resources (Chase et al., 1998; Gigerenzer & Gaissmaier, 2011; Morgan et al., 2015) there is evidence that social influence under uncertainty follows more sophisticated principles (De Martino et al., 2017; Diaconescu et al., 2014; Toelch et al., 2013, 2014; Toyokawa et al., 2019). For instance, when buying products online, others' product recommendations become more impactful when people are more uncertain about whether to buy or not (De Martino et al., 2017), suggesting a form of Bayesian learning. The same Bayesian principle applies for simple decisions. When people have to judge the orientation of abstract visual stimuli (Bahrami et al., 2010), or when complying to the judgments of a majority (Toelch & Dolan, 2015; Asch, 1955), social information becomes more impactful when people experience more uncertainty.

From the point of view of uncertainty, adolescents' propensity to be especially attentive to social information could serve two purposes. First, using social information can prevent costly trial and error learning (Molleman et al., 2014) and especially when adolescents are uncertain about whether to take a risk or not, relying on social information is an efficient strategy (FeldmanHall et al., 2017). Second, social information helps to learn about culture. The developmental milestone of adolescence is defined by a culture that adolescents are uncertain of and have to learn about: adolescents need to take adult roles in society. Thus, adolescents' neural and cognitive development and social attention might help them to make good decisions and eventually navigate the uncertain adult social world (Dahl et al., 2018; van den Bos et al., 2019; Worthman & Trang, 2018).

At this point a surprising gap in the literature becomes evident. It is known that adolescents take more risks than adults when confronted with real worlds' uncertainties. Uncertainty is likely a mechanism behind adolescents' propensity to take risks. It is further known that adolescents' risk-taking occurs mostly in social situations and social signals are incredibly important to adolescents. In adults, feelings of uncertainty contribute strongly to their social susceptibility. However, how adolescents leverage social information when they are uncertain whether to take a risk or not is not known. The remainder of this dissertation is concerned with filling this gap.

This dissertation: Uncertainty, social information and adolescence

In my dissertation I investigate how adolescents take risks and use social information under different degrees of uncertainty. Each of the following chapters approaches this topic from a different angle and methodology and is prepared for publication or is published in a scientific journal.

In chapter 2, I first review different theories on adolescent risk-taking and social susceptibility. I then point out that current theories are unspecific. Research on adolescent risk-taking is stuck in a stage where most evidence is consistent with most theories that have been formulated about adolescent risk-taking; severely hampering our understanding of the latter. I therefore put forth a formal approach that helps to differentiate these theoretical standpoints. I use model comparison on two previously published decision-making studies to negotiate between those theories. This procedure synthesized the original studies' disparate conclusions about the nature of social influence in adolescence.

In chapter 3, I establish that social influence depends on individually experienced uncertainties by formulating a Bayesian updating model of social influence in combination with a newly developed experimental paradigm wherein uncertainty can be manipulated. The modelling approach also enabled me to show that developmental differences in social information use could be fully explained with developmental changes in uncertainty. This chapter therefore provides a novel angle by which adolescent risk-taking should be understood.

In chapter 4, I investigate adolescent social susceptibility by taking the perspective offered by research on social norms. I took a classic psychometric approach but combined it with modern Bayesian analysis to show that adolescents may not be more susceptible to social norms than members of other age groups. However, I also point to that adolescents may perceive social norms to be more risk-liberal, which adds another dimension to the understanding of adolescent social susceptibility.

In chapter 5, I advocate that adolescent risk-taking may partly be re-cast from doing something harmful towards a goal directed act of exploration and show how this angle accounts for adolescents increased social susceptibility. I present an agent-based learning model as a metaphor for development that is motivated by recent directions in machine learning. I emphasise that if we want to understand adolescents risk-taking, we need to understand the environment they are confronted with. Doing so, leads to the realization that the adolescent environment and their developmental goals are very different from the environment and goals encountered by children or adults. Using agent-based simulations I show that risk-taking is inevitable and social susceptibility beneficial when a developing, learning agent explores novelty in an uncertain and sometimes hazardous environment.

In chapter 6, I jointly discuss the results of the previous chapters and point to the main empirical and theoretical contributions of my dissertation.

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2

Social Influence in Adolescent Decision-Making: A Formal Framework

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Abstract

Adolescence is a period of life during which peers play a pivotal role in decision-making. The narrative of social influence during adolescence often revolves around risky and maladaptive decisions, like driving under the influence, and using illegal substances (Steinberg, 2005). However, research has also shown that social influence can lead to increased prosocial behaviours (Van Hoorn et al., 2017) and a reduction in risk-taking (Braams et al., 2019). While many studies support the notion that adolescents are more sensitive to peer influence than children or adults, the developmental processes that underlie this sensitivity remain poorly understood. We argue that one important reason for this lack of understanding is the absence of precisely formulated models. To make a first step toward formal models of social influence during adolescence, we first identify three prominent verbal models of social influence in the literature: (1) social motivation, (2) reward sensitivity, and (3) distraction. We then illustrate how these can be translated into formal models, and how such formal models can inform experimental design and help identify developmental processes. Finally, by applying our formal models to existing datasets, we demonstrate the usefulness of formalization by synthesizing different studies with seemingly disparate results. We conclude with a discussion on how formal modelling can be utilized to better investigate the development of peer influence in adolescence.

Introduction

Peers impact almost all aspects of adolescent lives, from the more trivial, such as taste in music and clothing, to the more serious, such as the use of illicit drugs or engaging in unprotected sex (Steinberg, 2008). These latter, riskier, choices may carry life-long consequences for the adolescent and bring significant cost to society. It is empirically well established that the presence of peers influences risky behaviour in adolescence (Gardner and Steinberg, 2005; Chein et al., 2011; Pfeifer et al., 2011; Smith et al., 2014), but the underlying developmental processes remain poorly understood. Understanding these processes, however, is important for at least two reasons. First, empowering adolescents to become more competent decision-makers will be more effective if we succeed at tailoring interventions to their developmental affordances. Second, we can only identify these affordances if we succeed at linking adolescent neuronal and cognitive development with adolescent behaviour across different social contexts.

Here we argue that this link cannot be made without formal models of adolescent peer influence. In this article we thus aim to take the first steps toward a quantitative and testable framework of adolescent social influence. Adolescence is marked by several developmental changes which offer multiple biological explanations of social influence on adolescent decision making. We refer to the current theoretical perspectives of these changes as "verbal models." Verbal models are distinct from formal models in that they do not make quantitative predictions. In order to establish formal models that do make quantitative predictions, we first review existing verbal models and the associated empirical findings about social influence in adolescents, focusing on risky decision-making. We identify three verbal models of social influence which can be subject to developmental change; these are then formalized by grounding them in expected utility theory. Next, we show that our formal models can reliably be recovered and therefore can be used to compare hypotheses via quantitative model comparison. Finally, we fit these models to existing data and reveal previously overlooked patterns of peer influence. We conclude with a discussion on how the specificity provided by this formal approach contributes to a deeper understanding of the developmental processes behind social influence.

Social Influence on Adolescent Decision-Making

We identify three main families of verbal models in the existing literature, hereafter named as follows: (i) social motivation model, (ii) reward sensitivity model, and (iii) distraction model. These three models focus on two distinct neurodevelopmental explanations of altered decision-making during adolescence. Social motivation verbal models stress the importance of the developing "social brain." The other two verbal models (reward sensitivity and distraction) both emphasize the relatively slow maturation of cognitive control systems. Previous works that fall into the reward sensitivity family of verbal models often refer to it as "dual-systems" models, as they also stress the relatively fast maturation of reward-processing brain regions and explain adolescent behaviour with the maturational imbalance between reward processing and cognitive control brain regions (Casey et al., 2008; Steinberg, 2008; Geier et al., 2010; Shulman et al., 2016). By contrast, the distraction model has a single focus on the development of cognitive control. Our subsequent review of the existing experimental evidence shows that all three of these families of verbal models are currently equally well supported in the literature, even though each model provides a different explanation for similar observations.

Verbal Models: Social Motivation

The first verbal model we consider states that adolescents have increased social motivation. Demonstrating risky behaviour, or conforming to behaviour of the peer group, are considered ways to reach these social goals. In other words, social motivation models assume that during adolescence there are situations where a high social value is attributed to displaying risky behaviour (Crone and Dahl, 2012; Ruff and Fehr, 2014) which is independent from the non-social value of the outcome (e.g., money).

Verbal Models: Reward Sensitivity

The verbal reward sensitivity model is based on research which suggests that adolescence is the time where fast maturation of reward processing brain systems coincides with relatively slow maturation of cognitive control systems. According to the reward sensitivity model, the biological imbalance between these two systems gives rise to risky adolescent decision-making (Casey et al., 2008; Ernst et al., 2015; Shulman et al., 2016). Here we will not address the debate concerning the validity (Pfeifer and Allen, 2016) or the different variants of these models (Casey et al., 2008; Steinberg, 2008; Larsen and Luna, 2018). Instead, we focus on the element that is suggested to be most relevant for understanding developmental changes in peer influence: reward sensitivity. Reward sensitivity states that social influence has such dramatic effects on adolescent risk-taking because a social context "may sensitize the incentive processing system to respond to cues signalling the potential rewards of risky behaviour" (Chein et al., 2011, p. 2). Indeed, Chein et al. (2011) showed that while being observed during a risk-taking task, brain regions related to reward processing were more active in adolescents than in adults. This was interpreted as evidence for a reward sensitivity model as it suggests that, in adolescents, the social context itself leads to changes in the processing of rewards in general.

Verbal Models: Distraction

The relatively slow maturation of cognitive control brain regions forms the basis of a third verbal model that we call "distraction model." Here, maturational imbalance and arousal is not only specifically associated with altered representations of reward but more generally with poor self-control and diminishing cognitive skills in emotionally salient situations (Dumontheil, 2016). This lack of self-control can lead adolescents to show more erratic or distracted behaviours in a social as compared to a solitary context. The distraction model does not assume any changes in value computation, but rather suggests that behavioural changes are due to stochasticity in the decision process.

Social motivation, reward sensitivity and distraction models do not assume mutually exclusive processes. Although it is plausible that the defining processes emphasized in each of these models simultaneously impact peer influence, it is important to examine which are most relevant in a particular context.

This is essential because different models provide different footholds for interventions. For example: if adolescent risk-taking is subject to social motivation it can be fruitful to provide other, less risky, means to acquire social status for instance by using meaningful roles interventions (Ellis et al., 2016, see also: Yeager et al., 2018). Adolescent reward sensitivity suggests it is useful to prohibit teens from gathering in risky situations. For instance, many states in the United States and Canada prohibit teenage drivers from taking other teenage passengers along. Distraction suggests that training in mindfulness and meditation are a good prospect for increasing desirable behaviours in adolescence (Kuyken et al., 2013). These implications for interventions underscore how crucial it is to comprehend the most relevant determinants of adolescent behaviour in a given context. We therefore inspect experimental work which manipulated aspects of social contexts with respect to the three verbal models of adolescent social influence: (i) social motivation, (ii) reward sensitivity, and (iii) distraction.

Seeing and Being Seen – Empirical Studies of Social Influence

Despite the complexity of social exchange, studies investigating social influence can be roughly divided into two types of situations: those where the participant observes others and those where the participant is being observed. In the light of this distinction, we review experimental studies about peer influence in adolescent risky decision-making.

Observing Others

When uncertain of what to do, observing the behaviour of others can help with making a decision. Monetary lotteries are often used as an experimental setting with uncertain prospects, wherein the effect of observing the behaviour of others can be investigated. In such experiments, participants observe others' previous decisions (Blankenstein et al., 2016; Reiter et al., 2019) or receive explicit advice (Haddad et al., 2014) while making private decisions. These studies suggest that the impact of social information is greatest in early to mid-adolescence and then declines with age. Notably, in a recent study, adolescents were influenced more by safe than by risky advice (Braams et al., 2019). However, currently evidence seems most in line with models that emphasize social motivation, as an increase in safe decisions is not predicted by reward sensitivity models. A small increase of participant safe choices in studies such as Braams et al. (2019) however, could also be attributed to a greater distraction during adolescence. Notably, none of these studies provided adolescents with information about the outcomes of others' decisions. In real life, such outcomes are observable; there is evidence that observing others' risky real-world behaviours, such as smoking or drug use, increases the likelihood of adolescents to adopt these behaviours themselves (Clark and Lohéac, 2007; Liu et al., 2017). This can reasonably be explained using social motivation models, if adolescents anticipate peer approval. It can also be explained with reward sensitivity models when assuming that the rewarding properties of risky behaviours (smoking) themselves become subjectively more rewarding in this social context.

In sum, experimental results from paradigms in which participants observe the choices of others are sometimes more consistent with the social motivation model, and sometimes more consistent with reward sensitivity. Paradigms designed for testing distraction models when observing others are underrepresented, so their pertinence here cannot yet be sufficiently evaluated. As such, which verbal model family best accounts for adolescent behaviour when they observe others remains unclear.

Being Observed

When a decision maker is observed by another individual, risk-taking also sends a social signal to the observer (Baker and Maner, 2009). For instance, adolescents can show how "cool" they are by taking extreme risks, or signal that they are or want to be part of a group by mimicking its members' risk-taking behaviour. Thus, if adolescent behaviour in peer contexts is sending a social signal to their peers, their beliefs about the risk-norms of observing peers should impact their behaviour. In line with this, one study found that exposing teenagers to risk-accepting peers increased their risky driving while exposure to a risk-averse peers did not (Shepherd et al., 2011). Further, there is evidence that risk perception and understanding of social norms are important predictors of adolescent risky driving (Carter et al., 2014). Social motivation models can therefore explain increased risk-taking in paradigms when participants are being observed.

However, even without assuming complex social motivation, behaviour change in a social context was traditionally explained with social facilitation theory (Zajonc, 1965), which foreshadowed both reward sensitivity, and distraction models by one principled observation: Being observed induces arousal.

The reward sensitivity model suggests that arousal leads to altered reward processing, making risk-taking more appealing. Indeed, most developmental studies of how being observed impacts risk-taking report an increase in the number of risky choices made by adolescents in social contexts (Gardner and Steinberg, 2005; Chein et al., 2011; Smith et al., 2014; Somerville et al., 2018). In the context of social facilitation theory this increase in risk-taking can be seen either as facilitation, for example by increasing explorative behaviours and socially acceptable risk-taking, or impediment, when the risks are illegal and dangerous (Duell and Steinberg, 2019). In one remarkable neuroimaging study along these lines (Chein et al., 2011), found evidence for the reward sensitivity model. The presence of another person increased activity in the ventral striatum when adolescents received rewards, as compared to a solitary reward condition. This was true for adolescents but not for adults.

However, in another variant of social facilitation theory (Sanders et al., 1978), social arousal is thought to result in distraction from the task at hand, thus mostly resulting in detrimental or sub-optimal behaviour. In fact, there is evidence that arousal leads to decreased cognitive control, which results in more distracted behaviour in decision-making tasks (Starcke and Brand, 2012). There is also evidence that distraction accounts for typical adolescent behaviour in some experimental paradigms. For instance, Dumontheil et al. (2016) demonstrated reduced reasoning abilities in adolescents when monitored by peers. Similarly, another study found that adolescents who showed poor conflict monitoring in an emotionally arousing Stroop task also turned out to be risky drivers in a driving simulator (Botdorf et al., 2017).

Consequently, changes in risky choice while being observed could be the result of the motivation for social signalling, of arousal-based reward sensitive decisions, or distraction, and each of these three processes possibly has a different developmental trajectory. Merely observing an increase in risky decisions in adolescents seems insufficient to specify which underlying psychological process is most relevant.

In sum, different studies have emphasized different models and found results in favor of each. This holds for paradigms when adolescents are observing others and even more for paradigms in which they are observed. These mixed results may be due to the fact that each study has used different experimental paradigms with large variations of the key variables (e.g., known risk vs. uncertainty, best friend vs. unknown peer) and most studies do not directly compare different social contexts in order to identify if they are subject to different psychological processes (but see Somerville et al., 2018). Another reason for the diversity of experimental findings, which can also be attributed to variations in key variables, is that studies likely differ in their affective content. For instance, the affective content of a study on social influence which only uses information about choices of strangers who are not currently present is fundamentally different from a study wherein social influence is examined by looking at changes in behaviour in the presence of a close friend. The distinction between affectively "hot" and "cold" contexts is a useful heuristic to understand adolescent risk-taking. There is evidence that adolescents make more risky choices in "hot" contexts. Notably, reward sensitivity and distraction models explain behaviour change via affect (arousal) as well (Blakemore and Robbins, 2012; Rosenbaum et al., 2018). In order to comprehend adolescent socio-emotional development, we need to better understand how affect and social processing interact and impact each other. We argue that the specificity provided by formal modeling might help to disentangle these important components in developmental research, similar to the field of computational psychiatry (Montague et al., 2012; Huys et al., 2015; Jolly and Chang, 2018).

However, before further elaborating on the benefits of formal models in developmental research we first want to pay credit to the neuroscience of adolescent development. Neuroimaging studies may provide better clues to what extent different processes underlie behaviour. In addition, it may be possible to generate more specific hypotheses about which psychological processes are involved based on the localization of neural activation.

Social Influence and Brain Development

Most verbal models of adolescent social influence are inspired by recent findings from developmental neuroimaging. Here we will review some of those findings and indicate to what extent they support existing models. Given that neural activation is a more direct reflection of the processes underlying behaviour, neuroimaging may be instrumental to identify which process is most relevant in which context.

Adolescent social motivation models are supported by findings about the development of a network of brain regions associated with social cognition. This network, sometimes subsumed as the "social brain," continues to develop during adolescence (Mills et al., 2014). The most prominent regions of this network are the temporo parietal junction (TPJ), the posterior superior temporal sulcus (pSTS), the anterior temporal cortex (ATC), and the medial prefrontal cortex (mPFC). When reasoning about others, the social network seems more active in adolescents than in adults or children (van den Bos et al., 2011). Further, in a study by Somerville et al. (2013) observed by others resulted in increased mPFC activity in adolescents. However, activity in these regions is not unique to social processing. For instance the same study found an adolescent increase in connectivity of the mPFC with striatal brain regions, which are relevant for processing rewards. Further, the mPFC itself is also involved in basic reward processing (Harris et al., 2007; Silverman et al., 2015). Taken together, the increased mPFC activity when being observed can also be interpreted as supporting the reward sensitivity model.

Neural correlates of the role of adolescent reward sensitivity in non-social contexts were recently examined in a meta-analysis (Silverman et al., 2015). This study estimated an increased likelihood of activation in adolescents within a broad range of regions associated with reward processing. These comprise the ventral and dorsal striatum, subcallosal cortex, insula, and amygdala as well as the anterior cingulate cortex (ACC), the posterior cingulate cortex (PCC), and the paracingulate region and the medial prefrontal cortex (mPFC). One study found increased activity in the ventral striatum when adolescents were taking risks in a social but not in a solitary context, whereas this activity difference was not found in adults (Chein et al., 2011). These results are evidence in favor of the reward sensitivity model, but there are multiple possible interpretations. For instance, increased reward related neural activity could either be the result of altered reward perception or of an orthogonal, social value of conforming to a norm. Both social and non-social value is represented in the striatum (Ruff and Fehr, 2014); both mechanisms can lead to riskier behaviour in certain tasks.

Distraction models emphasize the development of the lateral prefrontal cortex (lPFC) and the inter parietal sulcus, which make up the main regions of the cognitive control network. Studies based on the distraction model consistently found increased IPS activation during cognitive control in adolescents, whereas lPFC findings were mixed (Dumontheil, 2016). One study investigating the effects of social context on neural processing while performing a relational reasoning task found that adolescents recruited this cognitive control network more strongly than adults when an audience was present, while performance changed in a similar magnitude for both age groups (Dumontheil et al., 2016). This result also allows for multiple interpretations. Adolescents may be more distracted, but on the other hand it may also be that they exert more control to counteract their distraction, and thus stay on par with adult's behaviour. The fact that they exert more control could potentially be the result of an increased motivation to perform well while observed by others.

In summation, we have seen that all verbal models are supported by neuroimaging research. Different models emphasize the development of different brain networks, but these networks often overlap with respect to functional and structural components. As long as a one-to-one mapping between cognitive and neural processes is not given, it is not justifiable to make the reverse inference about the presence or absence of a cognitive process purely on the basis of observed, or unobserved neural activity (Poldrack, 2006, 2011).

We do not wish to discredit the existing studies on neural correlates of adolescent peer influence; On the contrary, we believe that these are excellent and well-designed neuroimaging studies. In combination with appropriate experimental control conditions, reverse inference is valid and insightful (Hutzler, 2014). However, experimentally isolating a cognitive process becomes exponentially difficult when the processes in question increase in complexity. Different attempts have been suggested to attenuate the issue, such as large-scale brain decoding (Poldrack, 2011; Yarkoni et al., 2011), using functional localizers (Saxe et al., 2006), and formal modeling (Marr and Poggio, 1976; Montague et al., 2012; Stephan et al., 2015; van den Bos and Eppinger, 2016; Hauser et al., 2018). None of these strategies will completely solve the problem of reverse inference, however, each may increase our confidence in reliably identifying the neural correlates of a particular cognitive processes. This article is motivated by the advantage of formal models; in what follows, we will illustrate how verbal models of social influence in adolescence might be translated into formal ones.

Formal models of social influence

Here we demonstrate how the three verbal models about adolescent socioemotional development which we introduced earlier can be formalized as variations of expected utility models. We then show that model comparison can be used to infer underlying social mechanisms. The rationale behind formal modelling of cognition is that in order to identify if behaviour is consistent with a proposed cognitive process, we need to formulate algorithms that represent the process mathematically. Comparing the behaviour of the algorithms with actual behaviour observed in participants can subsequently be used to quantify support for the hypothesis which is represented by the algorithm. In this section, we aim to translate verbal models of adolescent development into formal ones (figure 2.1).

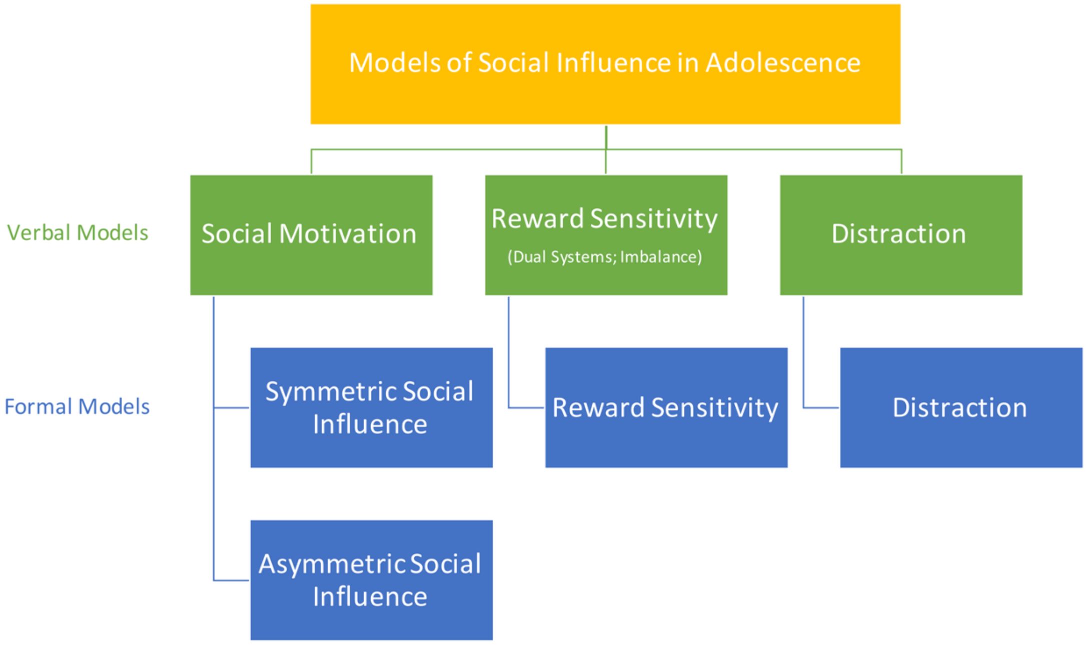

Figure 2.1: Verbal models of social influence during adolescence, and how they map to our taxonomy of formal models.

However, current models often lack the details required in order to be directly translated into formal models. To formalize the models, we have therefore made several assumptions rooted in expected utility theory. The model space that we present here is not exhaustive. Nevertheless, the current framework illustrates how formal modelling can be used in developmental science, and provides a strong starting point for developing more elaborate models. More importantly, it enables precise discussions on which models are favoured by existing experimental data. To formalize models of adolescent decision-making First, we address how risk seeking behaviour is understood within the expected utility framework in order to familiarize the reader with its' assumptions. Then we extend these models with parameters that can be read as social sensitivity, reward sensitivity and distraction. This finally enables us to test models of adolescent development against one another, even within the same experiment.

Expected Utility

The first assumption of expected utility theory is that people have a subjective experience of objective rewards. For instance, the first dollar someone ever earns is worth more to them than the hundredth. The change in wealth from nothing to $1 feels different from the change in wealth from $99 to $100. This transformation of objectively equal values ($1 in both cases) into a subjective utility is often modelled by a power function borrowed from psychophysics (Helmholtz, 1896), where it is used to describe the nonlinear relationship between subjective psychological experience of a stimulus intensity and the objective physical intensity of the stimulus:

$$U = V^{\rho}, \tag{2.1}$$

where V denotes the objective value of a reward and ρ determines the convexity of the utility function (Figure 2.2). Often times this parameter is referred to capturing "outcome" or "reward sensitivity" of an individual (Kellen, Pachur, & Hertwig, 2016). When considering risky choices rewards are not certain; they occur probabilistically. The subjective utility of a probabilistic reward is then simply described as:

$$EU = p * V^{\rho}, \tag{2.2}$$

where p denotes the probability of the reward. Note that in more elaborate models, such as cumulative prospect theory, the probability itself is also transformed to a subjective probability weight (Tversky & Kahneman, 1992). Although this would allow for even more detailed insights in developmental differences in risky behaviour (Engelmann, Moore, Monica Capra, & Berns, 2012), we do not further consider subjective probability here, as it would exponentially increase our model space and thus not serve our purpose.

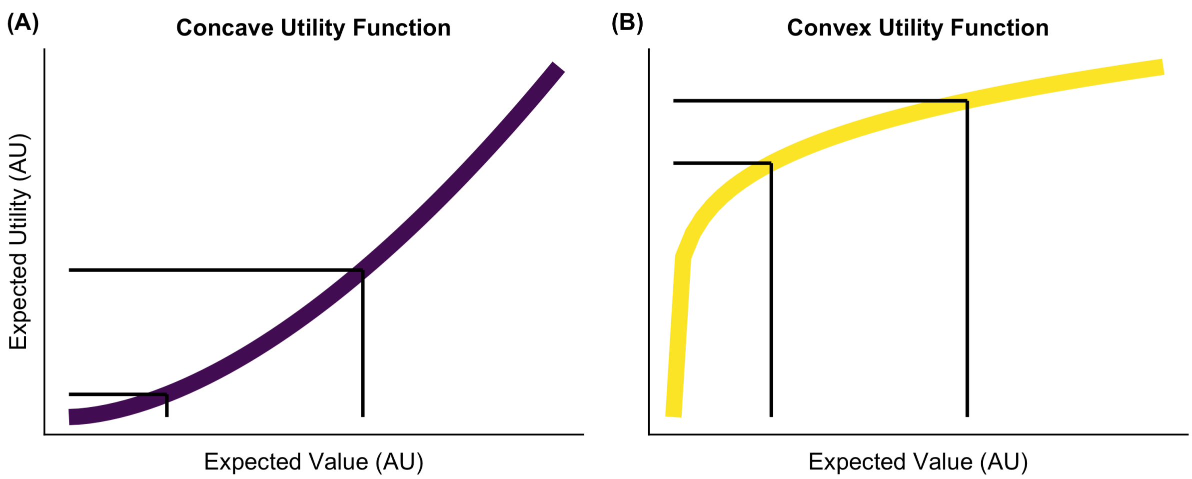

Figure 2.2: Two utility functions which are used to model reward sensitivity and risk-taking. The x axis depicts the expected value of potential choice options. The y axis shows the subjective utility of these expected values given different reward sensitivity parameters. (A): A concave utility function generated by ρ=1.7. The difference between reward magnitudes is subjectively amplified, which makes it more attractive for the individual to take risks in order to obtain higher rewards. (B): A convex utility function generated by ρ=0.2 Risk aversion occurs here because potential rewards are compressed, therefore more similar to each other and in turn it will be less attractive to take a risk in order to obtain the higher reward. The black lines illustrate that while the difference in expected values is equal in both graphs (x axes), the difference in subjective utility

of these options (y-axes) is smaller in the right figure. Axes ticks and labels are not shown to, to emphasize the relative, not the absolute difference as exponential functions scale very differently.

When individuals are repeatedly presented with the same choice options, their decisions will most likely differ from one another. Consequently, we need to account for this probabilistic nature of choice in a model of behaviour. To achieve this, a model for choosing between two rewards feeds the difference between reward utilities into a sigmoid function, through which we obtain an estimate of the *probability* that a decision maker chooses one option over another

$$p_{ChooseRisk} = \frac{1}{1+e^{-(EU_{risk}-EU_{safe})*\tau}} . \tag{2.3}$$

Here, τ accounts for individual differences in choice sensitivity. The smaller τ the less sensitive the decision maker is to the expected utility differences (and the more random the choice pattern appears). We now turn to examine how different models of social decision-making can be represented within this framework.

Modelling social influence

In our earlier example, we used the subjective value of objective monetary amounts as the key variable for decision making, but there is ample evidence that people also attribute utility to social outcomes such as fairness (Fehr & Schmidt, 1999) and social status (van den Bos, 2009). Furthermore, there is evidence that humans integrate value information from social and non-social sources into a common currency when making a choice (see Ruff & Fehr, 2014, for a review). Consequently, the expected utility framework can be extended to include social rewards and represent social behaviour.

Social sensitivity

Social rewards, such as belonging or expected status gains, can add to the expected utility associated with a non-social decision, because the prospects of social and non-social rewards are combined by the brain when making a choice (Ruff & Fehr, 2014). Within expected utility theory, the changed valuation of an option due to the presence of social information can be expressed as a single parameter that shifts subjective utility. For example, if we consider a typical experiment where there are two options, a relatively safe option and a risky option (defined by outcome variance differences). A social signal, for instance seeing that a peer chose the risky (safe) option, contributes to the utility of the risky (safe)option, while the expected value of the choice option and reward sensitivity remains the same (Chung, Christopoulos, King-Casas, Ball, & Chiu, 2015). This can be implemented with a single additional parameter:

$$\mathrm{EU_{Social}} = \mathrm{p} * \mathrm{V}^{\rho} + \psi, \tag{2.4}$$

where ψ corresponds to the impact of social information on risky and safe choice options. We call this model "symmetric social influence model". The larger ψ the more likely the participant is to move into the direction of the social information (see Figure 2.3A).

It is likely that social information has asymmetric effects on behaviour depending on whether social information favours risk aversion or risk seeking. For instance, Braams et al., (2019) showed that risky advice had less impact than safe advice. This can be captured by adding two independent parameters to the utility function that vary depending on whether social information favours safe or risky choices (see Figure 2.3B)

$$\begin{aligned} \mathrm{EU_{Social_{Risk}}} &= \mathrm{p} * \mathrm{V}^{\rho} + \psi_{risky} \quad \forall\ \text{Social Signal} = \text{Risky}\,, \\ \mathrm{EU_{Social_{safe}}} &= \mathrm{p} * \mathrm{V}^{\rho} + \psi_{safe} \quad \forall\ \text{Social Signal} = \text{Safe}\,. \end{aligned} \tag{2.5}$$

We call this model "asymmetric social influence model". Note that the precise interpretation of ψ depends on the specifics of the experiment. In an experiment where the participant is observed it could represent the expected value of gaining status by taking more risks. In an experiment where the participant observes others, social information can reduce the participants uncertainty about what to choose, and in yet another experiment, Ψ can represent the value attributed to conforming to the behaviour of others (e.g., status vs. belonging motivation). In addition, such a framework offers insight in how different aspects of the outcomes are weighted (e.g. money vs. social gains).

Reward Sensitivity

Developmental theories on social impact that focus on imbalance suggest that in a social context, rewards are valued more by adolescents because the socially induced arousal triggers reward-processing brain regions (Chein et al., 2011). Reward sensitivity is a basic feature of expected utility models; it is governed by parameter ρ (see Eq. 2.1). This parameter has already been used to characterize individual and developmental differences in risk attitudes (e.g., van den Bos & Hertwig, 2017; Blankenstein et al, 2016). To capture changes in reward sensitivity due to social facilitation one can add a parameter ω to the "reward sensitivity" part of the utility function:

$$\mathrm{EU_{social}} = \mathrm{p} * \mathrm{V}^{(\rho+\omega)} \mid \omega \in \mathbb{R}\colon \omega > 0 \tag{2.6}$$

The larger ω, the more risk seeking an individual becomes (see Figure 2.2 and Figure 2.3C). This equation will henceforth be called "reward sensitivity model". In our reading of verbal reward sensitivity models, ω will never be smaller than 0 given that it is the expectation that is there is an increase, not a decrease, in risky behaviour due to arousal.

Distraction

Other work emphasizes that arousal in social situations creates distracting goal conflicts, especially for adolescents (Botdorf et al., 2017; Breiner et al., 2018; Dumontheil, 2016; Dumontheil et al., 2016). For choices that are value- or preference-based, it is hard to judge whether a decision results from distraction or inattentiveness; there is no objectively correct benchmark to evaluate correct and incorrect responses. However, formal modelling provides the means of unmasking choice stochasticity unique to social contexts that could otherwise be falsely interpreted as an increase or decrease in risk-taking. Distraction or inattentiveness would lead to an increase in choices that are less determined by expected value. In decision models this kind of behaviour is often captured by a "trembling hand" choice rule (Loomes, Moffatt, & Sugden, 2002). This rule modifies the choice function by adding a fixed probability that the individual does not use expected utility to guide their choice, but rather chooses randomly. To capture this increase in distraction we can estimate how this probability of choosing randomly increases in the social context:

$$p_{\mathrm{ChooseRiskSocial}} = (1-\zeta)\frac{1}{1+\mathrm{e}^{-(\mathrm{EU}_{\mathrm{risk}}-\mathrm{EU}_{\mathrm{safe}})*\tau}} + \frac{\zeta}{2} \mid \zeta \in \mathbb{R}\colon\ 0 < \zeta < 1\ , \tag{2.7}$$

where a larger ζ indicates more random behaviour. We will refer to this equation as the "social distraction" model. Note that more random behaviour means an increase in risk-taking when one would normally show risk averse behaviour, and vice versa (see Figure 2.3D)

Model Predictions

These formalizations of the different psychological processes involved in social influence make distinguishable predictions (Figure 2.3). Only the social influence models (figures 2.3A & B) clearly predict that behaviour will shift in a way that is dependent on the social information content (e.g., other advice is safe or risky), or the beliefs of the subject (e.g., believe the norm is safe or risky). In contrast, for reward sensitivity or distraction models, the social context has a unidirectional main effect on behaviour. The fact that the models can generate different patterns of behaviour is in itself no proof that these models are actually distinguishable and suitable for model comparison. For this we need to run simulations as well as model and parameter recovery analyses in the context specific experimental settings (Palminteri et al., 2017), which we will do below.

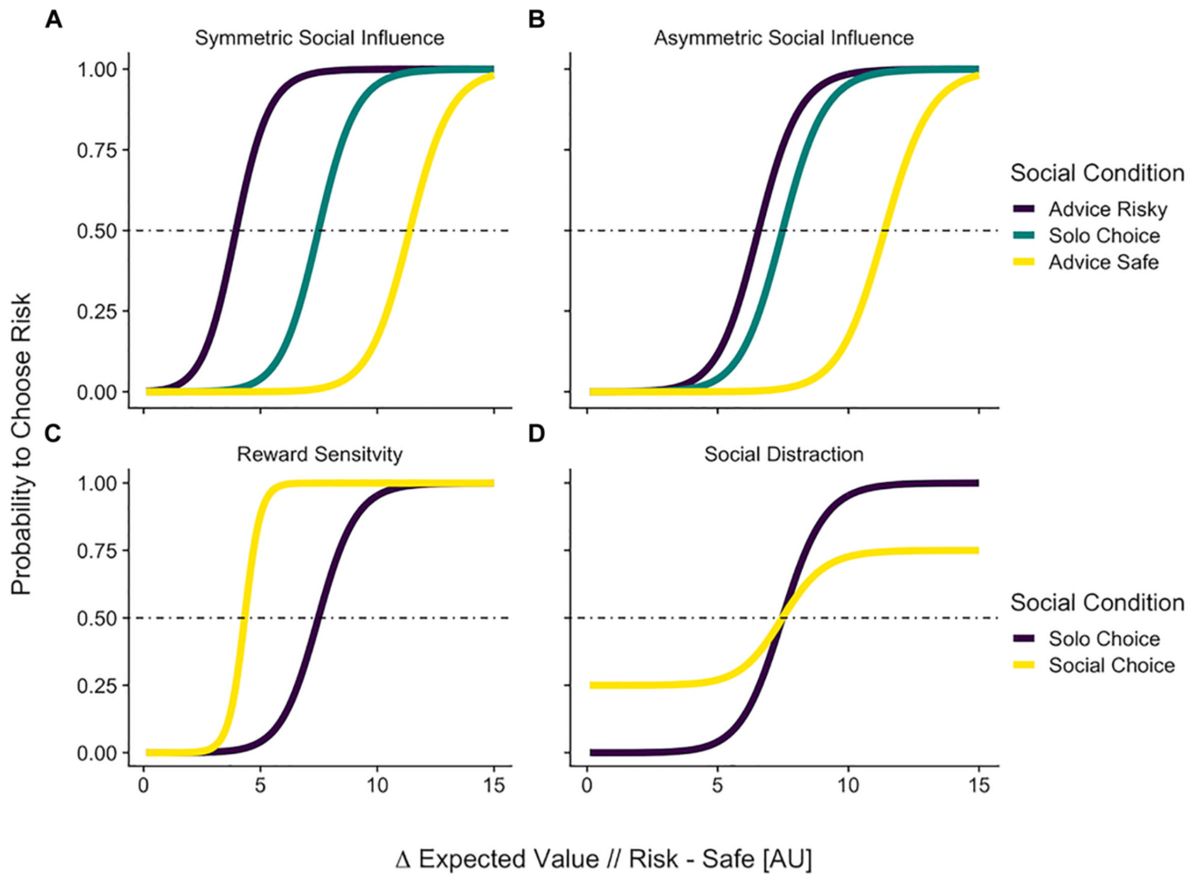

Figure 2.3. Predictions of the formal social models. The x-axis shows the difference in expected value of two choice options. The y axis shows the probability that a decision maker would choose the risky option. The horizontal line indicates the chance level for binary choice. The choice probabilities shift as a function of social information. Top panel: Predictions of models that take the content of social information into consideration. (A) Symmetric social influence in Eq. 4. Risky and safe social information impact choice equally. (B) Asymmetric social influence of Eq. 5. In this model, risky and safe social information can impact choice differentially. Bottom panel: Predictions of models that do not take the content of social information into consideration. (C) A reward sensitive decision maker (Eq. 6) would always be more likely to choose risky in a social context. (D) A distracted individual's choices (Eq. 7) would be closer to chance in a social condition, even when the differences in expected values are extreme.

Methods

Simulation Study and Model Quality

To assess the quality of our formal models, we first simulated decisions on a set of risky gambles with varying expected value, based on all outlined models. We explicitly included the standard expected utility model without any social parameters (Eq. 2), to control for the possibility that expected utility is itself flexible enough to describe a wide range of choices. We simulated decisions in a classic economic paradigm that requires repeated choices between a probabilistic lottery with a high reward and a non-probabilistic small reward. Lotteries combined values 8, 20, and 50 (Arbitrary Units) with winning probabilities 0.125, 0.25, 0.375, 0.5, 0.675, and 0.75. The safe reference always had an expected value of 5. These values resemble those used in Blankenstein et al. (2016). Social information provided in the simulations consisted of the choices of one risk seeking subject in Blankenstein et al. (2016). For each social influence model, agents were divided into 12 different groups based on the distributions used to sample the parameters ψ or which represent behaviour change in the face of social information in a given model (see Table 2.1 for details). Reward sensitivity, ρ and temperature, τ were sampled from the same distributions for all individuals, with sufficient statistics $\rho \sim N(\mu = 0.4, \sigma = 0.3)$ and $\tau \sim N(\mu = 0.8, \sigma = 0.1)$. For each group and model, we simulated 50 individuals, resulting in a total of $5*12*50$ simulated subjects that responded to 432 choice problems, 144 of which contained risk seeking social information, 144 risk averse social information which was generated by inverting the choices in the risk seeking condition and 144 featured no social information. To summarize, we modeled the behaviour of subjects over a range of variables of risk- and social preferences and simulated how they would respond to different choice problems in the presence of social information. We then investigated to what extent we could correctly identify the underlying data generating models, by fitting all models to the responses we generated.

Table 2.1 details of the parameter recovery.

Model	Social Parameter	Groups
Symmetric Social Information	$\psi \sim \mathcal{N}(\mu_1, 0.5)$ $\mu \in G_1$	$G_1 = \{0.0; 0.45;\ 0.90;\ 1.36;\ 1.81;\ 2.27;\ 2.72;\ 3.18;\ 3.63; 4.19;\ 4.54; 5.00\}$
Asymmetric Social Information	$\psi_{risk/safe} \sim \mathcal{N}(\mu_2, 0.5)$ $\mu_2 \in G_2$	$G_2 = \{0.0; 0.45;\ 0.90;\ 1.36;\ 1.81;\ 2.27;\ 2.72;\ 3.18;\ 3.63; 4.19;\ 4.54; 5.00\}$
Reward Sensitivity	$\omega \sim \mathcal{N}(\mu_4, 0.5)$ $\mu_4 \in G_3$	$G_3 = \{0.0; 0.45;\ 0.90;\ 1.36;\ 1.81;\ 2.27;\ 2.72;\ 3.18;\ 3.63; 4.19;\ 4.54; 5.00\}$
Social Distraction	$\zeta \sim \mathcal{N}(\mu_5, 0.1)$ $\mu_5 \in G_4$	$G_4 = \{0.0, 0.09, 0.18, 0.27, 0.36, 0.45, 0.54, 0.63, 0.72, 0.81, 0.90, 1.00\}$

Note. For every model (left column), the social parameter (middle column) was sampled 12 times without replacement from the tuple in the right column, resulting in 12 unique groups per model that differ in their susceptibility to social influence.

Model and Parameter Recovery

We evaluated all models with regard to their fit to the data we had previously generated. This enabled us to check whether our analysis was suitable to correctly identify the data generating model. That is, if successful, model fitting and comparison would indicate that the best fitting model was the one we used to generate the data. Only then can one confidently use these models to test specific hypotheses (Palminteri et al., 2017). We judged the fit of all five models given the simulated data by consulting the deviance information criterion (DIC). Lower DIC values indicate better model fit. The rule of thumb cautiously introduced by Spiegelhalter et al. (2002) is to treat DIC values higher than 3–7 relative to a better fitting reference model to be considerably less supported by the data. It is possible that different parameter values of a model result in the same pattern of behaviour. To rule out the possibility that our models are "sloppy" in that respect, we correlated the generative parameter values with the mean of the posterior parameter distribution which we obtained by inverting the generative model on itself. A high correlation between the simulation parameters and the parameter estimates obtained from inverting the data generating model on itself is indicative that we can approximate the "true" parameter values well, when inverting the model on human choices.

Fitting Hierarchical Bayesian Models of Social Influence

We formulated the models introduced above in a hierarchical Bayesian way. This was advantageous because individual parameters could be pulled from group specific hyper distributions, which made us more sensitive to identify differences between groups and reduced outliers that often occur using frequentist fitting procedures. In our case, we drew parameters form hyper distributions for each group separately, specifying the same prior for each age group (graphical model and priors in the supplement). Non-centered parametrization was used to effectively sample subject-level parameters from the hyper distributions (Betancourt and Girolami, 2013). We obtained posterior parameter distributions using the No-U-Turn-Sampler implemented in Stan (Carpenter et al., 2017). For each model, we used 6,000 iterations of four parallel chains each and no thinning. The first 1,000 samples were discarded as warmup.

Results

The results of our analyses indicate a good model and parameter recovery (see Figure 2.4). However, not all models performed equally well. While all Markov chains converged as indicated by the Gelman Rubin statistic (Gelman and Rubin, 1992) and most of the parameters could be recovered reliably, the temperature parameter τ of the social distraction model was not recovered very well (0.24 on the diagonal). Additionally, ζ was negatively correlated with the temperature parameter of the choice function ($r = -0.6$). Functional attribution to either of these parameters should be made with caution in case the social distraction model is best descriptive of the data.

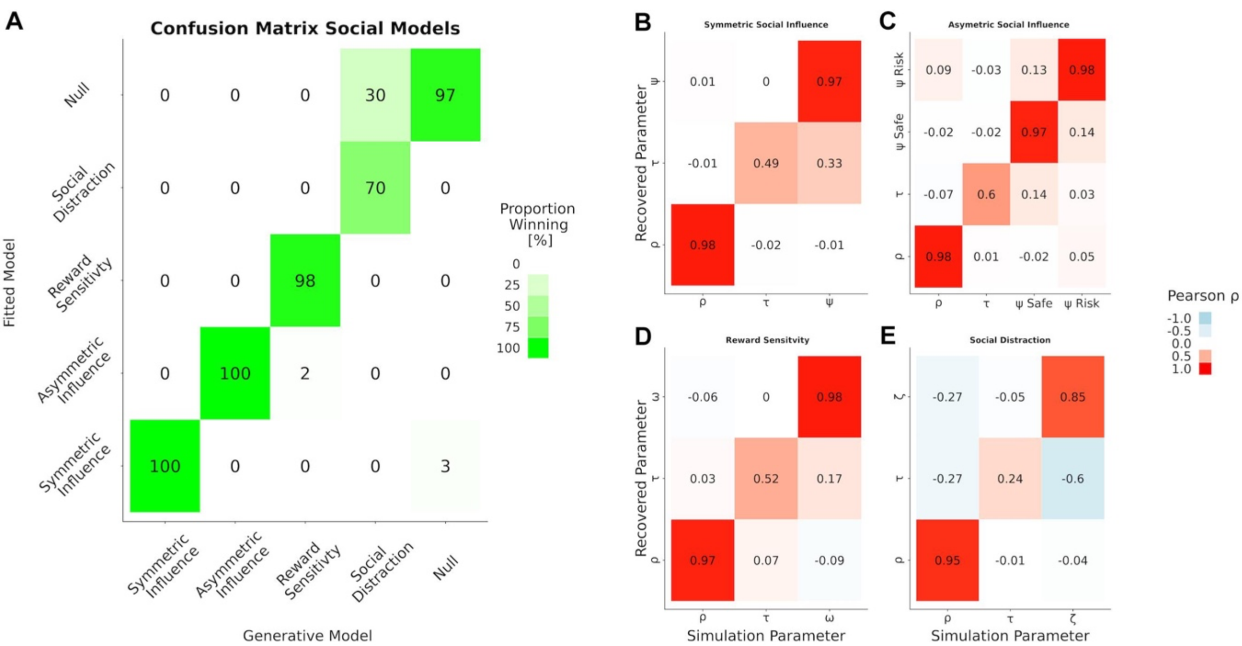

Figure 2.4. Results of the model and parameter recovery. (A) Confusion matrix for model recovery. Each cell depicts the frequency with which each model is best predictive for data generated under itself (columns) and inverted by itself and all other models (rows). Elements that diverge from the diagonal are evidence that one model is at danger to be "confused" with another one. The four panels on the right show the parameter recovery as correlation between the parameters used for simulation (columns) and those obtained by inverting the model (rows) for our different social influence models. (B) The symmetric social influence model, (C) the asymmetric social influence model, (D) the reward sensitivity model, and (E) social distraction model.

Applying the Models Synthesizes Seemingly Divergent Experimental Results

Having established that our proposed formal models and their parameters were recoverable, we applied the formal social influence, reward sensitivity and distraction models to data of two published studies, in order to quantify to what extent the studies support either model. Both studies investigated social influence when adolescents observed social information as they chose between different monetary lotteries (Blankenstein et al., 2016; Braams et al., 2019). Using our formalized versions of models on social influence in adolescent risk-taking, we investigated how well either study supported social information, reward sensitivity or distraction models. Both studies provided the participants with safety- and risk-promoting social information. The studies investigated how explicit information about another person's choices changed risk-taking behaviour in monetary lotteries and how this change in risk-taking was related to the participants' developmental stage. The combined age range of both studies was 10–26. The first study focused on adolescent reward sensitivity and reported that social impact on risk-taking decreases with age (Blankenstein et al., 2016). The other focused more on adolescent social motivation and found that social impact for safe behaviour was strongest in adolescence (Braams et al., 2019). Notably, these two studies used very similar paradigms but report results in line with different verbal models of adolescent risk-taking in social contexts. Below we will re-analyze both studies and show that formal model comparison can synthesize these seemingly divergent explanations. Our re-analysis was restricted to these two studies because these studies are so similar which made a straightforward showcase for the benefits of formal modeling.

Analysis

In both datasets, we compared the formal models via DIC. The experimental paradigms included risky choices where the probability was known, and ambiguous choices where the exact probabilities where not known. For sake of simplicity, we have currently ignored the ambiguous trial types in the main manuscript. However, we believe that the discussion of risk, ambiguity or even experience-based choice in relation to adolescent risk-taking is very important, but beyond the scope of the present paper [but see Rosenbaum et al. (2018) for review]. Thus, in this articles' Supplementary Material we report how we adjusted the formal models to include an ambiguity attitude parameter (Tymula et al., 2012; van den Bos and Hertwig, 2017) and repeated all analyses with expected utility and ambiguity models. The main results of the model comparison remained the same (see Supplementary Material).

For inference on age trends in the best fitting models' parameters, we used Bayesian general linear models, implemented in the rstanarm package (Stan Development Team, 2018) utilizing rstanarm's default priors. The age predictor was binned to represent pre- (age < 13), early- (age 13–16), late- (age 16–19), and post-adolescent (age > 19) groups. To test linear and quadratic age trends we constructed orthogonal regressors using R's poly function. We subsequently inverted the quadratic age predictor, so that the beta estimates were more positive, when its contribution to the dependent variable increases. For each regression, we ran 3 chains with 30,000 samples each and set a warmup of 1,000 samples. Convergence of the chains was inspected by consulting stan's implementation of the Gelman Rubin statistic (Gelman and Rubin, 1992). Generally, we report the mean of the posterior and the two-sided 95% credible intervals (CI) around each mean. We treat the contribution of a predictor as negligible if the credible interval of the regression weights includes a zero.

Experiment 1: Reanalysis of Blankenstein et al. (2016)

Blankenstein et al. (2016) tested n = 157 participants aged 10–26. In this study, participants were asked to choose between a risky gamble and a safe option on 216 trials. In order to investigate susceptibility to peer influence, Blankenstein et al. (2016) programmed a virtual agent very prone to risk-taking and showed its choices to the participants prior to their choice in half of the trials. Note that this agent was very risk-taking on average, but sometimes chose the safe option as well. The probabilities and values associated with the gambles were presented as wheels of fortune (Ernst et al., 2004) and were the same as the ones we used for our simulations. A full combination of gain values and probabilities resulted in 24 unique trials. The authors reported an overall increase in risky choices in the social condition; the increase was most pronounced in youngest participants and linearly diminished with age. The original analysis was motivated by the reward sensitivity model. The study design and their model-based analysis focused on a change in risk attitude as measured by the reward sensitivity parameter, ρ, which we introduced earlier. However, their reported result is, in principle, consistent with all three verbal models of risk-taking under consideration in this paper. Our reanalysis goes beyond the original analysis as we specifically designed formal models to compare competing models about the nature of social influence during adolescence within the same task.

Results

Model comparison via DIC identified the asymmetric social influence model as best fitting (Figure 5B). Reward sensitivity and distraction models performed considerably worse in comparison. The best fitting model replicated the behaviour of participants with great accuracy (Figure 5A). All age groups made more risky decisions when social information was risky, and made more safe choices when social information was safe. Strikingly, and contrary to our expectations given the original article, all participants showed a greater social influence when being confronted with safety-promoting social information (Figure 5C). As a next step, we performed Bayesian generalized linear regressions using age and quadratic age as predictor of the social model parameter estimates. We ran separate regression analysis on ψ risk and ψ safe, treating them as separate dependent variables. We found that the older the participants, the less they took risky advice [βAgeLin = −1.5, CI = (−1.9, −1.2)]. Older participants additionally took safe advice more often [βAgeLin = 1.4, CI = (0.9, 2.0)] as compared to younger participants. We also found adolescent decrease in taking risky advice as indicated by a negative quadratic contribution of age for following risky [βAgeQuad = −0.6 CI = (−0.9, −0.2)] but no adolescent effects on taking safe advice [βAgeQuad = 0.5 CI = (−0.0, 1.1)]. In sum, participants of all ages were influenced by both safe and risky social information. In agreement with the original author's conclusions, we found that the impact of risky social information was strongest in youngest participants. Crucially however, safe social information had an even stronger impact than risky social information in all age groups, a conclusion which was not noted in original analyses.

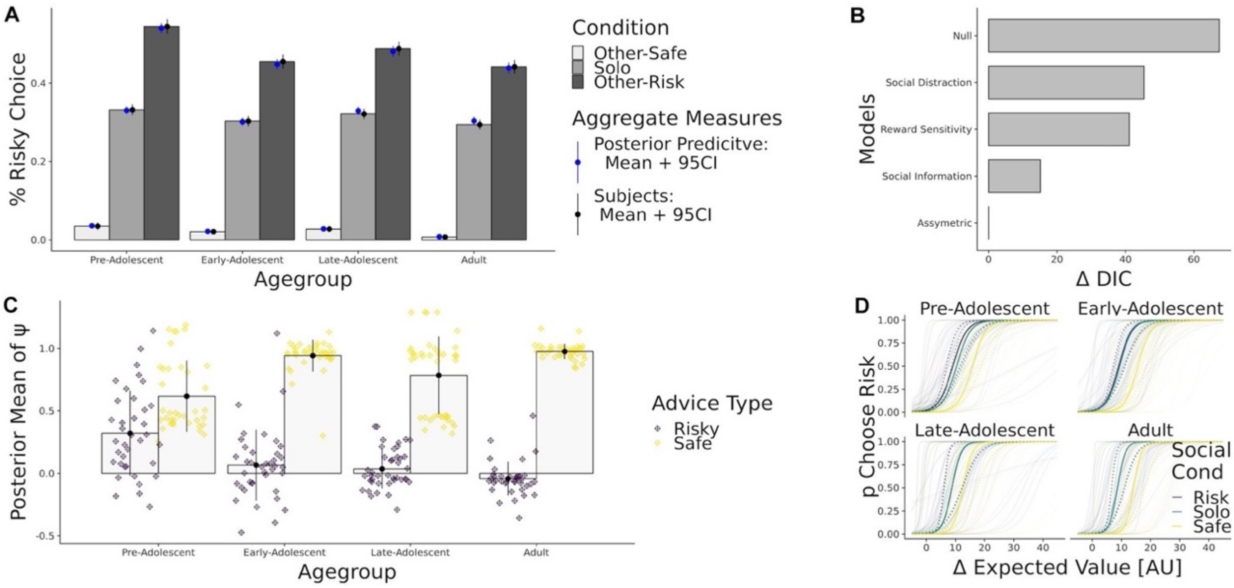

Figure 2.5. This panel shows the results of our model comparison procedure. (A) Percentage of risky decicions in Blankenstein et al. (2016), by age group and conditions. Black error bars represent the bootstrapped 95% confidence interval. Next to the mean and CI of the subjects choices (black), we show simulations under the full posterior from the winning model' parameter estimates (blue). (B) Difference in DIC fit indices for the whole model space, using the winning model as a reference. (C) Posterior Parameter Estimates of ψ risk (purple) and ψ safe (yellow), binned by age group. (D) Predicted probability to choose the risky option given the difference in expected value of the gambles. Coloured solid lines correspond to model predictions obtained by computing the mean of subject-level parameters in each age group. Coloured dashed lines denote upper and lower confidence bounds obtained by computing the standard error of the posterior mean. Transparent lines refer to subject-level predictions.

Experiment 2: Reanalysis of Braams et al. (2019)

In this experiment n = 99 participants aged 12–22 chose between risky and safe gambles on 300 trials. Similar to Blankenstein et al. (2016), the authors were interested in the impact of social information on risky choice across development and presented subjects with computer generated decisions that participants believed were choices from other participants of the study. Other than in Blankenstein et al. (2016), risky and safe options were both gambles with equal probabilities: there was no sure option to choose from. In both gambles, it was either possible to win a low or a high reward. Risky gambles could result in either very low or very high rewards. For the risky options, the difference between the high and low rewards varied from \$3.63 to \$5.51. For safer options, there was less to lose as the difference was between \$0.06 and \$1. The probability of winning the high reward varied with a step size of 10% from 40% up to 90%. The lotteries were presented as colored bars, with color proportions indicating the winning probability. The authors concluded that participants followed risky and safe choices of peers and that adolescents use safe more than risky social information. Such a result speaks for social motivation models. However, as seen above: drawing conclusions about mechanisms is hard without a formal model comparison. In order to be able to apply formal model comparison here, the models were adapted to reflect the conceptualization of risk as the variability in outcomes (Weber et al., 2004) used in Braams et al. (2019). Hence, the utility of one choice option in this re-analysis is described as:

$$EU = p * V_{high}^{\rho} + (1 - p) * V_{low}^{\rho}, \tag{2.8}$$

while the social extensions to this model (equations 2.4-2.7) remained the same.

Results

Model comparison via DIC again indicated, like in Blankenstein et al. (2016), that the asymmetric social influence model fit the overall behaviour best (Figure 6B). Again, reward sensitivity and distraction models had considerably worse fit than the models which assume that social impact depends on the content of social information. Simulating data under the obtained posterior distributions again revealed that our models could predict the participant choices well (Figure 6A). As before, most participants put higher weight on safety-promoting social information than on risky social information (Figure 6C). To judge the statistical relevance of this pattern, we performed Bayesian generalized linear regressions, again using age and quadratic age as predictors while treating ψ risk and ψ safe as separate dependent variables. We found that linear age was not a good predictor for using risky [βAgeLin = 0.0, CI = (−0.2, 0.3)] nor safe advice [βAgeLin = −0.2 CI = (−0.4, 0.0)]. However, quadratic age trends were substantial for both risky [βAgeQuad = −0.5 CI = (−0.7, −0.3)] and safe advice [βAgeQuad = 0.6 CI = (0.4, 0.8)], implying that adolescents used risky social information less and safe social information more to guide their choice. In sum we find that safe social information has a greater impact on choice than risky information, especially during adolescence. Again, model comparison provides evidence that all age groups differentially assign weight to risky and safe social information.

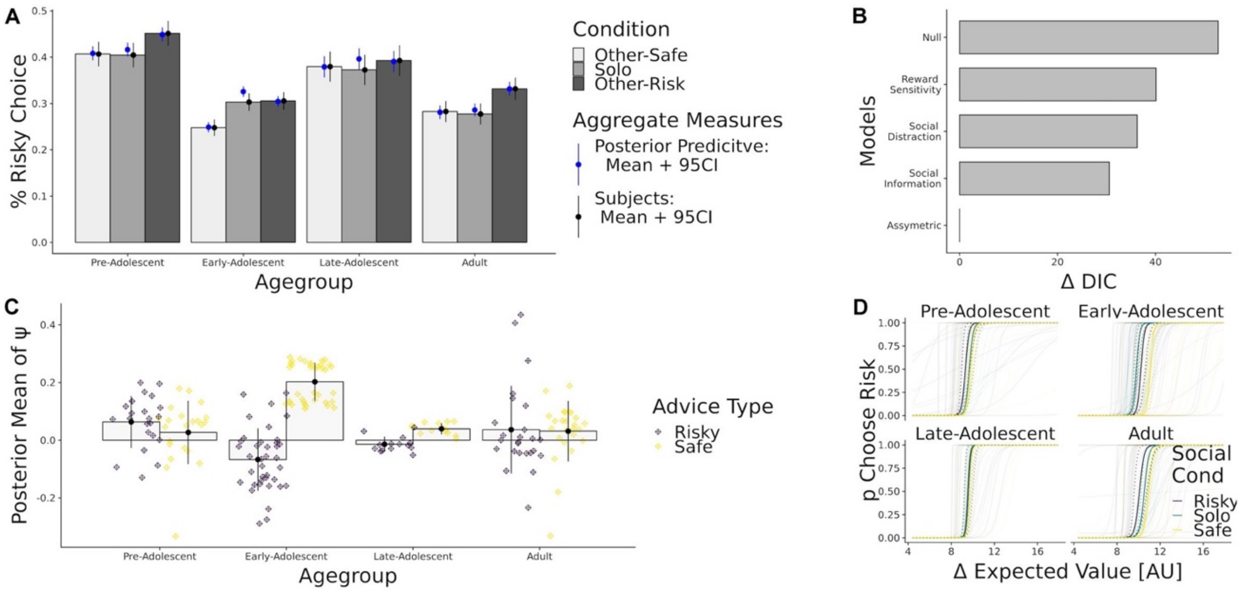

Figure 2.6. The same as figure 2.5 but for the data reported in Braams et al. (2019)

Discussion

It is a widespread assumption that adolescents take risks more frequently and are more sensitive to social information than members of other age groups. Why this is the case, and in which situations this occurs remain open questions despite extensive theory development and empirical research. Several verbal models of adolescent decision-making have identified elements that may play a role in increased risk-seeking behaviour. Some point to high social motivation as the principle driving force of adolescent decision-making. Others emphasize reward sensitivity or increased arousal in social situations; yet others have focused more on diminished cognitive control and increased distraction in social contexts. Most of the current experimental evidence is consistent with more than one of these explanations, resulting in a handful of plausible verbal models that explain social influence in adolescent risk-taking well. Further progress requires the systematic testing of models against each other, within different social contexts (Pfeifer and Allen, 2016; van den Bos and Eppinger, 2016). With this goal in mind, we translated verbal models of adolescent social decision-making into formal models (c.f. Figure 1), which make distinguishable quantitative predictions (c.f. Figure 3). Using simulations and Bayesian model inversion, we first demonstrated that these models can be recovered and thus can be tested against each other using a single experimental setting (c.f. Figure 4). We then reanalysed two published studies investigating the development of social influence, and showed how the model-based approach can synthesize the results of two studies on social observation (c.f. Figures 5, 6). Here we will discuss the implications of our findings regarding the re-analyses and, more importantly, the general applications and limitations of the modelling approach. Additionally, we provide specific suggestions for research on social influence in adolescence.

Adolescents Are Influenced More by Safe Social Information Than Risky Social Information

Even though the reanalysed studies (Blankenstein et al., 2016; Braams et al., 2019) share a similar paradigm, they are different in terms of stimuli (wheels of fortune vs. bars), reward magnitudes (high vs. low), choices (risky/safe vs. low/high risk), and the source of social information (peer vs. peer/computer/non-peer). This resulted in considerable differences in the aggregate behaviour of the subjects (Figures 5A, 6A). However, applying our models yielded similarities between the two studies which were not easily gleaned from the original articles. First, we showed that in both experiments, participants of all ages took safety and risk promoting social information into account. This is consistent with the original interpretation of Braams et al. (2019), but not clear from the original analysis of Blankenstein et al. (2016). Second, model comparison and the parameter estimates of both re-analyses indicated that safer social information consistently weighs stronger than risky information, especially for adolescents. We can therefore conclude that, when risk aversion is valued by peers, social information can induce safety-promoting behaviours in adolescents. This is worth emphasizing because assuming that adolescent decision-making is maladaptive or flawed is unhelpful in designing social interventions. Restrictive public interventions solely based on that notion have been at best only mildly successful in making adolescents "better" decision-makers in the past (Albert and Steinberg, 2011; Rosenbaum et al., 2018). Mobilizing the finding that social information can favour safe decision-making could lead to better interventions and perhaps reduce dangerous real-world risk-taking. Taken together, our results confirm a positive outlook on adolescent decision-making and add further evidence that adolescent social motivation can be used for the good (Perkins et al., 2011; Liu et al., 2017; Telzer et al., 2018; van Hoorn et al., 2018). However, it is important to note that our conclusions are limited to paradigms where social information is passively observed; it may well be very different when applied to data of experiments where the participant was observed by others.

Formal Modeling Can Inform Experimental Design

In principle, formal models make it possible to quantify social impact in various contexts and increase the specificity of a given hypothesis, but they are no panacea. Models require well-designed experiments: the conclusions that can be drawn from model parameter estimates and model comparison depend on the experimental paradigm. For example, as previously noted, experiments where the participant is observed could lead both to unspecific arousal and also to specific social messaging by the participant (e.g., signaling they are a risk-taker to gain status). Both phenomena can lead to an increase in risk-taking, and this behaviour can be consistent with all of our formal models. In order to be able to draw informative conclusions about social mechanisms, experiments need control conditions where adolescents can achieve social status by demonstrating safe behaviour. Similarly, an experiment where participants only observe the risky decisions of others is by design unable to generate support for a social sensitivity model, and would likely furnish behavioural data consistent with all models, verbal or formal. The relationship between formal model parameters and experimental elements additionally allows for an unambiguous specification of the conditions needed to distinguish between models, fostering better experimental design. Model simulations can be used a priori to show whether the specific implementation of a proposed experiment can distinguish between models1. In other terms, although formal models cannot compensate for poorly designed experiments, they significantly contribute to the development of experimental designs that generate testable hypotheses.

Formal Models Can Help Interpret Neuroimaging Results

All theories about the nature of adolescent decision-making are supported by neurodevelopmental research using techniques like (f)MRI. However, the often-used practice of reverse inference from observed neural activity about the engagement, or the absence of a specific cognitive process is problematic (Poldrack, 2006, 2011). Formal models are helpful in order to overcome some logical fallacies associated with reverse inference (Poldrack, 2011). When using formal modeling, the engagement of cognitive processes is quantified by comparing plausible process models which are subsequently fitted to observed behaviours. In the example of expected utility models, used throughout this article, formal modeling provides insight into the otherwise hidden process of subjective utility computation. Crucially, model comparison happens before regressing the winning models' parameter estimates to measured neuronal activity. Inference can thus be made more rigorously, avoiding logical aberrations such as assuming that activity in the mPFC solely equates social motivation, whereas this activity could also reflect reward sensitivity. Additionally, the model-based approach helps the understanding of developmental processes (van den Bos et al., 2017). In summation, computational modeling is useful to attenuate some issues associated with reverse inference and can lead to more detailed, process-based insights about cognitive development.

Limitations and Future Directions

Naturally the current article is not free of caveats, some of which we will discuss in the following section. Most strikingly, our results only apply to two paradigms in which people observe behaviour, and thus we cannot conclude that this pattern generalizes to behaviour where participants are being observed. Real-life decisions are additionally more complex than the decisions in the binary choice tasks we have highlighted here. In the real world it is rare to be presented with accurate information about outcomes and probabilities associated with choices; there are usually multiple sources of uncertainty (Bach and Dolan, 2012). Although beyond the scope of the current article, there are several computational frameworks that aim at understanding behaviour under different types of uncertainty. This can take different forms such as ambiguity extensions of expected utility (Tymula et al., 2012; van den Bos and Hertwig, 2017) or Bayesian decision frameworks, which assume that social influence is stronger when individuals are more uncertain (Toelch and Dolan, 2015). There has been much attention on the distinction between risk and ambiguity in the literature; both datasets reanalysed here also originally tested age trends in attitudes toward ambiguity. We did not focus on the ambiguous trials in the main article, as our focus was on formalizing verbal models. However, there is reason to expect that ambiguity increases social influence (Toelch and Dolan, 2015) which is why we repeated the same analysis using ambiguity extensions and classical expected utility models (see Supplementary Material). This did not affect the conclusions of our model comparison. We encourage further studies that investigate if the social parameters of the models differ between risky and uncertain or ambiguous choices. Of additional note is that in real life there is not only uncertainty about what to choose, but real-life knowledge of probabilities and outcomes is acquired dynamically through experience (Hertwig and Erev, 2009). Learning in dynamic environments can be modelled within the reinforcement learning framework (Dayan and Niv, 2008), which can be adapted similarly to the models we proposed here in order to comprehend the development of social influence in experience-based tasks (Behrens et al., 2008; Biele et al., 2011; Diaconescu et al., 2014; Bolenz et al., 2017; Rodriguez Buritica et al., 2019).

As briefly mentioned, affect is another important modulator of adolescent risk-taking. In affectively arousing (i.e., “hot”) contexts, adolescents make risky decisions more often than in less arousing (i.e., “cold”) contexts (Figner et al., 2009; Defoe et al., 2015; Laube and van den Bos, 2016; Rosenbaum et al., 2018). In fact, social facilitation theory as well as reward sensitivity and distraction models all imply that social behaviour is influenced by arousal, which itself is often understood as affectively hot. Therefore, research on social influence needs to closely examine the interaction between affect and social processing. “Cold” social situations might be where the participant is merely observing others and “hot” situations might be those where the participant is being observed or interacts with others. However, we believe that a one-to-one mapping between social and affective contexts seems overly simplistic. In the future, it will be interesting to see how different processes like reward sensitivity, social motivation or distraction have different weights in different affective contexts and how strong affect mediates behaviour change. From our current understanding of the literature, “hot” contexts might be best described with reward sensitivity or distraction models whereas behaviour in "cold" contexts might be better described by models emphasizing social motivation. Careful experimental design in combination with formal models may delineate the importance of each process in explaining developmental changes in peer influence.

Summary and Conclusion

Adolescents are often thought to be excessive risk-takers, especially in social contexts. Since adolescents' risky decisions constitute a major health hazard and can have long term consequences, several attempts have been made to understand the determinants of adolescent social risk-taking. Plausible verbal models of social influence in adolescent risk-taking have been formulated, but it is difficult to identify which of the proposed processes determine adolescent behaviour in a particular social situation. We argue that this is because verbal models make unspecific predictions: a broad range of observations is consistent with one, or even several, verbal models. Here we make a first attempt to specify models of social influence in adolescent risk-taking by connecting the developmental literature to theories of social psychology and representing them as simple formal models. Reanalysing two published studies on social influence in risky choice yields that adolescents, like adults, are sensitive to the quality of social information and carefully integrate it into private decisions. In both studies, safe social information had a stronger influence than risky information on adolescents' decisions. These results add further evidence that adolescent social sensitivity can result in safe, health promoting behaviour. Investigating if and how this pattern generalizes to other contexts for instance when adolescents are being observed, will be most insightful. We hope this article encourages further work on isolating the building blocks of developmental models, through harnessing the specificity of formal modelling and model comparison.

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3

Uncertainty explains social information use across adolescence

This chapter is being prepared for publication.

Abstract

Adolescents are known for their propensity to take risks, which may be especially strong in social contexts. However, in many laboratory tasks, adolescents take fewer risks than adults. This discrepancy was explained with the notion that experiments are an inadequate proxy of the uncertainties and risks that adolescents face in real life. How subjective uncertainties develop and how they relate to the development of social susceptibility across adolescence is unknown. We, therefore, developed the marble task and asked 165 subjects (aged 10-26) to take risks under different levels of uncertainty, either by themselves or after observing the advice of someone else. We show that risk-taking and social information use decrease across development despite uncertainty. We propose cognitive model a wherein uncertainty is a mechanism of belief change in the light of social information. This model revealed that across development, people became less uncertain about how to decide. Age-related changes in uncertainty fully accounted for age-related changes in social susceptibility. Our results

imply that their uncertainties are a previously overlooked mechanism behind adolescent risk-taking and social susceptibility.

Introduction

Adolescence is the transition from childhood to adulthood. During adolescence, people become more autonomous than they have been as children and eventually learn to take on adult roles and responsibilities. Along the way to becoming an adult, people show increased exploration and risk-taking (Romer et al., 2017; Somerville et al., 2017), are sensitive to rewards (Chein et al., 2011) and put strong emphasis on social information (Blakemore, 2008; Crone & Dahl, 2012). While most people survive their adolescence in perfect health (Willoughby et al., 2013), a disproportionate number of adolescents suffer from health issues that are a direct consequence of their risky behaviour such as using drugs (Defoe, Khurana, et al., 2019; Johnston et al., 2014), binge drinking (Centers for Disease Control and Prevention (CDC), 2012; Spear, 2018), risky driving (Romer et al., 2014; Shepherd et al., 2011) or having unprotected intercourse (Kirby, 2002). Notably, adolescents mostly engage in risky behaviours when they are with others (Blakemore & Mills, 2014; Gardner & Steinberg, 2005; Romer & Hennessy, 2007; Shepherd et al., 2011; Steinberg, 2008). Knowing why they take risks would benefit adolescents greatly, because it would enable researchers to design evidence-based interventions helping adolescents to become healthier adults. However, it has proven notoriously difficult to capture this behaviour in the lab. For instance, a recent meta-analysis of experimental research on adolescent risk-taking suggests that risk-taking does not peak in adolescence but steadily declines from child to adulthood (Defoe et al., 2015; Defoe, Semon Dubas, et al., 2019).

The discrepancy between experimental and real-life risk-taking in adolescents may be due to the mismatch between laboratory paradigms and the real-life ecology of adolescent risk-taking. Many experiments require description-based decisions, where all information about outcomes and probabilities is provided (Braams et al., 2015; Chung et al., 2020; Defoe et al., 2015; Kwak et al., 2015; Rosenbaum et al., 2018; Rosenbaum & Hartley, 2019; Smith et al., 2014; van Duijvenvoorde et al., 2016). However, the hazards of most adolescent risk-taking behaviours are often not so readily available. Many real-life risks are experience-based; they are subject to greater uncertainty because people must learn the individual consequences of their behaviours from experience (Hertwig et al., 2004; Hertwig & Erev, 2009).

Tasks, designed to capture such experience-based dynamics, like the balloon analogue risk task (Braams et al., 2015; Lejuez et al., 2003), or the chicken game (Gardner & Steinberg, 2005; Rosenbaum et al., 2018) show stronger correlations to real-life risk-taking in adolescents (Braams et al., 2015; Op De MacKs et al., 2011; Rosenbaum et al., 2018; van Duijvenvoorde et al., 2014; van Duijvenvoorde et al., 2016). However, experience-based tasks conflate learning processes, for instance learning from prediction errors (Nussenbaum & Hartley, 2019), with decision-making processes and subjective uncertainty attitudes (Bach & Dolan, 2012). This is problematic because it is well known that experience-based learning still undergoes profound developmental changes across adolescence (Davidow et al., 2018; DiMenichi & Tricomi, 2016; Hartley & Somerville, 2015;

Nussenbaum & Hartley, 2019; Palminteri et al., 2016; van den Bos et al., 2012; van den Bos & Hertwig, 2017). Thus, developmental differences in experience-based decisions could stem from developmental differences in learning, uncertainty attitudes, or both.

Research also suggests that adolescents' propensity to take more risk than adults or children is most pronounced in social contexts (Blakemore & Mills, 2014; Blakemore & Robbins, 2012; Ciranka & van den Bos, 2019; Gardner & Steinberg, 2005; Steinberg, 2008). In adults, it is established that when they experience more uncertainty, people rely more on social information (Bahrami et al., 2010; Ciranka & van den Bos Bos, 2020; De Martino et al., 2017; FeldmanHall & Shenhav, 2019; Toelch & Dolan, 2015). Even studies with infants have long shown that when they are uncertain of how to behave, they seek reassurance from their caregivers (Walden & Ogan, 1988; Zarbatany & Lamb, 1985). However, while there is evidence that adolescents' decision-making differs from adults' when there is uncertainty (Cassotti et al., 2014; Davidow et al., 2018; Rosenbaum et al., 2018; Rosenbaum & Hartley, 2019; van den Bos & Hertwig, 2017), and that adolescents are especially sensitive to social information (Blakemore & Mills, 2014), the mechanistic link between uncertainty and social susceptibility has not received attention in recent research on adolescent risk-taking.

To isolate developmental differences in subjective uncertainties from differences in trial-and-error learning, we have developed a novel paradigm, the *marble task,* in which subjects learn outcome probabilities by both experience and description. Opposed to previous research, the *marble task* guarantees that everybody bases their decisions on the same objective information. Previous evidence about adolescents' uncertainty-tolerance (Tymula et al., 2012; van den Bos & Hertwig, 2017) lead us to hypothesise that adolescents would take more risks than adults and children in experience-based risks but consistent with previous findings, a linear decrease in risky decisions when risks were merely described to them (H1).

Further, the *marble task* allowed us to study social susceptibility under description and experience-based uncertainty. Where we expected that greater uncertainty leads to greater social influence (H2). Given adolescents' alleged sensitivity to social information, we expected adolescents to use social information most (H3). Finally, previous studies have found safe advice has a different impact than risky advice in developmental populations (Braams et al., 2019). Therefore, we also expected to find that safe and risky advice has differential effects on our subjects' decisions (H4).

To understand how the same experience differentially impacts the beliefs of our subjects across development, we also put forth a Bayesian model of social influence in risk-taking. In combination with this model, the marble task enables us to disentangle subjective uncertainty attitudes in experience- and description-based risks and study these uncertainties' differential effects on social susceptibility across development.

In short, research implies that adolescent risk-taking is related to adolescents' uncertainties. It is known that people use more social information when they are uncertain, but despite abundant evidence for adolescents' social susceptibility, the link between uncertainty, social susceptibility and adolescent risk-taking is not understood. Previous experiments did not allow for a clean assessment of peoples' subjective uncertainties. We therefore propose a novel paradigm and Bayesian modelling enabling us to investigate (1) how risk-taking and subjective uncertainties develop when people either take experience- or description-based risks, and (2) how adolescents' social information use depends on their subjective experience of uncertainty (preregistration of task, sample and analysis of H1-H4 under https://osf.io/nsy69).

Methods

We report the data of n=165 subjects (aged 10-26, *m*= 15.82) who completed the task in our laboratory. The data collected was approved by our institutes' local ethics committee as part of a bigger developmental study. Subjects performed the *marble task* and a battery of other social decision-making tasks reported elsewhere, as well as the digit-span test for working memory capacity (Ramsay & Reynolds, 1995) and the CFT-20R, a culture fair intelligence test (Weiß, 1998).

The marble task

In the *marble task*, we manipulated rewards, uncertainty and social information. The task was programmed in jspsych (de Leeuw, 2015) and presented in a regular browser. In 144 trials, we asked our subjects to draw a marble out of a risky or a safe marble-jar to accumulate as many bonus points as they could. Risky and safe jars differed in their proportion of red and blue marbles. Subjects could win points had they drawn a blue marble on a given trial. The risky option was a marble-jar containing red and blue marbles. The safe option only contained blue marbles. When subjects chose risky, they could win either 8, 20 or 50 points. The risky points were only awarded with one of the following probabilities 0.125, 0.25, 0.375, 0.5, 0.625 and 0.75. When subjects chose safe, they always gained five bonus points. Across trials, the risky option combined all possible values with all probabilities equally often, and value-probability combinations appeared in random order. After making 36 decisions, subjects received feedback about how many points they collected so far. Points were transformed into a monetary bonus (factor 0.0025), which was added to flat compensation of 10 € at the end of the experiment. Risks differed in two conditions, presented in a trial-wise random order and were either experience-based or description-based. In the experience-based condition (figure 1A), subjects were presented with a sequence of 9 pseudo-random draws of marbles from the jar before deciding. Based on this sequence, they had to infer the underlying proportion of marbles to make a good decision. Before they decided, we asked the subjects to indicate their estimate of the underlying proportion of red and blue marbles using a slider. To ensure that all subjects were presented with the same information, we randomly sampled binomial sequences before the experiment until the sequences' mean was as representative of the underlying probability as possible.

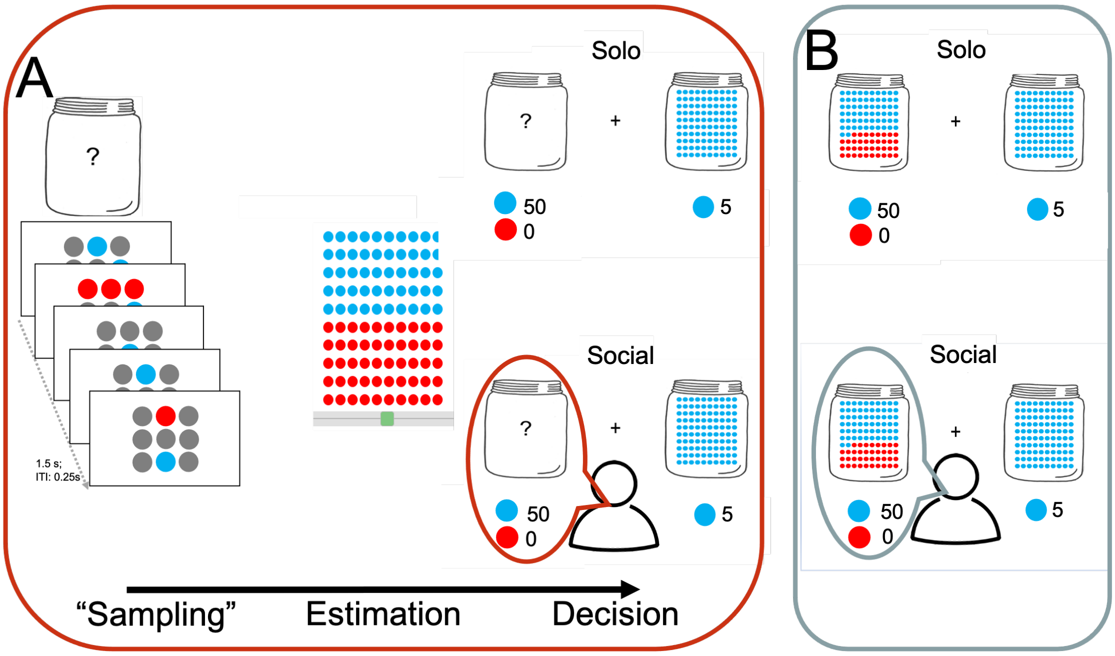

Figure 3.1: The marble task, where subjects decide between a risky or a safe marble jar. A) Subjects experience risks. They see a sequence of possible outcomes sampled from the outcome distribution and are then asked to indicate their estimate of the underlying probabilities on a slider. Then they decide whether they want to gamble with the distribution they had just experienced or gain a small number of bonus points with certainty. Subjects either are presented with social information (bottom) or not (top). B) Risks are described to the subjects by showing them the exact proportion of red and blue marbles in the jar. Decisions are either made with (bottom) or without (top) social information.

In the description-based condition (figure 1B), probability information was presented by showing an image of a jar containing 100 marbles. The proportion of blue and red coloured marbles in this jar represented the underlying probabilities, where the number of blue marbles shown indicated the probability of winning. Finally, in both risk-conditions subjects had to decide whether they wanted to take a risk and draw a marble from the jar containing a mix of red and blue marbles, thus have the chance to receive a large bonus or take a blue marble for sure, but only receive a small bonus. Described and experienced risks were nested within a solo and a social condition. After subjects made 72 decisions by themselves (solo), they made the same decisions again but saw a peer's advice before deciding (social). Because of an error, gambles with a probability of 0.675 were not included in the social condition. To find an advisor, we computed how many trials the current subject chose the risky option. We then selected an advisor who chose the risky option on average 20% more often than the subject. The advisors always were real subjects who participated in a previous experiment (Blankenstein et al., 2016).

Social influence in risk-taking as Bayesian learning

To comprehend how confidence, reward, and social information use interact across development, we formulated an *uncertain utility model* in which social susceptibility is understood as Bayesian updating; hence social impact depends on the subjects' uncertainty before receiving social information (equations in the supplement). The model has three components, the first two of which are rooted in stochastic utility theory (Blavatskyy, 2007) and the third implements Bayesian updating of the utility in the face of social information (Etz, 2017). The first component is reward-sensitivity, quantified by the parameter λ (figure 2.1).

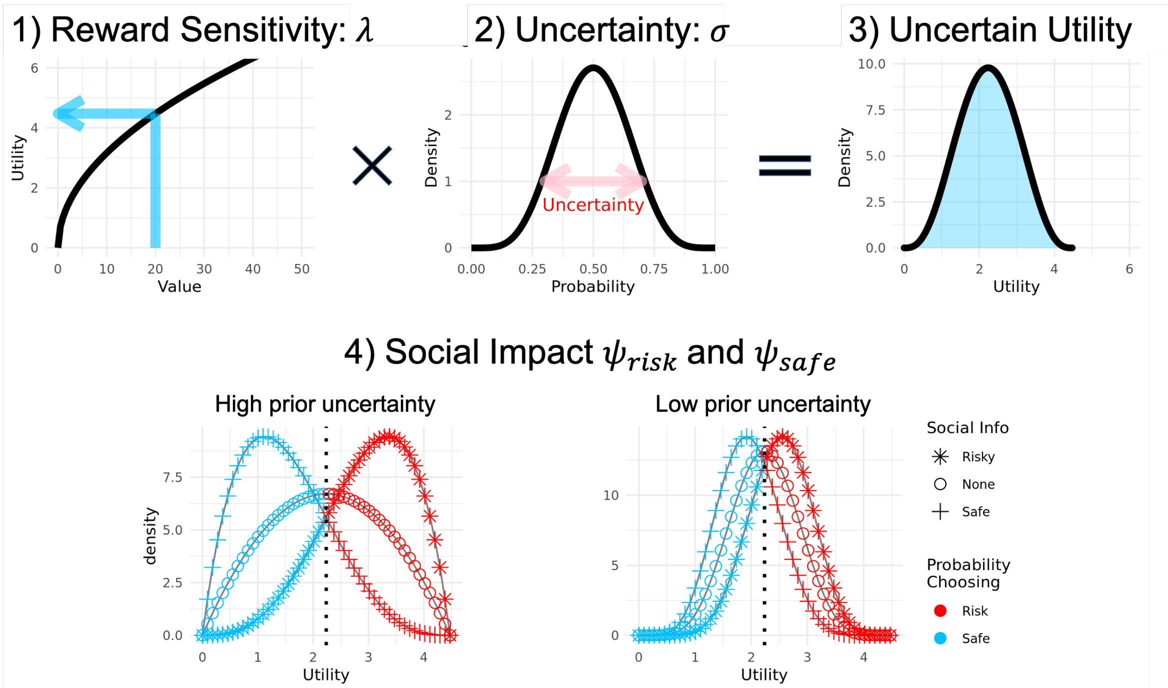

Figure 3.2: Uncertain utility model with social influence for one option with a value of 20, which is granted with some probability, about which the decision-maker is uncertain. 1): Objective values (x-axis) are transformed into a subjective utility (y-axis) using a power function, where λ models the curvature of the utility function. $\lambda < 1$ describes risk-aversion and $\lambda > 1$ risk-seeking attitudes. Shown is a utility function of a risk-averse individual. 2) Beta distribution, which models the subjects' uncertainty, σ, about whether the risky outcome will be received. 3) Convoluting the two components results in a distribution over utilities. 4) Social Influence and choice. The probability to choose the safe option with a utility of 5 on a given trial is determined by the integral from 0 to the utility of the safe choice option (vertical black line). Social information skews the distribution, which results either in a riskier (asterisks) or safer (crosses) decision policy as compared to a choice problem which is subject to the same underlying utilities and probabilities but does not feature any social information (circles). The impact of the same social information depends on individuals' uncertainties and is high when prior confidence is low (left) and low when prior confidence is high (right).

This parameter transforms objective, expected values in the task into a subjective utility where greater values speak for a greater reward sensitivity and risk preference. The second component assumes that people are uncertain about which utility the risky option holds. We model subjective uncertainty with parameter σ (figure 2.2). The third component, ψ (figure 2.4)., relates to the weight of social information on an individual's belief. Note that in a Bayesian framework, the impact of novel information can be different from the weight that individuals assign to novel information. In our case this means that certain individuals (with a low σ), the same social information with the same weight will have a lower impact on the overall decision as compared to individuals who are uncertain (with a high σ). We quantify this social impact with the Kullback-Leibler-Divergence (KL-Divergence) between solo and social choices. Social impact thus depends on how strongly subjects weigh social information and on how uncertain they were before observing social information. The parameter λ denotes the subjects' general reward-sensitivity independently of whether they take experience- or description-based risks. The other parameters take different values depending on whether subjects take experience- or description-based risks. While in the model, subjects use social information to reduce their uncertainty; this is not the only mechanism by which adolescents are thought to be susceptible to social information. In line with the framework presented in Ciranka & van den Bos (2019), we implemented three alternative models relating to the hypotheses that social influence mostly 1) distracts adolescents or 2) makes adolescents more sensitive to rewards and 3) a baseline model which did not assume any impact of social information (see supplementary equations 6 & 7). Using approximate leave one out (loo) cross-validation and the resulting loo-information criterion (looic; Bürkner et al., 2020), we judged which model best predicts our subject's behaviour. The models themselves are Bayesian models of cognition, but we also formulated the models in a hierarchical Bayesian way (supplementary figure 1). Hyper priors for the model parameters have been assumed based on different age groups (10-12; 13-15; 16-19; 19-22; >22). Model fitting was done using the NUTS sampler implemented in stan (Carpenter et al., 2017), with four chains and 6000 iterations per chain, 2000 of which we discarded as a warmup. The Markov chains' convergence was verified visually and by consulting $\hat{R}$ (Vehtari et al., 2020).

Statistical analysis

In our preregistered "model free" analysis, we inspected whether the experimental manipulations had different effects on our subjects' decisions, depending on their age. For this, we constructed a generalized linear model, predicting each decision with a logit link function, by coding a risky choice as "1" and a safe choice as "0". We dummy-coded risk-conditions ("0" for described and "1" for experienced) and the quality of social information ("-1" for safe "0" for none and "1" for risk) as categorical predictors and included the expected value of each decision as a continuous predictor. We also included orthogonal linear and quadratic polynomials of our subjects' age and their interactions with the experimental manipulations. By including regressors of subjects' test scores for working memory capacity (Ramsay & Reynolds, 1995) and fluid intelligence (Weiß, 1998), we attempted to control for cognitive factors which might otherwise be a confound, especially in a developmental context. Finally, we included random intercepts per subject. We used stan (Carpenter et al., 2017) and the brms package (Bürkner, 2017) for R (R Core team, 2020), using brms default priors for all statistical inference. All analyses were conducted with heavy reliance on the tidyverse (Wickham et al., 2019). For understanding the relationship between age and the parameters of the *uncertain utility model*, we estimate a multivariate Bayesian linear regression that accounts for within-subject correlations in different model parameters. We include age predictors for linear developmental pattern and adolescent-specific (second-order polynomial of age) patterns in the *uncertain utility model*s' parameters.

Results

In the present study, we examined the developmental trajectories of social influence under different types of uncertainty by using a novel experimental paradigm and by specifying a formal model of social influence. Before we turn to the preregistered hypothesis on adolescent-specific effects and the modelling results, we report descriptive statistics and main effects of the logistic regression (figure 3).

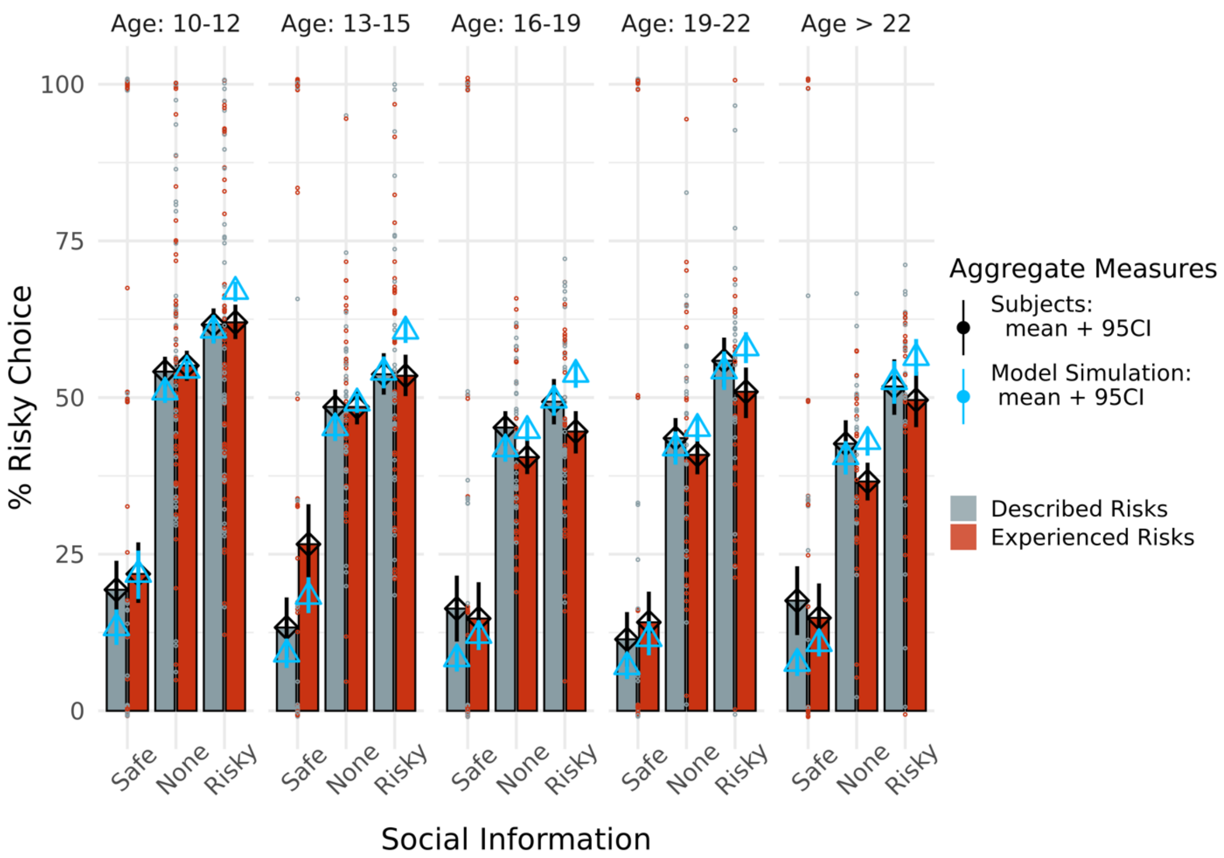

Figure 3.3: Behavioural results. Percentage of risky decisions in the marble task (y-axis) by social information type (x-axes). Age-groups are depicted in the panels. Bars and black shapes correspond to group-level means of risky choice, with the bootstrapped 95% confidence interval of the mean as error bars. Blue shapes denote posterior predictions from the model depicted in figure 2.

As expected, subjects chose the risky option more often when the expected value of the risky option was higher (b_EV= 0.20, CI = [0.20, 0.21]). Subjects were less risk-taking when taking experience-based risks as compared to description-based risks (b_experience = -0.14, CI= [-0.24, -0.04]). On average, all subjects reacted to social information as expected. More risk-taking occurred when social information was risky (b_socialrisk = 0.28, CI = [0.18, 0.39]), and less risk-taking when social information was safe (b_socialsafe = -0.32 CI= [-0.54 – -0.11]). Finally, risk-taking was not confounded with developing cognitive capacities; neither working memory (b_digitspan= 0.02, CI= [-0.04, 0.08]) nor fluid intelligence (b_cft= -0.03, CI= [-0.14, 0.08]) had a credible relationship with our subject's decision to take risks.

Now we turn to our preregistered hypotheses. We were interested in whether people in general used social information more when took experience-based as opposed to description-based risks in the marble task. We tested this by examining how social information interacted with whether subjects took experience- or description-based risks. When social information was risky, there was no credible difference between experienced or described risks (b_risky:experience = -0.03, CI=[-0.13, 0.18]). However, when social information was safe, people tended to use it more when they experienced risks first hand (b_safe:experience = 0.45, CI=[0.16, 0.73]). We thus only partly confirm this hypothesis. Further, the propensity to make a risky decision declined with age (b_age= -53.27 CI = [-92.98, -12.74]), whereas no quadratic age trend was observed (b_age^2= -15.42, CI = [-20.99, 49.89]). The second preregistered hypothesis was that there would be an adolescent peak in risk-taking when taking experience- but not description-based risks. This relates to the positive interaction between quadratic age and the risk-conditions. This interaction was not credible (b_age^2: experience = 5.21, CI=[-9.08, 20.38]). The same interaction was negative and credible for the linear age term (b_age: experience = -29.04, CI=[-43.74, -13.53]), suggesting that during development, individuals increasingly differentiate between risk and uncertainty. The third preregistered hypothesis stated that adolescents generally use more social information irrespective of uncertainty. We tested this with the interaction between quadratic age and social information use. Contrary to our expectations social information use did not peak in adolescence for risky (b_socialrisk: age^2= 6.11, CI=[-9.95, 22.00]) or safe social information (b_safe:age^2= 11.66, CI=[-20.83, 43.12]). Finally, the last preregistered hypothesis (H5) was the most specific of our hypotheses, which followed from H2 and H3. We were interested in whether the interaction between uncertainty and social information use is less strong during adolescence than members of other age groups. This corresponds to a negative three-way interaction between social information use, experience and quadratic age. This interaction was not credible either for safe (b_safe:experience:age^2= -14.53 CI= [-7.82, 37.93]), nor for risky social information (b_risky: experience:age^2= 5.30, CI= [-17.24, 27.52]).

Modelling results

To understand how social influence operates on the level of cognitive processes, we compared the uncertain utility model depicted in figure 2 to three other models that implemented different assumptions about the nature of adolescent social sensitivity (Ciranka & van den Bos, 2019). Based on this procedure, we found that the uncertain utility model which assumed that people integrate safe and risky social information into their beliefs in line with their uncertainties, described our subjects' behaviour best, and the distance to the next best models' looic was considerable (>500). As such, model comparison confirms the preregistered hypothesis (H4), that our subjects' social susceptibility would be best characterized as social learning under uncertainty. The best-fitting model predicts subjects' behaviour in all age groups shown (figure 3 blue and black point ranges, respectively). Unlike the previous behavioural analysis, modelling also allowed us to get an insight in the development of the cognitive processes that are implied by the models' parameters. Having established that the model reproduces our subjects' decisions, we were therefore interested in how age and quadratic age relates to the model's parameters.

For this, we fit a multivariate regression model on the posterior modes of the model parameters using age and quadratic age as predictors. We depict the full posterior of the regression weights in figure 4. Reward sensitivity (λ) was getting smaller with age but surprisingly, adolescents might have been least reward sensitive as implied by the credible quadratic age regressor (figure 4A). Experienced risks resulted in much greater subjective uncertainty (σ) compared to described risks (figure 4 B). Subjective uncertainty decreased linearly with age. Older subjects also were slightly less uncertain than younger subjects (figure 4 B). Together this suggests that across development, people generally became more certain about whether to take a risk or not. Finally, ψ_{risk} and ψ_{safe} did not undergo any credible age trends neither under risk or uncertainty (figures 4 C and D). This suggests, that subjects in put a similar weight on incoming social information across development.

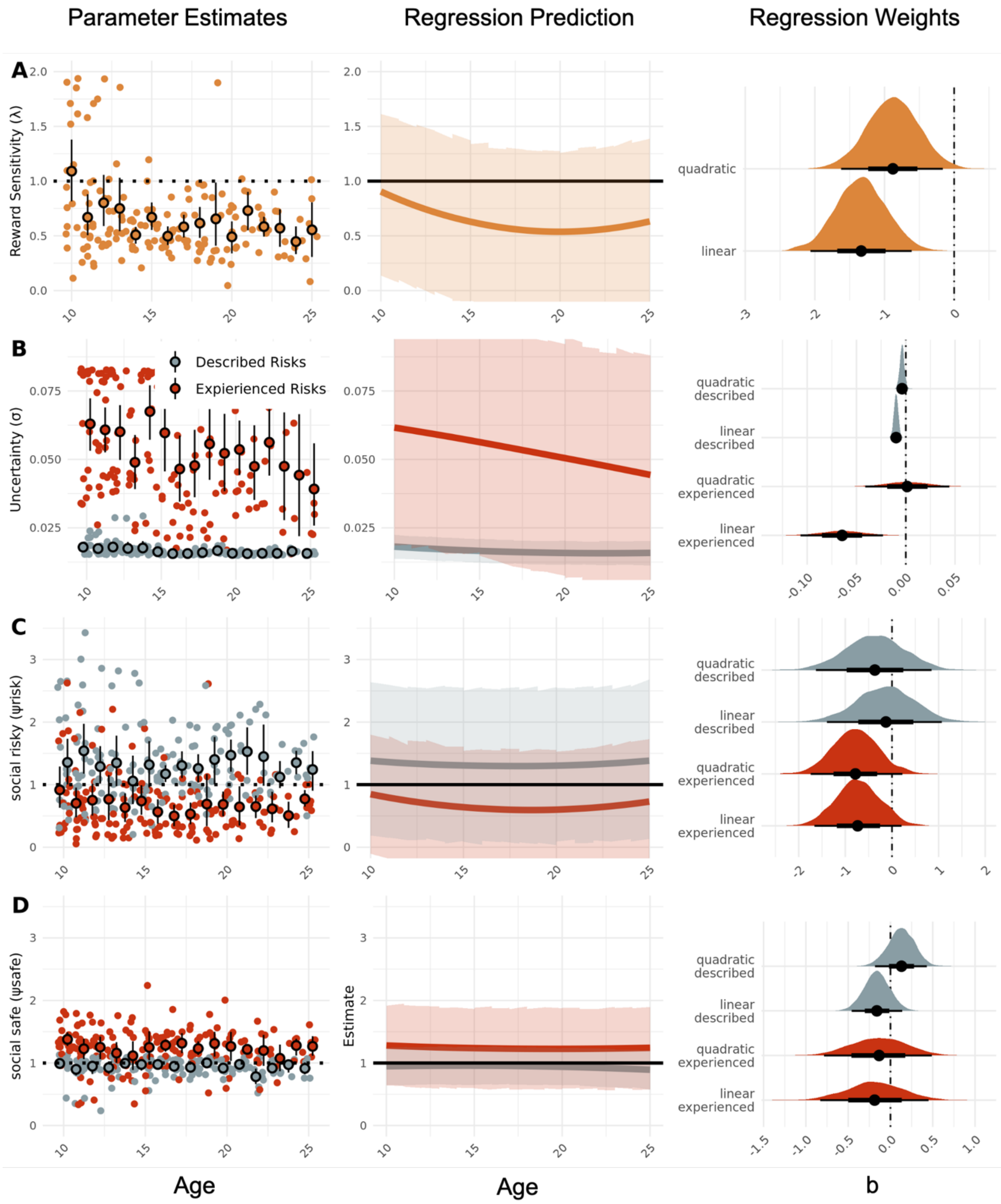

Figure 3.4: Age trends in the social influence model. The first column depicts the posterior mean of the parameter estimates for each individual (small dots) and on the group level with the bootstrapped 95% confidence interval of the mean (large dots) on the y-axes, by age on the x axes. The second row shows predictions from a multivariate regression model, where standardized, orthogonal predictors of linear and quadratic effects of age have been regressed on the respective parameters in the first column. The third column shows the posterior distribution of the regression weights. The point interval and grey hues correspond to the 95%, 80% and 50% highest density interval (HDI). The row in A) shows subjects' reward sensitivity, B) denotes their confidence, C) the weight of risky social information and D) the weight of safe social information where grey colours correspond to the estimates given decisions under risk and red to estimates given decisions under uncertainty.

To quantify the impact of social information given our subjects' uncertainties, we computed how strongly our subjects' beliefs differed between the solo and social condition. We quantified this difference with the subject-level average Kullback-Leibler divergence between solo and social utilities. For examining developmental differences in social impact, we consulted a regression model containing age and quadratic age and dummycoded experience and description trials as "1" and "0" respectively. In line with H2, social impact was bigger when subjects experienced risks as opposed to being provided with a description of risks (b_expierience=0.05; CI= [0.03,0.07]). Social impact decreased with age (b_age=-1.36 CI= [-2.19, -0.51]). We do not find a credible quadratic age component (b_age^2=0.63, CI= [-0.21, 1.47]) that would be indicative of an adolescent peak in social susceptibility. We also found no interaction between age or quadratic age and whether risks were experienced or described (b_experience:age= -0.86, CI= [-2.08, 0.32]; b_experience:age^2= 0.02 CI= [-1.16, 1.19]). These results allow to speculate that developmental differences in subjective uncertainties are a mechanism by which social susceptibility decreases across development.

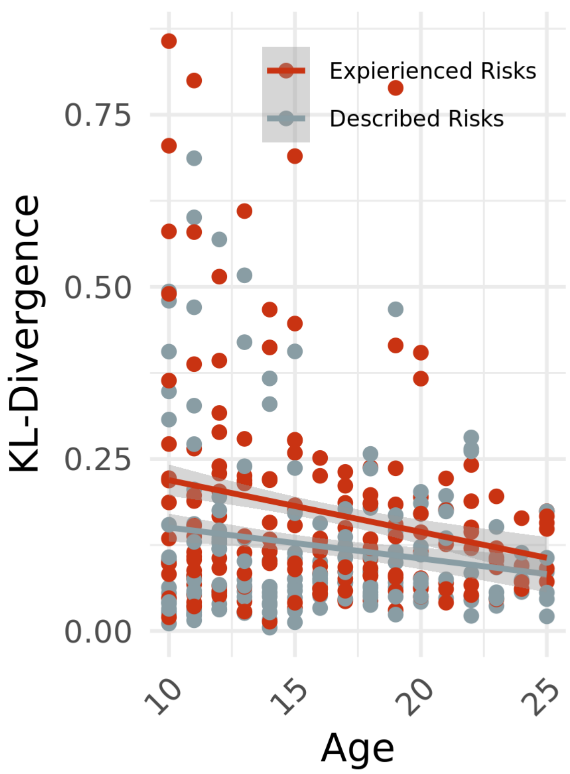

Figure 3.5: Kullback-Leibler divergence between the solo and safe utility distribution as a measure of social impact (y-axis) by age (x-axis). Lines show the linear fit between age and social impact.

Discussion

This study investigated the role of uncertainty in social susceptibility and risk-taking across adolescence. Adolescents are known to take more risks than people in other age groups, especially when they are with others. Here we hypothesized that developmental differences in risk-taking and social susceptibility relate to developmental differences in people's uncertainties. To test this idea, we introduced the *marble-task*, allowing us to manipulate different levels of uncertainty by comparing experience- and description-based risk-taking (Hertwig et al., 2004). To gain insight in the underlying cognitive processes, we formulated an *uncertain utility model* that quantifies subjective uncertainties in risk-taking and formalizes social influence as Bayesian updating. Our study yielded three important results: 1) subjective uncertainty linearly decreased across adolescence, and 2) this decline in subjective uncertainty fully explained why the impact of social information was strongest in early adolescence, because 3) there was no developmental difference in the weight assigned to social information. These results provide novel insights in the role of peer influence in adolescent risk-taking, which will be further discussed below.

As expected, subjects were more risk-averse and more uncertain when taking experience-based as opposed to taking description-based risks, which is in line with research showing that people are "uncertainty-averse" (Eichberger & Kelsey, 1996; Epstein, 1999; Tymula et al., 2012). Furthermore, we replicated earlier findings showing that description-based risk-taking declines with age (Blankenstein et al., 2016; Defoe et al., 2015; Rosenbaum & Hartley, 2019). Contrary to hypothesis H1, adolescents' uncertainty aversion was not reduced compared to children or adults. This is at odds with previous studies in which adolescents took more risks under uncertainty than adults (Cassotti et al., 2014; Figner et al., 2009; Tymula et al., 2012a; van den Bos & Hertwig, 2017). However, a crucial difference between the current and previous studies is that previously, uncertainty was either description-based (Tymula et al., 2012; van den Bos & Hertwig, 2017), or required exploration or trial-and-error learning (Cassotti et al., 2014; Figner et al., 2009; van den Bos & Hertwig, 2017). Opposed to previous experiments, but like many situations in real-life (Pleskac, 2008), our subjects took experience-based risks but could not "look before they leap", and did not get instant feedback about the outcomes of their choice, eliminating developmental confounds such as feedback processing or exploration. In sum, our results replicate previous findings by showing that people are uncertainty averse, but also show that the role of uncertainty in developmental trajectories of risk-taking is more complex than previously thought.

In line with the notion of uncertainty aversion, the *uncertain utility model* enabled us to show that subjects were indeed more uncertain when taking experience- as opposed to description-based risks. Importantly, our analysis revealed that younger subjects were generally more uncertain about how to decide (see also Jepma et al., 2020). These results are remarkably consistent with fuzzy trace theory (Reyna & Brainerd, 1995), suggesting that people develop a better intuition about how to decide and which risks they are willing to take as they mature (Rivers et al., 2008). For experience based risks, the developmental decrease in subjective uncertainty is likely amplified by the maturation of other processes like learning (Nussenbaum & Hartley, 2019) and attention (Kadosh et al., 2014). Our model also suggests that subjects were even somewhat uncertain when they took description-based risks (see also Moutoussis et al., 2016). This is in line with previous studies suggesting that when full information is available people still only have a vague grasp of their preferences, but that preferences become clearer across development (Reiter et al., 2019). In adults it was shown that uncertainties make novel information more impactful during learning (Behrens et al., 2007; Dayan & Daw, 2008; Nassar et al., 2010) and drive exploration (Daw et al., 2006; Schulz et al., 2019; Wu et al., 2018). That adolescents are more uncertain than adults might be an indicator of their increased tendency to explore (Romer et al., 2017) and help them to better adapt to changes in their environments (Gopnik et al., 2017; Tenenbaum et al., 2011). Acknowledging adolescents' uncertainties is thus crucial to comprehend other contextual modulators of their propensity to take-risks and explore outside of laboratory contexts, for instance why adolescent risk-taking changes when they are in a social context (Blakemore & Mills, 2014; Steinberg, 2008).

The *uncertain utility model* enabled us to tease apart uncertainty-driven susceptibility to social information, from other social motivations that would manifest in the weight that people assigned to social information independent of their uncertainties. In general, confirming H2, greater uncertainty was related to greater social information use. Because adolescents' risk-taking propensity is often influenced by their peers (Pfeifer et al., 2011; Steinberg, 2008), we expected adolescents to additionally put a stronger weight on social information than adults or children (H3). However, opposed to H3, we do not find any developmental differences in the weight that people assigned to social information. At first sight, this finding contradicts previous research showing that when taking risks, adolescents use social information more than adults (Braams et al., 2019; Chein et al., 2011; Ciranka & van den Bos, 2019). However, our results still show that social information impacted the youngest subjects most. Our finding that social impact in risk-taking declines with age matches other studies showing similar developmental trends of social impact in risk-taking (Blankenstein et al., 2016; Braams et al., 2019), risk-perception (Knoll et al., 2015, 2017), prosocial behaviour (Foulkes et al., 2018) and rule-following as well as belief formation (Molleman et al., 2021). However, our results offer a novel perspective towards these developmental trends. Subjective uncertainties potentially constitute a unifying mechanism explaining why social impact follows similar developmental trajectories in different domains. Younger people may simply be more uncertain of how to decide. These results also emphasise that to attenuate adolescents' alleged tendency to jump off the bridge that their friends jump off, it is important to identify when and why they are uncertain about which bridge to jump off in the first place.

Our study has limitations that provide starting points for future research. For instance, we did not manipulate the advisor's identity or presence. Research suggests, however, that adolescents' risk-perception is more easily changed by peers than by adults (Knoll et al., 2017) whereas when taking financial risks, adults' advice might be more impactful (Engelmann et al., 2012). Manipulating the advisors' identity in the *marble task* could help to shed light into which sources adolescents rely on most when reducing their uncertainties about whether to take a risk or not. Further, it was suggested that adolescent social susceptibility is more substantial in situations when adolescents feel observed by others (Somerville et al., 2018) and anticipate being rejected or evaluated (Crone & Konijn, 2018; Somerville, 2013). Manipulating peer presence in our task could help to differentiate the development of social learning in risk-taking from other motivational processes associated with being observed by others (Sanders et al., 1978; Zajonc, 1965). Finally, we gave our subjects no agency over their experiences. While this choice resulted in experimental control over their uncertainties, it could have made us insensitive to cognitive processes that may mediate developmental differences in experience-based risk-taking (van den Bos & Hertwig, 2017). Notably, different risks adolescents take in real-life tap into different uncertainties which in turn require different cognitive processes to act upon (Volz & Gigerenzer, 2012). To date, it is unknown which uncertainties impact adolescents' risk-taking vulnerability in the real world. Future research should therefore attempt to provide a better mapping between the uncertainties that adolescents encounter, how the related cognitive processes develop and which paradigms are valid tools for measuring these processes.

Summary and Conclusion

In sum, we showed that social susceptibility in risk-taking depends on peoples' subjective uncertainties. We found no evidence for developmental differences in how strongly people weighted social information. Nevertheless, social susceptibility was biggest in the youngest subjects and steadily decreased with our subjects' age. These developmental trends in social susceptibility could be fully explained by greater uncertainty in younger individuals. Our results imply that a focus on developmental changes in reward- (Shulman et al., 2016) or social sensitivity (Blakemore & Mills, 2014) may be insufficient to understand adolescent risk-taking and their susceptibility to peer influence. Instead, our results contribute to a unifying picture of the development of risky behaviour and social susceptibility by focussing on how peoples' uncertainties change as they mature. Our results imply that more effort needs to be spent identifying the uncertainties that young people face in different developmental stages.

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4

Social norms in adolescent risk engagement and Recommendation

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Abstract

Social influence is an important determinant of adolescent risk-taking, but little is known about how social norms contribute to adolescents' tendency to recommend and engage in risky behaviours. Using the Adolescent Risk-taking Questionnaire, we assessed subjects' (n=198, age=10-26) propensity to engage in and recommend risk-taking as well as their perception of risk-norms. Adolescents recommended risk-taking more often compared to children and young adults. Perceived social norms were the most important factor predicting engagement in risky behaviours, and adolescents perceived risk-taking to be more normative than children or adults. Our findings highlight two mechanisms that contribute to adolescent risk-taking; active recommendation and perceived social norms. On this basis, we discuss potential means to attenuate excessive adolescent risk-taking.

Introduction

The most important determinants of adolescent risky and deviant behaviour are thought to be social. For instance, the number of teenagers in a car is positively correlated with the likelihood of an accident (Carter et al., 2014), teenage crime is more often committed in groups than alone (Shulman et al., 2013) and peers play a pivotal role in adolescents' decisions to start smoking or use illicit drugs (Ragan, 2016). Despite the strong correlations between social factors and adolescent risk-taking, there still is much to learn about why adolescents seemingly take more risks when they find themselves in social contexts. While it was suggested that adolescents may simply join peer groups with similar attitudes (Kandel, 1978; Young et al., 2014), experimental evidence suggests that adolescents actively influence each other's risky behaviour and risk-attitudes (Albert & Steinberg, 2011;Blakemore & Robbins, 2012; Brechwald & Prinstein, 2011; Chein et al., 2011; Helfinstein et al., 2015; Knoll et al., 2015; Molleman et al., 2019; Schriber & Guyer, 2016; Shulman et al., 2016; Somerville, 2013; van den Bos et al., 2018; van Duijvenvoorde et al., 2016).

Most theories explain heightened adolescent risk-taking in social contexts by assuming that adolescents process social information differently than adults or children (Blakemore, 2008; Steinberg, 2008). Some state that merely being in a social situation itself forces adolescents to focus more on the rewards associated with risky behaviour and thus leads to increased risk-taking (Shulman et al., 2016). Other standpoints emphasise that adolescents are particularly sensitive towards social information in general (Blakemore, 2008). Experimental research based on these theories usually involves disclosing others' decisions to subjects, or manipulating peer presence, and examining how social context influences behaviour (Blankenstein et al., 2016; Braams et al., 2019; Chein et al., 2011; Ciranka & van den Bos, 2019; Knoll et al., 2015; Molleman et al., 2019; Reiter et al., 2019; Somerville et al., 2013, 2018). It is easy to imagine how "black sheep" pressure their friends to take risks or break the law, but social influence in the real world likely results from at least three processes — (1) copying observed behaviours (Bandura et al., 1961), (2) active peer pressure (Shepherd et al., 2011), (3) conforming to perceived social norms (Cialdini & Goldstein, 2004)— or a combination of the three.

Although, evidence suggests that adolescents are more likely than adults but less likely than children to directly copy observed peer behaviour (Blankenstein et al., 2016; Braams et al., 2019; Ciranka & van den Bos, 2019), little is known about adolescents' tendency to actively recommend risky behaviours. While it is long- established that peer-pressure has a strong impact on adolescent deviant behaviour (Brown et al., 1986), whether adolescents are more likely to actively recommend risk-taking has received less attention. However, the numerous reports of increased risk-taking in peer contexts during adolescence and the close connection between risk-taking and peer encouragement (Brechwald

& Prinstein, 2011; Brown et al., 1986; Shepherd et al., 2011), lead us to hypothesise that adolescents would be more likely than children or young adults to recommend risky behaviours.

It is also not known to what extent social norms contribute to engagement in risky behaviour across adolescence. Although studies have shown that adolescents, like adults, conform to social norms when taking risks (Ragan, 2016; van de Bongardt et al., 2015), it remains unclear if sensitivity to social norms peaks in adolescence in direct comparison to other age groups. Theory has it that peer approval and belonging are especially motivating for adolescents (Blakemore & Mills, 2014; Crone & Dahl, 2012; Telzer, 2016), and conforming to peer norms is a straightforward way to gain approval and increase belonging (Blakemore, 2008; Blakemore & Mills, 2014; Cialdini & Goldstein, 2004; Ciranka & van den Bos, 2019; Crone & Dahl, 2012; Pickett et al., 2004). For this reason it is to expect that, relative to children and young adults, adolescent risk-taking would be more strongly influenced by social norms (Albert & Steinberg, 2011; Blakemore & Mills, 2014; Nelson et al., 2016).

In sum, adolescent risk-taking occurs more often than not in social contexts. Despite the big role of social information in adolescence, not much is known about whether adolescents are also more likely to actively recommend risk-taking than are people of other ages. It is also not known to what extent they are more sensitive to perceived risk-norms (in absence of overt peer behaviour). Addressing these questions will help to understand why and when adolescents are more likely to engage in risky behaviours than other age groups and how the interaction between social factors and individual judgments contribute to the potential of adolescent risk-taking to escalate. In this study, we therefore investigate two main questions: (1) are adolescents more likely than adults and children to actively encourage risky behaviours? (2) does the relationship between perceived social norms and the engagement in risky behaviours peak in adolescence? To answer these questions, we assessed our participants' propensity to engage in and recommend risky behaviours, as well as their perceptions of how frequently others engage in those behaviours as a measure of their perception of descriptive social norms.

Methods

We invited N = 198 (90 female) German subjects aged from 10 to 26 years (M = 16.15, SD = 4.6) to our laboratory for completing multiple social experiments (Molleman et al., in prep), an assessment of their general cognitive (CFT-20; Weiß, 1998) and emotional intelligence (Reading the mind in the eyes; Megías-Robles et al., 2020) as well as a survey study. We detail the results of the survey study in this paper. Subjects were recruited from our institute's local database from which, after a telephone screening, all healthy minors and 64 legal adults were invited. While our statistical analysis treats age as a continuous variable, in the text we refer to subjects between 12 and 21 years as adolescents, thus adopting a similar heuristic as Shulman et al., (2016). Other than Shulman et al., (2016), we label 10-12 year olds as children because puberty (and therefore the onset of adolescence) related physiological changes are greatest on average at 12.8 years of age (Petersen et al., 1988). The paper and discussion focus on adolescence, but we also recruited children and young adults, otherwise we would not be able to make statements about adolescents in comparison to other age groups.

We asked subjects to complete the German version of the Adolescent Risk-Taking Questionnaire (Gullone et al., 2000). The ARQ consists of 22 examples for risky behaviours (see supplementary table 1 & 2). Respondents were asked to indicate on a scale ranging from 0 to 4 how risky they perceive each behaviour to be and how often they engage in each behaviour described. Additionally, we asked participants to evaluate the questionnaire scenarios on two dimensions not included in the original inventory: how many of their peers engaged in this behaviour (from 0 = very few to 4 = very many) and how recommendable they considered behaviour to be to someone in general (from 0 = not at all recommendable to 4 = highly recommendable). Each of the four surveys was interleaved with other experiments and presented in random order. The authors of the ARQ identified four factors of the questionnaire: thrill-seeking behaviours, reckless behaviours, rebellious behaviours and antisocial behaviours. These factors can be further collapsed to describe desirable (thrill-seeking) and undesirable (reckless, rebellious, and antisocial) behaviours. An adult study similar in the design to this study found opposite patterns of engagement and recommendation for "desirable" and the "undesirable" risk behaviours (Helfinstein et al., 2015). Further it has recently been proposed that this distinction provides a more relevant framing for understanding adolescent risk-taking (Duell & Steinberg, 2019), we therefore applied this distinction in our analyses as well. Participants completed the survey individually on computers using jsPsych (de Leeuw, 2015). All subjects—and, if they were underage, their parents—gave their informed consent to participate in this study, in accordance with the Declaration of Helsinki. Prior to any data collection, the present study was approved by our internal ethics committee (protocol number: A 2018/23).

Statistical Analysis

Responses were analysed using Bayesian multivariate generalized mixed models with random intercepts for subjects and questionnaire subscales, utilizing a cumulative link and fitted via the No-U-Turn sampler (NUTS) implemented in *stan* (Carpenter et al., 2017), using the *brms* package (Bürkner, 2017) for R. Dependent variables were the reported propensities to engage in a behaviour and to recommend the same behaviour. The multivariate model assumed that the dependent variables were correlated within subjects. Predictor variables were participant age, ratings of the riskiness of the behaviour in question, and perceived social norms, as quantified by an estimate of how many friends and acquaintances engaged in the behaviour. Developmental changes in social influence were modelled as the interaction between age and perceived social norms. We adjusted for gender differences. We ran two separate regressions: for desirable and undesirable risks. For each regression, we ran six chains with 20,000 samples each and set a warmup of 10,000 samples in order to ensure an effective sample size of at least 10000 samples for each predictor. We performed approximate leave-one-out cross-validation on the log-likelihood from the model posteriors (Vehtari et al., 2017) to and thus compare alternative explanations to the one we mainly consider in this article with regard to their predictive accuracy.

Specifically, we asked whether the age predictors should be included and if so, if they should be linear, quadratic, or both. Further, we post-hoc explored the possibility that general or social intelligence constitutes a confound in our results by adding the outcomes of age-appropriate versions of the "CFT-20" and of the "reading the mind in the eyes" test as main effects and their interactions with age in another regression model

The quadratic age regressor as constructed by us had its maximum at 18 years of age. Thus, a higher estimate of this regressors weight suggests stronger propensities during late adolescence. This specific peak was the result from creating orthogonal predictors for linear and quadratic age using R's "poly" function and the age range of our sample. The predictor is sensitive to a recently reported peak in risk-taking propensities during late adolescence (Steinberg et al., 2018). In a post hoc analysis, we explored age effects in the perception of social norms by using subjects' norm-estimates as a dependent variable, with a quadratic age predictor, random intercepts for subjects and subscales, and a cumulative link.

We report the mean of the posterior distribution and the two-sided 95% credible intervals (CI) around each mean of the regression weights. Importantly, the Bayesian CIs which we report allow their direct comparison and interpretation as mean of and uncertainty about the regression weights; an interpretation that is unwarranted when using frequentist methods (Morey et al., 2016; Rouder et al., 2016). The inference criteria about the magnitude of and difference in magnitude between predictors are as follows: If the credible interval includes zero, the contribution of a predictor to the outcome is considered negligible. If their credible intervals overlap, the difference between predictors is considered negligible.

To determine whether the difference in engagement and recommendation was substantial, we tested the hypothesis that both measures differed with respect to a normally distributed effect size, δ. To establish the magnitude of this effect size, we fitted a Bayesian model, assuming

$$\Delta_{eng-rec_i} \sim \mathcal{N}(\delta_i * \sigma_i, \sigma_i^2), \qquad (4.1)$$

where $\Delta_{eng-rec}$ denotes the difference between propensity to engage and propensity to recommend, σ is the standard deviation, and i is an index for questionnaire subscale. We defined a region of practical equivalence, or ROPE (Kruschke, 2018), for δ with boundaries $[-0.1, 0.1]$, which corresponds to the generally adopted definition of a small effect size. We treated effect sizes as practically equivalent to a null effect (indicating that there is no difference in recommendation and engagement) when the two-sided 95% CI of δ overlapped with the ROPE. By defining a ROPE over the range of a small effect size we explicitly adopt a conservative inference strategy in order to protect us from overestimating the credibility of this difference. Finally, we compute Cronbachs' alpha of all scales analysed in order to judge the reliability of the survey instrument that we chose for the study.

Power

We use two methods to judge whether the effects reported by us are sufficiently large to be reliably detected with the analysis strategy we chose. First, we compute Bayes factors for all credible regression coefficients by comparing the posterior estimates to the priors implemented in brms (for a discussion on Bayes factors and frequentist power see Wagenmakers et al., 2010). Bayes factors quantify the strength of evidence in favour of the reported effects, given the uncertainty about the effect size. Second, we simulate 1000 new datasets based on the full posterior of the estimated regression weights. We then proceed to fit the same regression model again to each of these synthetic datasets, using four chains and 2000 samples per chain and then evaluate the probability with which we can credibly replicate the effect based on the effect size, uncertainty about that effect size and our sample size (post hoc power).

Results

We investigated the developmental and social correlates of participants' propensity to recommend and engage in risky behaviours. Overall, subjects were more inclined to engage in risky behaviours than they were to recommend them to others, when the scenarios described undesirable risk-taking. When the scenarios described desirable risk-taking, the opposite pattern was observed (Figure 1). We note that the inventory we used was sufficiently reliable as indicated by Cronbachs' alpha of 0.76 for both, engagement and recommendation (item level characteristics in supplementary tables S4.1 & S4.2). In what follows, we summarize the results of the regression analysis.

To begin with, we used approximate leave-one-out cross-validation to determine the predictive accuracy of the regression models containing different age predictors and potential confounds (Vehtari et al., 2017). This procedure yielded that the regression models containing quadratic *and* linear age as predictors but no measures of IQ, working memory or emotional intelligence, outperformed all other models we considered (see supplementary table S4.3 & S4.4 for details). Table 4.1 presents the results of the regression models estimating the propensity to engage in and recommend risky behaviours. Almost all credible effects reported in this table had Bayes factors exceeding 100, compared to the null hypothesis that there was no effect.

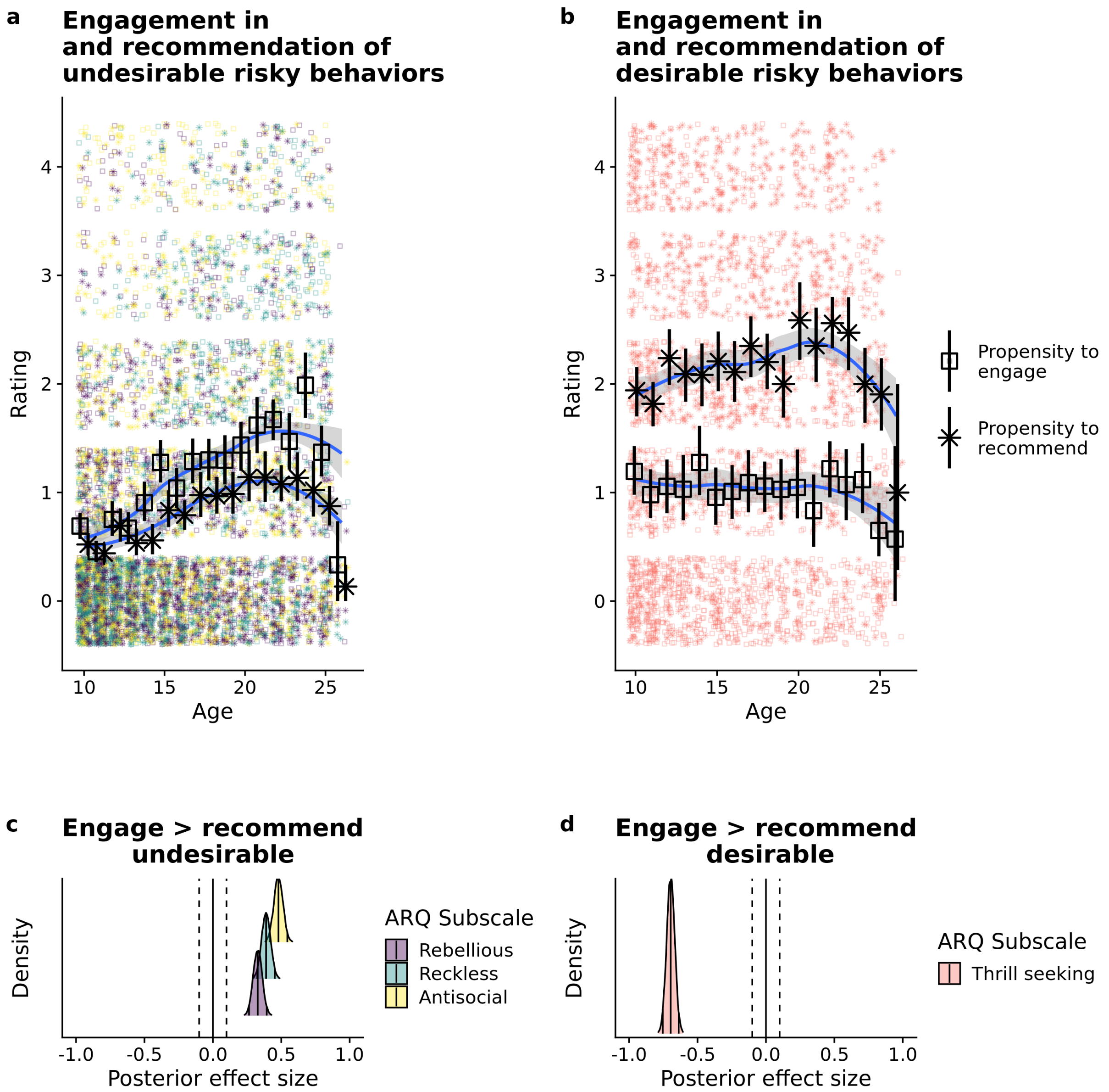

Figure 4.1: Propensity to engage in and recommend risk behaviours by age. The upper panel shows the difference between participants' propensity to engage in and to recommend the (a) undesirable and (b) desirable behaviours. The lower panel shows the posterior effect size distribution of this difference by ARQ subscale. Vertical lines denote the region of practical equivalence of the effect size, with boundaries [−0.1, 0.1], for (c) undesirable and (d) desirable risky behaviours. It can be seen that while undesirable subscales (c) are not credibly different from one another, they jointly show the opposite pattern of the desirable subscale (d).

One exception is the interaction between quadratic age and social norms in our participants propensity to recommend risky behaviour, which had a Bayes factor of 89. These large Bayes factors speak for strong effects and hint to that we indeed were able to detect those within our sample.

We also examined whether we could replicate the direction of the effects in table 1 on 1000 synthetic datasets generated from the full posterior of the fitted models (post hoc power). This was mostly the case with a replication probability of 1, except for regression terms involving linear age fitted on our subjects' propensity to recommend desirable behaviours ($p_{rep\_age} = .35$; $p_{rep\_age:HowManyOthers} = .59$).

Taken together, these two Bayesian approaches converge and allow some confidence that the methods we used were adequate for the inferences reported in this article.

Table 4.2. Regression weights of the multivariate mixed models. Values in brackets denote the 95% credible interval of the posterior.

Predictor	Recommend: Undesirable	Recommend: Desirable	Engage: Undesirable	Engage: Desirable
Risk	**-1.11 [-1.21, -1.02]**	**-0.33 [-0.43, -0.22]**	**-0.67 [-0.75, -0.59]**	**-0.50 [-0.62, -0.38]**
sex:female	0.07 [-0.38, 0.23]	-0.16 [-0.39, 0.06]	-0.14 [-0.38,0.10]	-0.1 [-0.35, 0.16]
HowManyOthers	**0.74 [0.66, 0.81]**	**0.54 [0.45, 0.62]**	**1.29 [1.20, 1.37]**	**1.17 [1.06, 1.29]**
LinearAge	6.59 [-10.73, 23.86]	**40.84 [29.99, 54.79]**	3.72 [-11.41, 17.85]	-10.24 [-29.04, 8.28]
QuadraticAge	**19.79 [2.50, 37.41]**	**29.26 [15.59, 42.93]**	-8.94 [-23.46, 5.57]	-3.94 [-14.25, 22.63]
HowManyOthers x LinearAge	-1.80 [-6.62, 3.07]	**-13.23 [-18.17, -8.35]**	4.07 [-0.43, 8.61]	0.94 [-4.90, 6.77]
HowManyOthers x QuadraticAge	**-5.70 [-10.45, -1.05]**	**-8.32 [-13.15, -3.47]**	3.20 [-1.10, 7.47]	-1.39 [-7.16, 4.30]

Note: Bold are the predictors with credible intervals that do not include a 0. The first column shows the estimates for the participants´ propensity to recommend undesirable behaviour. The second column shows the estimates for the propensity to recommend desirable behaviour. The third column shows the regression weights for participants propensity to engage in undesirable risky behaviours and the fourth column shows the propensity to engage in desirable behaviours.

We found that perceived social norms positively affected the propensity to recommend both desirable and undesirable risks. In line with our expectations, individuals were more likely to recommend risky behaviours if they believed that many others engaged in those behaviours. Moreover, quadratic age predicted recommendation of undesirable risky behaviours and, to an even greater extent, desirable risky behaviours. We also found a negative interaction between perceived social norms and quadratic age, which implies that late adolescents were more likely to recommend risks of which they thought that others' do not frequently engage in. For desirable risks, this negative interaction was on top of a credible negative linear age effect, suggesting that the influence of descriptive social norms on recommendation behaviour generally decreased across adolescence. Perceived social norms also predicted participants' propensity to engage in risky behaviours. Notably, against our expectations, neither age nor quadratic age was a good predictor of engagement in desirable or undesirable risks. Also, we did not find a credible interaction between perceived social norms and quadratic or linear age regressors; in other words, there was no indication that adolescents are particularly sensitive to social norms (Figure 4.2).

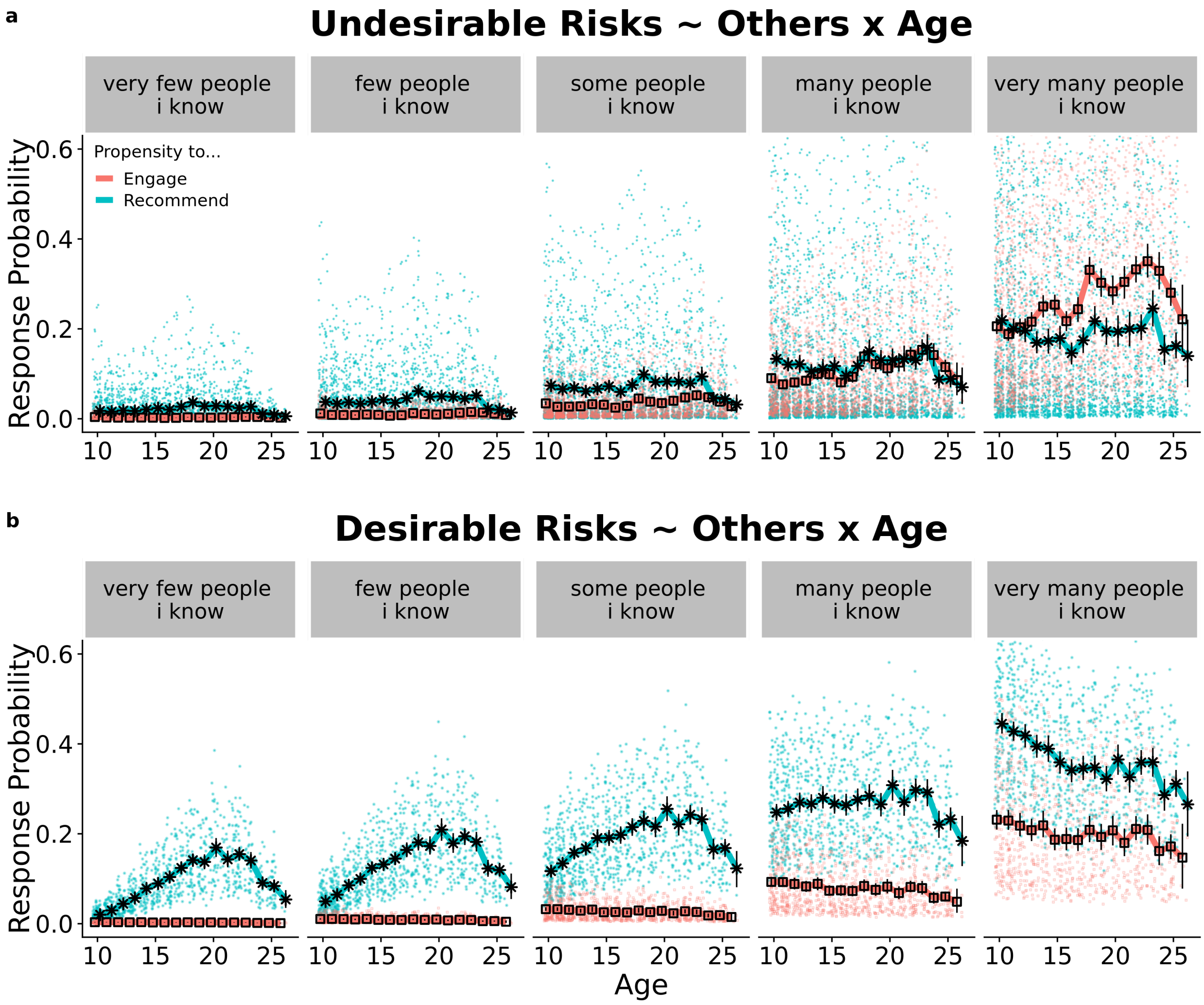

Figure 4.2: Posterior response probability for the strongest propensity to recommend (blue) and to engage in (red) desirable and undesirable risky behaviours by age and by strength of the descriptive norm. We show the posterior means, with the two-sided 95% confidence interval of the mean as error bars. Coloured dots refer to individual predictions under different covariate values. The panels visualize the interaction between perceived norms and age for risk engagement and risk recommendation. (a) Undesirable risks. As the perceived norm becomes stronger, adolescents are more likely to engage in risks than are other age groups (red line) but seem less likely to recommend them (blue line). (b) Desirable risks. There are no age differences in participants' propensity to engage in risky behaviours, but adolescents are more likely to recommend risky behaviours. As the perceived norm becomes stronger, this difference becomes smaller, as indicated by the negative quadratic interaction between perceived norms and age.

Finally, the absence of evidence for a direct interaction of age with social norms on risk engagement notwithstanding, exploratory analysis suggests an adolescent-specific *perception* of social information; they report that others engage in risky behaviours ($b_{quadratic\_Age}$= 11.50, CI = [3.00, 20.09]) more often than children or adults report. To investigate if this quadratic trend might be indicative of an over estimation, we calculated to what extent individual judgments about the propensity of others' risk engagement deviates from the mean of our samples' self-reported propensity (figure 3). Adolescents estimate overall deviates positively which could imply such overestimation, however confirmatory studies are needed.

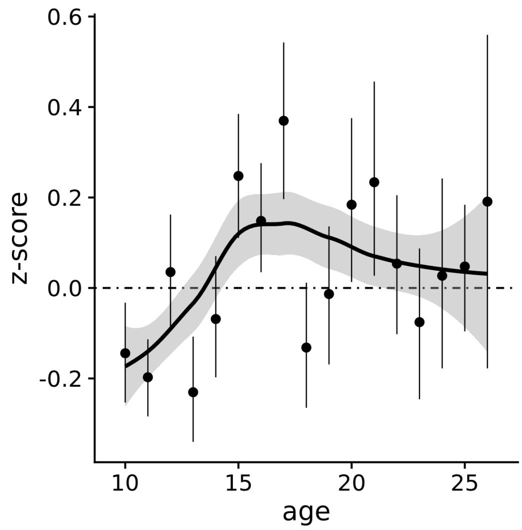

Figure 4.3: Over- and under estimation (positive and negative values, respectively) of others' engagement relative to the collected sample (y-axis) by age (x-axis). We show the mean and bootstrapped 95% confidence interval of the z-scored difference between the average self-reported propensity to engage in risky behaviours versus individual participants estimate of others' engagement by age. The fit line corresponds to locally estimated scatterplot smoothing with a bootstrapped 95% confidence interval.

As expected, participants' propensity to engage in risky behaviours generally differed from their propensity to recommend those behaviours (see Figure 1). We found opposite patterns of results for desirable and undesirable risks, which replicates a previous study using a similar approach (Helfinstein et al., 2015). That is, relative to their propensity to engage in risky behaviours, participants were less likely to recommend undesirable risks, but more likely to recommend desirable risks. This adds further evidence that desirable, recreational risk-taking and maladaptive risk-taking may be distinct constructs (Duell & Steinberg, 2019).

We also investigated how the differences between the decision to engage versus to recommend risky behaviours were related to our subjects' perception of risks and to their perception of social norms. Perceived risk contributed negatively to both engagement and recommendation. Notably, for undesirable risks, subjects' perception of risk reduced the propensity to recommend more strongly than the propensity to engage, as indicated by the nonoverlapping credible intervals of the respective predictors. In order words, it appears as if people give more consideration to risks when recommending risky behaviours than when engaging in those behaviours themselves. Along similar lines, the credible interval of the social norms predicting engagement in both desirable and undesirable risks was higher than and did not overlap with the credible interval of the social norms predicting recommendation of those behaviours. This implies, again in line with previous work, that subjects relied more strongly on social information when judging whether behaviours were appropriate for themselves than when judging whether they were appropriate for others.

Discussion

Adolescents are often seen as risk-takers, especially when in the company of their peers. Recent studies support the idea that directly observing and copying others can explain at least some of these social influence effects, and that social influence may be stronger in younger individuals than in adults (Blankenstein et al., 2016; Braams et al., 2019; Ciranka & van den Bos, 2019; Foulkes et al., 2018; Gardner & Steinberg, 2005; Knoll et al., 2015; Smith et al., 2014). However, these experiments addressed only part of the dynamics of social influence, leaving several questions unanswered. Here we addressed two of those questions based on cross-sectional survey data. Specifically, we examined (1) whether adolescents reported an increased propensity to recommend risky behaviours, and (2) whether adolescents' perception of social norms relates to their self-reported propensity to engage in risky behaviour. We found that adolescents were more likely to recommend risky behaviour than children or adults. However, in contrast to our expectations, we found no particular evidence of adolescent-specific sensitivity to social norms. Together, our results have implications for understanding peer influence in adolescent risk-taking and for attempts to attenuate the latter, some of which we discuss in the following.

Do as I say? Risk recommendation

Consistent with the findings of previous studies with adults (Helfinstein et al., 2015; Ubel et al., 2011; Zikmund-Fisher et al., 2006), our results showed that children and adolescents were also less likely to recommend than to engage in risky behaviours. Furthermore, they also focussed stronger on perceived risks when recommending behaviours than when engaging in them. Taken together, this suggest that the general pattern of more "rational" thinking when recommending as compared to engaging in risky behaviours thus also holds for adolescents and children. However, adolescents were most likely to recommend risky behaviour. On top of that, our data suggests that adolescents were most likely to recommend risks that they thought were only infrequently taken by others (Fig 2). This trend that was stronger for desirable behaviours (e.g., parachuting or skiing), but also present in undesirable behaviours (e.g., riding without a helmet or getting drunk). That adolescents recommend risk-taking more strongly than people in other developmental stages could imply that they hold more favourable attitudes towards risk-taking. If adolescents believe that being a risk-taker is a valuable asset; they will also be more likely to endorse risky behaviour. Paired with adolescents' increased sensitivity to social signals (Blakemore & Mills, 2014), their readiness to encourage others to take risks may well contribute to the rise of risky behaviours during this age period. These findings open up avenues for interventions that aim to attenuate the consequences of adolescent risk-taking. For instance, adolescents could be made more aware of their role and responsibility in spreading risky behaviours and asked to take the perspective of others more frequently.

Do as others do? Risk engagement

In line with previous findings, our data showed that—across age groups—perceived social norms were positively correlated with participants' self-reported propensity to engage in risky behaviour. That is, participants who believed that more of their peers engaged in a risky activity, were more likely to report that they were willing to engage in that activity themselves. Contrary to our expectations, we found no interaction of age with perceived norms and propensity to engage in risky behaviours. Social norms were equally related to our participants willingness to engage in risky behaviour, regardless of age, implying that unobserved social norms may not have the outsized impact on adolescents as directly observed behaviour does. This suggests that the adolescent peak in social susceptibility is context dependent, (Crone & Dahl, 2012) and I it is peer presence that affects adolescent decision-making processes the most (Albert & Steinberg, 2011; Chein et al., 2011; Steinberg, 2005).

However, our data suggests that there is another way that social norms may have an outsized influence on adolescents. While other studies have shown that children and adults alike conform to social norms and adjust their conformity to an objective majority (Asch, 1955; Morgan & Laland, 2012; Morgan et al., 2015), social norms often need to be inferred and cannot be directly observed (FeldmanHall & Shenhav, 2019). Our post hoc analysis suggests, that adolescents may be ill- calibrated when performing this inference. We show, that late-adolescents estimated the general frequency of risky behaviours to be higher than other age groups and suggest that adolescents may overestimate others' engagement. As a result, the influence of social norms on risky behaviour may still be larger in adolescence; even though they are equally sensitive to norms, they have a greater tendency to overestimate the frequencies of risk behaviours. Taken together, these results have implications for interventions that aim at attenuating the consequences of adolescent risk-taking. Adolescents could be informed about true descriptive norms, a kind of intervention which has proved successful against bullying (Perkins et al., 2011) and seems more effective than training resistance to peer pressure directly (Graham et al., 1991). Note that our result may also reflect a false consensus effect (Botvin et al., 1992). That is the finding that those who engage in risky behaviours expect more others to engage in these behaviours as well (Brechwald & Prinstein, 2011). Biased perception of consensus can itself contribute to change in future adolescent behaviour (Henry et al., 2011). Thus, a false consensus effect can indirectly (via the perceived norm) contribute to the propensity to recommend and to engage in risky behaviours. Therefore, even if adolescents show a stronger false consensus effect, giving them information about actual peer norms will still be an effective intervention when it comes to attenuate the transmission of risky behaviour among adolescents.

Limitations and future directions

Because our study was not longitudinal, we cannot make causal claims about the relationship between social norms and risk-taking behaviour. While numerous experimental and longitudinal studies show a strong relationship between social norms and behaviour (Hansen & Graham, 1991; Litt & Stock, 2011; Perkins et al., 2011; Van Hoorn et al., 2017), further research is necessary to understand how social norms, risk-perception but also environmental factors impact risk-taking propensities across adolescence. For instance, some scenarios of our survey are illegal for minors, but not for adults. While minors de facto engage in activities that they would not be permitted to engage in (Moffitt, 2018), younger children still may perceive behaviours like drinking or stealing to be more risky than adults, simply because they are illegal for them and therefore recommend and engage in them less. As they grow older, breaking the law might appeal to thrill- and status-seeking adolescents. It is thus undoubtedly important to study which norms motivate young individuals to break which rules.

Further, our analysis is based on self-report data, which does not mimic the affective content of real-life risk-taking. As a result we may have underestimated adolescent engagement in risky behaviour given that it is hypothesized that emotionally engaging situations are those where developmental differences are most likely to occur (Rosenbaum et al., 2018).

Regardless of these caveats it was recently demonstrated that self-reports capture real-life behaviour better than many experimental paradigms (Frey et al., 2017; Hertwig et al., 2019; Pedroni et al., 2017), demonstrating that they remain a valuable tool for understanding the development of risk-taking.

Further, while we focussed on risky behaviour, it is possible that adolescents are more likely to recommend any kind of behaviour or overestimate the prevalence of many other behaviours, too. Adolescent social susceptibility will be better understood if recommendation and conformity would be studied in non-risky domains as well.

The current study provides starting points for further investigating the relation between norms and behaviour in adolescence. For instance, when it comes to social impact, the source of social information is important, especially during adolescence (Knoll et al., 2015; Molleman et al., 2019). We asked our subjects to think about "someone in general", when assessing their propensity to recommend risks, but did not give any specific instruction whom to think about. However, it is surely important whether subjects think about their friends or their parents (Knoll et al., 2015).

Future work should therefore ask individuals to think about specific groups of others or manipulate the presence, quality, and source of social norms in order to investigate which sources are used by individuals across development to construct their social norms. Finally, in this study we focused on descriptive norms—specifically, estimates of how often others engage in risky behaviours—and not on injunctive norms, which constitute judgements about the appropriateness of a behaviour (Cialdini & Goldstein, 2004; McDonald & Crandall, 2015). Future studies may benefit from eliciting perceptions of appropriateness, relating them to descriptive norms, and investigating the respective developmental trajectories across adolescence.

Summary and Conclusion

We identified two mechanisms that may contribute to the adolescent-specific increase in risky behaviours, and the role of peers in it. We showed that although adolescents, like other age groups, are less likely to recommend risky behaviours than they are to engage in those behaviours themselves, they are more likely than children or adults to recommend risky behaviours. At the same time, while being similarly sensitive to social norms, adolescents might be overestimating the frequency of others´ risk engagement. Although experimental and longitudinal studies are needed to better comprehend the determinants of these effects and their developmental course, it is likely that adolescents' increased propensity to recommend risky behaviours, paired with their overestimation of others' engagement in risky behaviours can trigger a vicious cycle that spreads risky behaviour through the adolescent population. However, our findings also show that adolescents do not mindlessly follow whatever they believe is normative behaviour—they may overestimate the normative character of some behaviours but likely use the same social heuristics as adults and children to decide whether to take risks. This offers the potential for interventions that aim at attenuating adolescent risk-taking behaviour: In line with successful attempts to reduce bullying or smoking in schools, our results suggest that informing adolescents about actual risk norms as compared to their perception of others´ risk-taking can be utilized to advance health-promoting behaviour. Because after all, the very social mechanisms that contribute to greater risk-engagement during adolescence can be used to foster and spread positive behaviours (Tankard & Paluck, 2016).

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5

Adolescent risk-taking in the context of exploration and social influence

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Abstract

Adolescents are often described as a strange and different species that behaves like no other age group, typical behaviours being excessive risk-taking and sensitivity to peer influence. Different theories of adolescent behaviour attribute this to different internal mechanisms like undeveloped cognitive control, higher sensation-seeking or extraordinary social motivation. Many agree that some of adolescent risk-taking behaviour is adaptive. Here we argue that to understand adolescent risk-taking, and why it may be adaptive, research needs to pay attention to the adolescent environments' structure and view adolescents as learning and exploring agents in it. We identify three unique aspects of the adolescent environment: 1) the opportunities to take risks are increased significantly, 2) these opportunities are novel and their outcomes uncertain, and 3) peers become more important. Next, we illustrate how adolescent risk-taking may emerge from learning using agent-based modelling, and show that a typical inverted-U shape in risk-taking may emerge in absence of a specific adolescent motivational drive for sensation-seeking or sensitivity to social information. The simulations also show how risky exploration may be necessary for adolescents to gain long-term benefits in later developmental stages and that social learning can help reduce losses. Finally, we discuss how a renewed ecological perspective and the focus on adolescents as learning agents may shift the interpretation of current findings and inspire future studies.

Introduction

A time-honoured view of adolescence, often defined as the period between ages 10 and 21 (van Duijvenvoorde et al., 2016), is that as a period of trials and tribulations (Sturm und Drang) on the way to adulthood (Hall, 1904). Consistent with this view, adolescence is associated with a peak in risky behaviours such as reckless driving, crime, binge drinking, unprotected sex, and experimenting with drugs (Gullone et al., 2000; Johnston et al., 2014; Shulman et al., 2013; Steinberg et al., 2018). Typically, these behaviours occur in the presence or presumed influence of peers (Albert et al., 2013; Monahan et al., 2009; van Duijvenvoorde et al., 2016). Although it is often stressed that while adolescent risk-taking has detrimental side-effects, part of these behaviours may serve some adaptive function, how exactly, however, remains unclear. Here we argue that if we aim to understand how risk-taking and peer influence can be adaptive, we need to (1) put more emphasis on understanding the interaction between learning, exploration and risk behaviour, and (2) better understand the interaction between adolescents and their environment. The first point builds on the idea that taking a risk can lead to meaningful experiences that will be beneficial in a later developmental stage (Baumrind, 1987; Romer et al., 2017; van den Bos et al., 2019). The second point is vital because behaviour can only be adaptive in relation to the environment in which it occurs (Simon, 1956). We believe that such a broader perspective will enrich the general understanding of adolescent behaviour. We begin by reviewing how risk-taking is defined in the adolescent literature, indicating a distinction between impulsive and planned risk-taking, and a shift of focus from merely harmful behaviour to one on exploration and learning. Next, we identify some key factors that characterize the environment which adolescents have to explore. Finally, we implement such an environment and run an agent-based learning model providing evidence that "typical" adolescent peak in risky behaviour may emerge from the interaction of an exploring agent and the environment in the absence of adolescent-specific motivational drives for reward or social feedback. In addition, our simulations indicate that under certain circumstances, both risk-taking and social influence can have long-term benefits, even though there are also negative outcomes in the short term.

Risk, uncertainty and exploration

Risk-taking does not refer to a well-defined set of actions (Frey et al., 2017). Risk-taking is also not necessarily illegal or dangerous. Instead, taking a risk is taking an action for which the outcome is uncertain, and potential consequences can be both, beneficial or harmful (Duell & Steinberg, 2019; Hertwig et al., 2019; Duell & Steinberg, this issue). At least two types of risk-taking can be distinguished based on their differences in underlying motivational mechanisms. The first type, reactive risk, explains adolescent risk behaviour due to the combination between poor response inhibition and increased reward sensitivity (Rosenbaum et al., 2018; Shulman et al., 2016; Steinberg, 2008). According to several adolescent risk-taking frameworks, this mismatch is due to an adolescent-specific imbalance between neural systems that support cognitive control and those that support reward processing (Ernst et al., 2005; Luna et al., 2013; Shulman et al., 2016). Although there is no doubt that some of the typical reckless adolescent behaviour falls in this category, and that this can lead to some undesirable outcomes, more recently it has been suggested that a significant proportion of adolescent behaviour comprises reasoned risk behaviour. Reasoned risk is strategic, planned well in advance, and relies on increasing cognitive control capacity in combination with an increased drive towards sensation seeking (Romer et al., 2017). Along these lines, a recent study reported that risk behaviour was associated not only with higher levels of sensation seeking but also with better working memory and greater future orientation (Maslowsky et al., 2019).

Furthermore, other studies have shown that adolescent risk engagement like binge drinking is strongly negatively correlated with their risk-perception (Ciranka & Bos, 2021; Johnston et al., 2014), suggesting that adolescents consider costs and benefits before engaging in risky behaviour. What unites many current theories of adolescent risk behaviour is the assumption that it can be adaptive. It is hypothesized that taking a risk can generate meaningful experiences enabling adolescents to interact with their future environment beneficially, and help adolescents to explore and learn about the world and themselves (Baumrind, 1987; Crone & Dahl, 2012; Rodman et al., 2017; Romer et al., 2017; Telzer, 2016; van den Bos et al., 2019; Worthman & Trang, 2018). Indeed, the adaptive potential of adolescent risk-taking behaviour becomes apparent when considering the developmental tasks and environment which adolescents are facing. Adolescents have to learn how to set up an independent household, become economically self-sufficient, emotionally stable, find their place in novel peer groups, build their own identity and eventually establishing a family unit of their own. In other words, adolescents developmental task is to become an independent adult (Nelson et al., 2016). On the way to adulthood, adolescents could hardly succeed if they would not take the risk to "leave their nest" (Bowers & Natterson-Horowitz, 2020).

Such a notion dovetails with the general definition of risk-taking as "taking an action where outcomes are uncertain and could both be harmful or beneficial". As such, part of adolescent risk-taking might be re-cast, from simply doing something potentially harmful to a more goal-directed act of exploration. Taking the risk to explore novel environments may lead adolescents to discover new niches and learn about novel opportunities (Sercombe, 2014; Willoughby et al., 2013). This perspective also suggests that when a child enters the world of adolescence, and much is unknown, exploration has high benefits, but these benefits will inevitably decline as a function of learning. In other words, exploration-based risk-taking will introduce a sudden increase in risk-taking that decreases again towards adulthood leading to an adolescent peak in risky behaviour.

Peer influence and social learning

The adolescent peak in risk-taking is often attributed to an adolescent-specific response to their peers. Some theories emphasize that peer presence is especially arousing for adolescents (Gardner & Steinberg, 2005). This arousal leads adolescents to focus on rewards, resulting in impulsive decisions and risk-taking (Albert et al., 2013; Shulman et al., 2016). For instance, some studies suggest that the general arousal associated with peer presence makes adolescents drive riskier in a driving simulation (Chein et al., 2011; Gardner & Steinberg, 2005). On the other hand, adolescents may only show increased risk-taking behaviour when they believe that their peers expect them to drive aggressively – suggesting a form of reasoned risk-taking (Blakemore & Mills, 2014; Romer et al., 2014). According to this view, peer influence is more in line with planned risk-taking because it might be the result of a cost-benefit analysis in which one specifically considers the social benefits, for instance gaining status or belonging to a group (Blakemore, 2018; Cialdini & Goldstein, 2004; Ciranka & van den Bos, 2019; Yeager et al., 2018).

Yet there is a third perspective toward social influence, currently underrepresented in the adolescent literature: social influence comprises social learning which can increase ones' confidence about how to make decisions in a complex and uncertain environment (FeldmanHall & Shenhav, 2019; Gigerenzer & Gaissmaier, 2011; Morgan & Laland, 2012; Morgan et al., 2015; Toelch & Dolan, 2015). For instance, observing others may entail information about which actions are more or less likely to lead to rewards. When faced with a novel and uncertain environment, adopting others' behaviour can be beneficial (Chase et al., 1998; Mehlhorn et al., 2015) because it protects the individual from potentially costly trial and error learning (FeldmanHall et al., 2017; Molleman et al., 2014, 2019). Several empirical studies in adults (Behrens et al., 2008; Biele et al., 2011; Ciranka & van den Bos, 2020; Toyokawa et al., 2019) and children (Bandura, 1962; Morgan et al., 2015; Walden & Ogan, 1988; Zarbatany & Lamb, 1985) showed that when people are more uncertain, they use social information more. From a developmental perspective, this suggests that a life phase associated with novelty and uncertainty, like adolescence, will also be associated with more social information use.

Learning and the environment

To date, learning and experience do not play a significant role in many existing theories on adolescent risk-taking. Exceptions are fuzzy trace theory (Rivers et al., 2008) and the Life Span Wisdom Model (Romer et al., 2017). However, both are neither explicit nor formal models of learning. A formalism would aid in generating expectations about how experience and knowledge will impact future behaviour and how a normative learning process might look like across development.

To further our intuitions about how risky behaviour, specifically its developmental rise and fall, may emerge from the interaction between adolescents and their environment, we turn to the formal framework of reinforcement learning (Sutton & Barto, 2018). A reinforcement learning agent must learn to make good decisions in an uncertain environment by interacting with it (Collins & Cockburn, 2020), much like adolescents do (Davidow et al., 2018). Good decisions are those that reap the most long-term rewards for the agent in a given environment. Eventually, the agents' behaviour will be optimally adapted to their experience with their environment (figure 5.1).

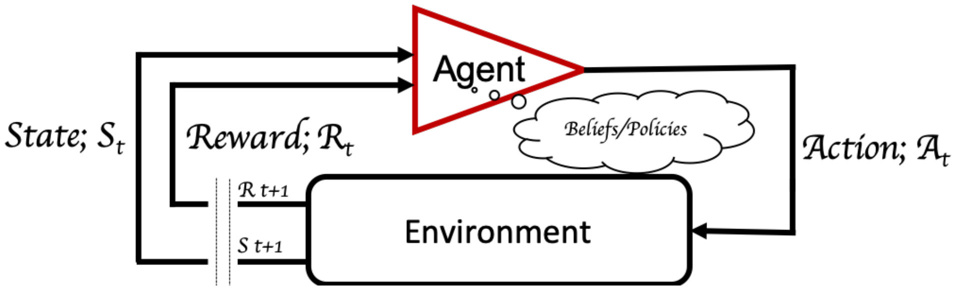

Figure 5.1: Schematic overview of the reinforcement learning framework (Adapted from Sutton & Barto, 2018).

Evidence suggests that learning to interact with novel environments can be characterized by some form of Bayesian learning (Daw et al., 2005, 2006; Dayan & Daw, 2008; Knill & Pouget, 2004; Marković & Kiebel, 2016; Mathys et al., 2011; Nassar et al., 2010). In Bayesian learning, in contrast to classic reinforcement learning, learning occurs faster when the learner experiences more uncertainty. Because of this feature it was argued that Bayesian models resemble how individuals assimilate new information into their beliefs across development (Frankenhuis & Panchanathan, 2011; Gopnik et al., 2017; Stamps & Frankenhuis, 2016; Tenenbaum et al., 2011).

From this point of view, many developmental tasks are about navigating a complex and uncertain environment in order to find a good solution based on experience. Such a task presents the learner with an explore-exploit dilemma (Addicott et al., 2017; Gopnik, 2020). Too much exploitation (choosing known good options) prevents the learner from gathering new information, and thus one may miss out on even more rewarding options. Too much exploration (gathering novel information), may be inefficient because of the high opportunity cost associated with not sampling the best option, thereby reducing long-term prospects.

The most widely used paradigm to study this dilemma is the multi-armed bandit task (Daw et al., 2006). It mirrors a casino's slot-machine with multiple arms, where each arm is associated with a different reward distribution. Obtaining a reliable understanding of all possible rewards will require vast amounts of exploration; requiring time or resources that could be spent pulling the most optimal arm, hence the dilemma. How much exploration is rational not only depends on individual experience but also on the environment which learners find themselves in. For instance, in a novel or volatile environment, more exploration is beneficial, while in a stable and well-known world, exploitation becomes more attractive (Behrens et al., 2007; Mathys et al., 2011). When there is considerable uncertainty, social information can reduce the need for exploration by providing information about what should be exploited or avoided by simply observing others (Mehlhorn et al., 2015).

Studying learning of artificial agents provides a laboratory for understanding the dynamics in human learning as well (Gershman et al., 2015; Rahwan et al., 2019). Since reinforcement learning formalizes the interaction between agent and environment, we however need to zoom in on some specific aspects of the adolescent environment in order to generate a meaningful metaphor for adolescent development. First, parental oversight is decreasing when adolescence begins, and the opportunities for engaging in risky behaviour increase (Defoe et al., 2019; Sercombe, 2014; Willoughby et al., 2013, Willoughby et al., this issue). Second, these opportunities have often not been explored before, making their benefits uncertain and because losses are possible, exploring those opportunities carries a risk (Hertwig et al., 2019). Third, there are significant changes in the social world (Blakemore & Mills, 2014).

In the following, we focus on these three salient features of the adolescent environment: 1) increasing opportunity for risks, 2) uncertainty about the world and 3) the presence of peers, and implement Bayesian learning agents who explore this environment. These agents possess a simple set of rules according to which they act, but viewing their behaviour simultaneously and over time will unravel complex properties, beyond the simple decision rules of one individual at one point in time (Bonabeau, 2002). By these means, we show how exploration and learning, together with changes in the environment, can lead to outcomes that resemble developmental trajectories of risk-taking and social susceptibility observed in adolescents, without assuming developmental changes in reward or social sensitivity.

Methods

The simulated environment

We simulate an environment, carrying three features of the environment adolescents face to show that adolescent-specific risky-behaviour may emerge merely from learning and exploration. First, it increases in the number of options after an initial childhood learning period. Second, exploration is risky and could lead to gains but also losses. We assume that adolescents have access to more dangerous options (with more negative outcomes) than those provided in childhood (Baumrind, 1987; Defoe et al., 2015, 2019; Sercombe, 2014). Third, there is social information, meaning that similar agents explore the same environment simultaneously, and agents can observe each other. The simulated environment confronts our learning agents with a multi-armed bandit problem, which is often used to study how humans trade-off exploration with exploitation (Daw et al., 2006; Schulz et al., 2019; Wu et al., 2018). The problem consists of 144 different options, each associated with another reward distribution ( ), that agents can explore to find an option that maximizes long term rewards. Every time an agent decides for one option, the environment produces an outcome: a random draw from a normal distribution. The outcome is either positive (gain) or negative (loss).

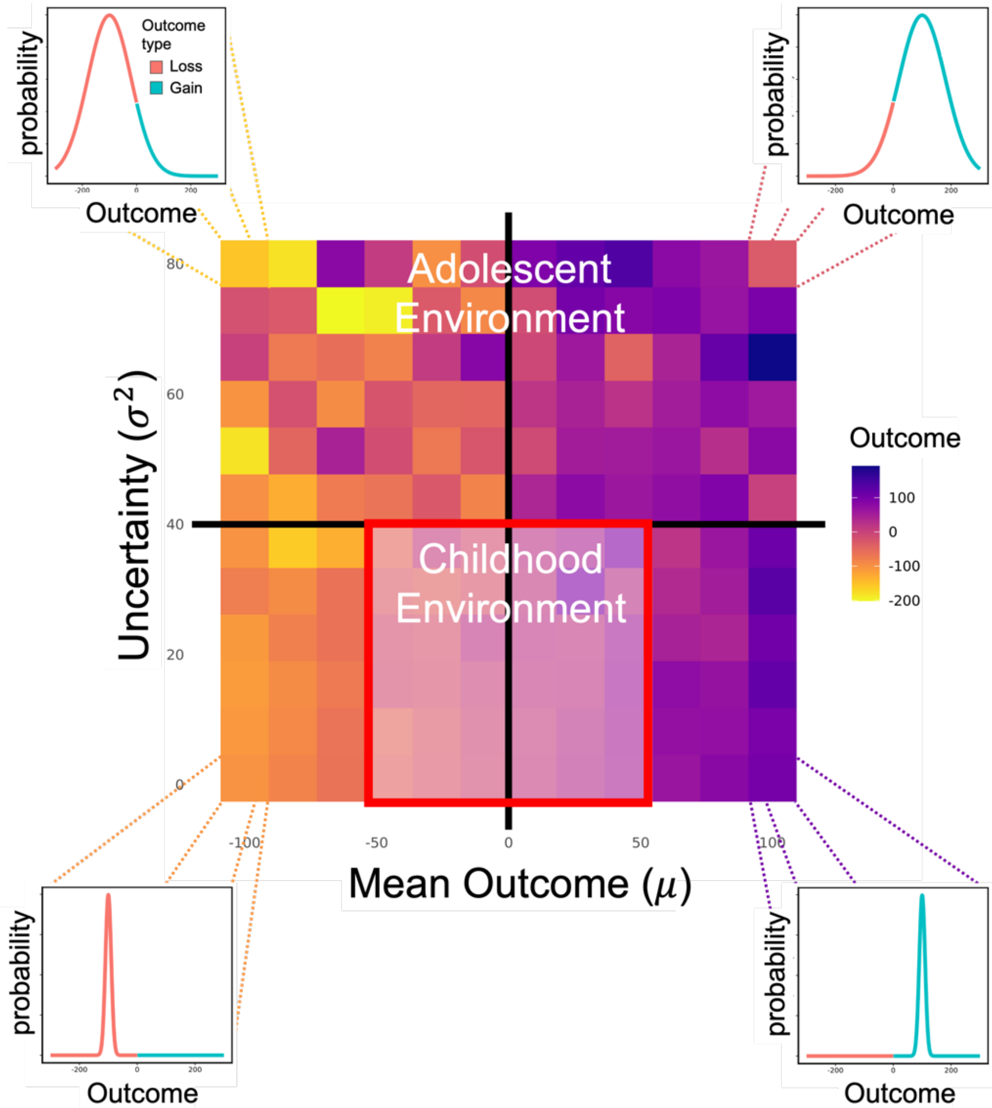

Figure 5.2: The 144-armed bandit used for our simulations. Each square represents one possible outcome from its underlying reward distribution. Examples for the most extreme distributions in our environment are depicted in the margins, where the y axis shows the probability to receive the outcome on the x-axis. The environment offers different amounts of expected rewards (x-axis) to varying degrees of uncertainty (y-axis). The middle grid within the red square depicts a "child" agent's search space, constricted to medium-sized gains and losses with relatively low risk. The whole grid shows an "adolescent" agent's search space, where large gains and losses are possible at high and low levels of risk.

Options differ in their expected reward (from -100 to 100) and variance (from 5 to 80). By varying mean and variance of the options' underlying distribution, we generated an environment in which exploration is risky (Sani et al., 2012), according to the definition of risk-taking: sampling a novel option can result in losses, and there is uncertainty about the outcomes (Hertwig et al., 2019). The environments' complexity increases in two stages. In the first stage, agents can only explore a constrained section of their environment, with 36 options to sample. These options are relatively predictable (the variance ranges from 5 to 40) and avoid great losses and rewards (the mean ranges from -50 to 50). This reflects a childhood period where adults strongly restrict the environment of children to keep them safe. In the second "adolescent" stage, we introduce novel options to explore. More precisely, all options in figure 2 become available for the agents to explore. This mirrors the increased risk-exposure that adolescents likely face in the real-world (Defoe et al., 2019; Willoughby et al., 2013). Adolescents' options are both better and worse than those presented in the childhood world, echoing the risks and opportunities of adolescence (Dahl, 2004). We note that in reality, it is unlikely that every risky behaviour becomes available for exploration at the same time. For simplicity we chose not to implement such gradual "opening", because while it could make the simulations more realistic (see discussion) their qualitative patterns will remain unchanged.

Agents

We can break down the agents into three elements: beliefs, a belief update rule and a choice rule.

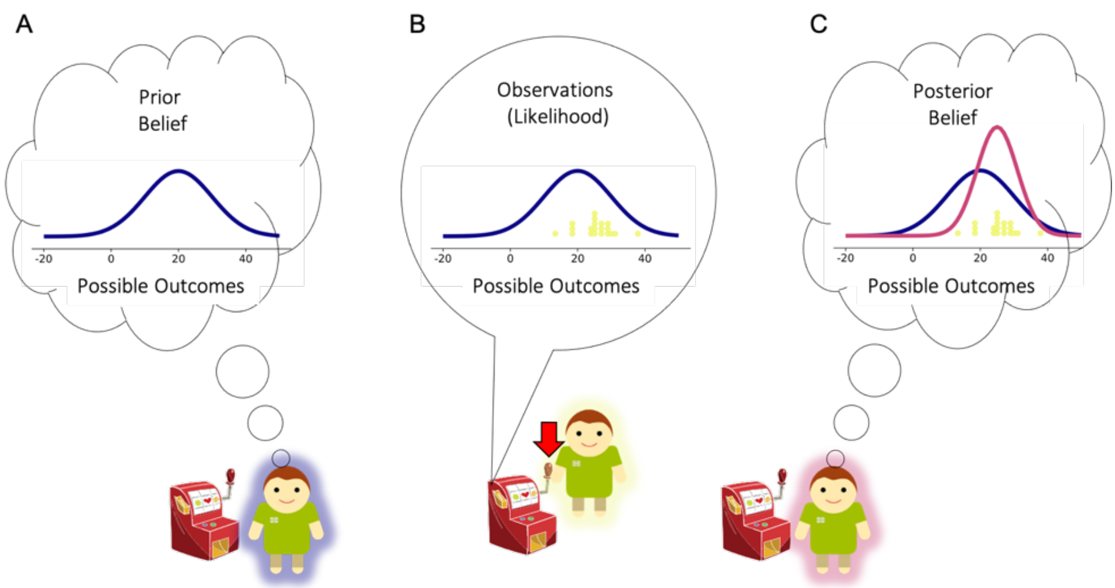

Figure 5.3: Belief update for the example of one option in the environment. A) An agent[2] approaches each option in the environment with a prior belief about how rewarding this option could be, but is uncertain about it, as can be seen in the spread of the prior distribution. B) Exploring this option will produce outcomes which the agent experiences. C) Experiencing outcomes will help the agent adapt its belief to the environment, as the mean of the agent's beliefs shifts towards the observations and the agent is more certain as the posterior's spread is smaller than the spread of the prior.

[2] The avatar image by LeonardoIannelliCOMPUTE is licensed under CC BY 4.0.

When making a decision, agents can either take a risk and switch away from the best option they know so far, or they can exploit their knowledge base and stay with this option. In our implementation (Daw et al., 2006; Schulz et al., 2019), agents learn and update their beliefs about their environment's statistical structure using Bayes rule (figure 3).

At every point in time, *t*, agents have a specific belief about each option, *j,* in their environment. Namely that each option will result in some reward (μ), but are uncertain (σ^2), about their expectations (figure 3A). They update their beliefs after every decision with a prediction error. The prediction error is the difference between the reward expected by the agent ($\mu_{j,t-1}$; figure 3A) and the actual reward received after deciding for an option ($y_{j,t}$; figure 3B). For a given option, the mean and uncertainty are updated when the option was selected (figure 3C):

$$\mu_{j,t} = \mu_{j,t-1} + \zeta_{j,t} K_{j,t} \left(y_{j,t} - \mu_{j,t-1}\right), \tag{5.1}$$

$$\sigma^2_{j,t} = \sigma^2_{j,t-1} * (1 - \zeta_{j,t} * K_{j,t}), \tag{5.2}$$

Where $\zeta_{j,t} = 1$ if option *j* is chosen on trial *t*, and 0 otherwise. K refers to the Kalman gain, which can be interpreted as a learning rate and is defined by the agents' uncertainty on the previous trial:

$$K_{j,t} = \frac{\sigma^2_{j,t-1}}{\sigma^2_{j,t-1} + \epsilon_j}. \tag{5.3}$$

ϵ is an error constant, denoting the range of outcomes expected in the whole environment. Notably, in an analogy to Bayesian models of human development (Frankenhuis & Panchanathan, 2011; Tenenbaum et al., 2011), when agents are more experienced they will change their beliefs about their environment less. We set the initial beliefs about unchosen options to be optimistic, but very uncertain ($\mu_0 = 100, \sigma_0^2 = 40$). We choose relatively optimistic priors (the mean expected reward prior was 100, whereas the actual mean reward rate of the whole environment is 0), for two reasons: First, this motivates agents to leave the safe "childhood" space, given that the agents expect to find higher rewards outside of it. Second, a single negative outcome will not directly lead to a very negative belief about an option, thus inviting further exploration.

Social learning

To understand how social information shapes risky exploration, multiple agents could observe each other while solving the explore-exploit trade-off simultaneously. Each agent expects an option to be more rewarding when other agents also explore it:

$$U_{j,t} = \mu_{j,t} + N_{j,t-1}^{\alpha}, \tag{5.4}$$

N is the total number of other agents exploring an option and α maps social mass N to social impact. In our simulations, we set this parameter to 0.8, which means that social impact increases strongly when a few individuals explore this option. When social mass gets bigger, one additional individual's impact declines (Latané, 1981). The "social bonus" is added to the observing agent's utility function (U) in the next round. Finally, all options' U_t are fed into a softmax function to obtain the probability that an agent will choose the respective option, j

$$p(j) = \frac{\exp(U_{j,t})}{\sum_{i=1}^{n} \exp(U_{i,t})}. \tag{5.5}$$

We do not model developmental changes in the model parameters that govern exploration or social impact, these are assumed to be the same at each developmental stage. Thus, the model is in contrast with theories suggesting that adolescents are more sensitive to social information (Blakemore & Mills, 2014) or rewards (Steinberg, 2008) than children and adults. It was our goal to show how typical adolescent behaviour may emerge simply by the interaction of experience and environmental changes.

Simulations

Each agent made 1200 sequential decisions, the first 400 of which in the "childhood environment", the other 800 in the "adolescent environment" (figure 2) after new options have been made available to the agents. We performed two sets of simulations. In a solo condition, agents explored the environment alone. In a social condition, 20 agents explore the environment simultaneously and influence each other according to equation 4. All simulations were performed in R (R core team, 2020) with strong reliance on the tidyverse (Wickham et al., 2019).

Behavioural measures

To assess the change in risky behaviour across "development" we calculated the average number of explorative decisions made by our agents in bins of 50 consecutive choices. In the multi-armed bandit problem, exploration can mean switching from one arm to another (Daw et al., 2006). Exploring is associated with risk because some options in the environment carry the danger of losses, and there is uncertainty about when and if these options will lead to bad outcomes (Hertwig et al., 2019). To understand the consequences of exploration, we examine how many losses and gains the agents encountered and their average magnitude. Finally, we quantified social learning by calculating how often an agent samples options that other agents sampled previously, in other words how often the agent followed others (again, the average per 50 trials). Given that we were interested in the adolescent period and the transition into adolescence, there is no explicit third transition into an "adult environment". This over-simplification means that in the adult period, no new options are introduced and adults live in the same environment as adolescents (see Discussion). However, for illustration purposes, we analysed the behaviour of our agents within three equally sized bins (childhood, adolescence and adulthood), each corresponding to 400 choices made by the agents.

Results

Exploration and social following

Here we investigate how explorative[3] behaviour changes as a function of experience and the environment in agents who did and did not access social information. As shown in figure 4A, both childhood and adolescence are generally characterized by exploratory behaviour that declines with age. Within our simulations, this can be attributed to the many new options that became available simultaneously. Such an adolescent peak and decline in exploration simply emerges from increased opportunities and subsequent learning in the absence of specific adolescent motivation for sensation-seeking or sensitivity to rewards. When agents had the opportunity for social learning, exploration was reduced as compared to solo behaviour during adolescence. We also see that there is substantial social following behaviour in childhood and another peak in adolescence (figure 4 B). As agents gain more experience, following others declines. In childhood, social information prolongs exploration and increases the variance over different simulations. In adolescence, where the search space is vaster and outcomes differ more strongly between each other, social information helps to find a good solution quicker and therefore decreases exploration.

[3] Our definition of exploration follows a convention in the literature, where staying with an option previously selected is considered exploiting, and other choices are seen as forms of exploration. It can be also argued that exploration is better defined by seeking to reduce uncertainty (cf. Wu et al., 2018). This would mean that sometimes staying with an option is still exploration. This definition requires to set some certainty threshold to separate exploration for exploitation. Using this operational definition of exploration - tallying uncertainty-seeking decisions (decisions over some threshold of σ)- yields the same inverted-U pattern as the one reported here (see supplementary figure S5.1).

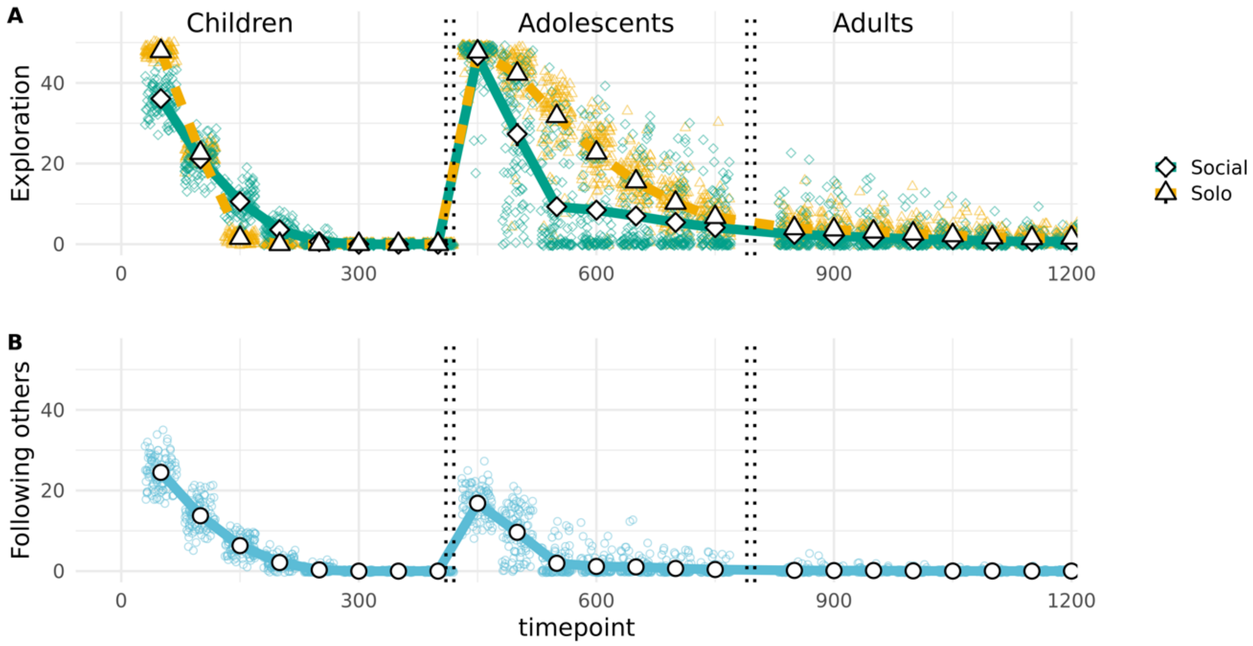

Figure 5.4: A) Exploration (y axis) by timepoints in the simulations (x-axis) and whether agents had access to social information (green) or not (yellow). Each shape denotes the average number of switches over the past 50 decisions per developmental stage and depending on whether agents had access to social information. Small transparent shapes denote individual simulations, and large shapes cover the mean and 95%ci of the mean of all simulations. Explorative decisions are defined as the decision to switch from one to another option. While both, childhood and adolescence can be characterized by relatively high exploration, the adolescent environment leads agents to explore their environment for a prolonged time. B) Decisions to explore an option that others had sampled before (y-axis), when the agent explored independently before. Both, exploration and social following increase in "adolescence" when there are novel options to explore.

Experienced outcomes

Here we show the number of positive and negative outcomes encountered by exploring agents in different "developmental stages" and show how severe those outcomes were. Overall, the number of experienced losses declines, the number of experienced rewards increases.

In both metrics, number of losses or gains and their magnitude, social information was beneficial, resulting in more gains and less losses as well as better outcomes for gains and losses (figures 3A and 3C). We further observe that adolescent agents experience the most severe losses (figure 3B) irrespective of whether social information was available or not, however on average using social information seemed beneficial for adolescent agents in the loss (figure 3C) and in the gain domain (figure 3D).

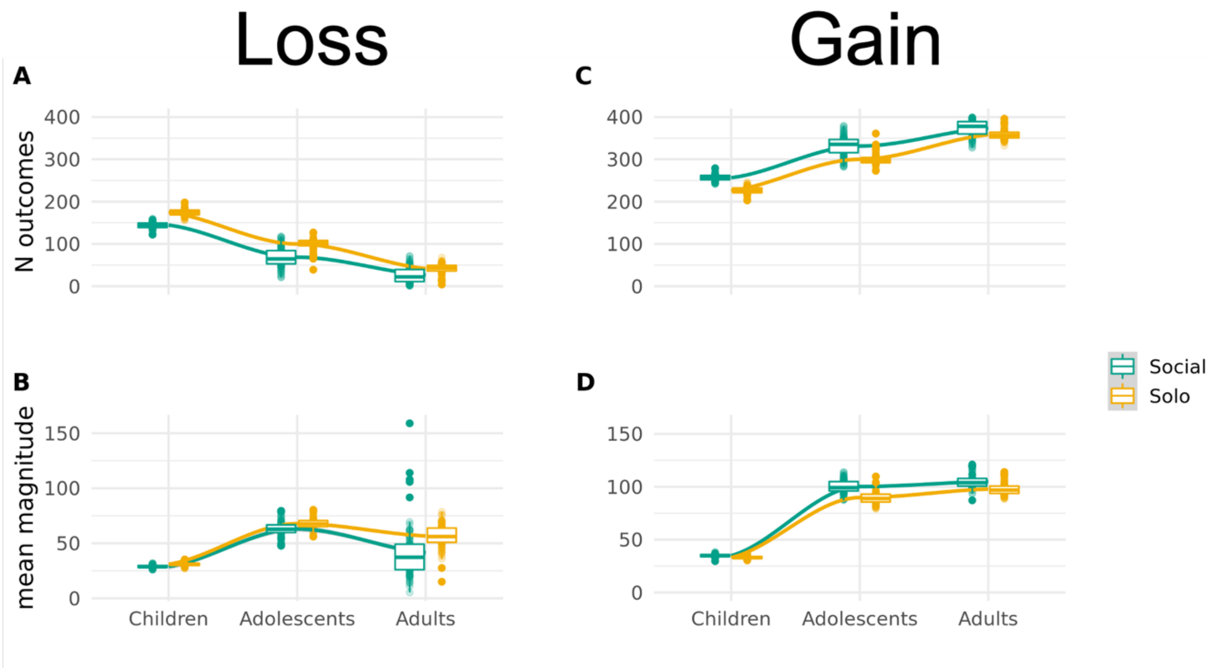

Figure 5.5: Outcomes experienced for non-social (yellow) and social (green) agents. Outcomes that are either negative (Loss) or positive (Gain) by age group for each of the 100 simulations (dots). The first row depicts the cumulative count of A) losses and C) gains. The second row shows the magnitude of a given outcome for B) losses and D) gains. As agents progress through the developmental stages, they encounter fewer losses and more gains. Notably, during adolescence, the social following rule induces a greater variability in outcomes that agents received overall on average, compared to simulations that did not include social information. This was true for negative (SD= 19.69 vs SD= 16.83) but also positive (SD = 32.43 vs SD= 29.28) outcomes.

Discussion

In his book "The Sciences of the Artificial", Nobel laureate Herbert Simon contemplates on the trajectory of an ant wandering on the beach. Looking from above, the ant's path is "irregular, complex, and hard to describe". An apt description for many adolescents' choices. But, as Simon points out, the complexity is in the surface of the beach, not in the ant; "An ant, viewed as a behaving system, is quite simple. The apparent complexity of its behaviour over time is largely a reflection of the complexity of the environment in which it finds itself", (Simon, 2019, p.52). Here we argue that we also have to pay attention to interaction between the adolescent and their complex environment. We stress that 1) adolescents are required to learn to interact with the novel adult environment (Sercombe, 2014; Willoughby et al., 2013), and 2) exploring this environment is inherently risky since it is often uncertain whether the behaviour will be harmful or not (Hertwig et al., 2019; Sani et al., 2012) and 3) the environment is filled with opportunities for social learning (Crone & Dahl, 2012; Nelson et al., 2016).

We illustrate how agent-based simulations help to further our intuitions about the interactions between adolescents and their environment.

One of the striking results is that our simulations reproduce a set of very typical adolescent behaviours; 1) an inverted U shape in risky exploratory behaviour (Romer et al., 2017; Steinberg et al., 2018), and 2) a similar inverted U shape in peer-following (Braams et al., 2019; Rodriguez Buritica et al., 2019). The increased exploration was associated with selecting risky high variance options, which resulted in a peak of severe losses during adolescence. However, this risky exploration was beneficial because it helped the agents maximize rewards in the long run. Additionally, social information helped them to avoid some severe losses and learn about good options faster. Importantly, these patterns emerged even without needing to invoke specific "motivational" changes in the adolescent agents. That is, the agents exploration bonus for novel options was the same across all stages, as was the utility attributed to options chosen by others. Instead, the changes in behaviour emerged from changes in the environment (e.g. opening up in adolescence) and experience (rewards and losses). These stylized facts generated in an oversimplified world provide valuable insights into how adolescent-specific risk behaviour may emerge, emphasizing a central role for learning and experience. In the following, we discuss how our perspective relates to findings and theoretical frameworks on adolescent risky and social behaviour and their neural development, suggesting novel avenues for future research.

Adolescent biology

Although the agents in our simulations do not go through any developmental changes, it is indisputable that there are major biological changes during adolescence in humans and animals (Luna et al., 2013; Mills et al., 2014; Worthman & Trang, 2018). First and foremost, the start of adolescence is defined by the start of puberty, which is marked by a significant rise in pubertal hormones. Second, neuroimaging studies revealed considerable changes in brain structure and function during the second decade of life. According to dual systems models of neural development (Luna et al., 2013; Nelson et al., 2016; Shulman et al., 2016), risk-taking peaks during adolescence because of a maturational imbalance between an early-maturing dopaminergic reward processing system and a still immature cognitive control system that is not (yet) strong enough to restrain reward-seeking impulses. Given the co-occurrence of puberty and maturational imbalance, it was suggested that hormonal changes related to puberty drive developmental changes in risk-taking (Braams et al., 2015).

We do not argue against the empirical findings that form the basis for these theories, however, we argue for a broader perspective, stressing that the interaction with the environment leads to experience, and experience itself leads to changes in brain and behaviour (Romer et al., 2017; Sercombe, 2014). For instance, dopamine and pubertal hormones are also known to enhance learning. A body of work shows that pubertal hormones play a pivotal role in regulating the mechanisms of experience-dependent neuronal plasticity during adolescence (for review, see Laube et al., 2020). In addition, changes in dopamine function during adolescence may play a key role in experience-based fine-tuning of neural systems (Murty et al., 2016). Early on it was pointed out that developmental changes in grey matter most likely reflect experience-based pruning of cortical networks (Giedd et al., 1999), but environmental changes can also cause changes in the mesolimbic dopamine system. For instance, the mesolimbic dopamine system's in vivo activity is enhanced by moving rats to an enriched environment (Segovia et al., 2010). A recent study showed that both striatal dopamine release and dopamine synthesis capacity are significantly elevated in immigrants compared to non-immigrants (Egerton et al., 2017). Thus, it is conceivable that the enhanced level of striatal dopamine, or other neural changes, associated with adolescence is also a response to being confronted with a novel and stressful social environment, rather than just a biological timer going off. In sum, a broader perspective on adolescent risk may also bring some nuance to the interpretation of current neuroimaging findings.

Understanding risk

We argue that to understand adolescent risk-taking, there is a need to conceive risk-taking not only as impulsive or flawed behaviour but also as an exploratory activity that resolves uncertainty and is necessary to achieve developmental milestones, generates wisdom and knowledge (Rivers et al., 2008) and is often planned (Romer et al., 2017). Refocusing on experience and learning has consequences for studying risk-taking in the laboratory. That is, instead of static forced-choice decision experiments, paradigms involving uncertainty or necessitating exploration might prove more valuable for understanding laboratory correlates of real-life risk-taking (Frey et al., 2017; Rosenbaum et al., 2018). Indeed, experimental research studying risk-taking under uncertainty (Blankenstein et al., 2016; Braams et al., 2015; van den Bos & Hertwig, 2017), or exploration (Somerville et al., 2017) elicit behaviour that is predictive of real-life risk-taking. The advantage of experimental studies is that they diminish the role of developmental differences in prior experience, knowledge, or exposure to risky situations by confronting everybody with a novel environment (Defoe et al., 2019).

Throughout this manuscript, we used Bayesian reinforcement learning to quantify intuitions arising from focusing on exploration across development (Frankenhuis & Barto, 2019), but the simulated environment also allows for a concrete implementation as experiment (Schulz et al., 2019; Wu et al., 2018). If children, adolescents and adults would be confronted with our environment in an experiment, this experiment would be sensitive to developmental differences in exploration not induced by their ecology but by differences in internal drives. Indeed, evidence from self-report and experimental studies shows that novelty and sensation seeking is at its peak during adolescence (Crone et al., 2008; Maslowsky et al., 2019; Wills et al., 1994). An increase in novelty seeking translates to more optimism in our agents and would lead to increased exploration. Sensation seeking, other than novelty seeking, involves a preference for activities that have high variance in expected value (Zuckerman et al., 1978). Translating this to our simulations and models, a sensation seeking agent would seek out uncertainty and prefer options in the top quadrants of Figure 2, containing high-variance options. Individuals with a propensity for sensation seeking will be driven to explore more, given that all unknown options are associated with high variance, and finally converge somewhere on the top right, generally experiencing positive outcomes, but also some infrequent very negative ones. If sensation seeking would decline with age, the agents would move to options with lower variance. Although, we here illustrated that an adolescent specific increase in novelty (Cloninger, 1986) or sensation seeking (Romer et al., 2017) is not a necessary prerequisite to explain an adolescent rise and fall in risky behaviour when considering their ecology, we believe a more complete model, for instance The Developmental Neuro-Ecological Risk-taking Model (Defoe et al., 2019) incorporates both, psychological as well as ecological factors.

Peer influence and social learning

In our simulations, there was a peak of social information use at the beginning of "adolescence" when novel opportunities raised for our agents, suggesting social sensitivity is related to exploration and uncertainty. In the real world, adolescence is a period of major social upheaval. During this period, adolescents become preoccupied with how their peers view them (Somerville et al., 2013) and how they fit into their social groups (Coleman et al., 1977). One might argue that the social context becomes an adolescent's main source of uncertainty. Learning how this social world works, who they are, and where they fit in, are major developmental tasks for adolescents (Nelson et al., 2016). The mere presence of peers, is arousing to adolescents, which may shift the neural balance between reward and control such that it leads to an increase in (impulsive) risk-taking (Chein et al., 2011; Gardner & Steinberg, 2005; Shulman et al., 2016). Others have emphasized that some risk-taking behaviour might aim at reaching social goals, such as status and belonging (Blakemore, 2018; Blakemore & Mills, 2014; Telzer et al., 2018). Here, we highlight another aspect: following or copying others' behaviour, can be a smart form of social learning (Bandura, 1962). Research in adult social learning has shown that social information use often follows a basic principle which is that people use more social information when they are more uncertain or feel less confident (Ciranka & van den Bos, 2020; De Martino et al., 2017; Molleman et al., 2014; Moutoussis et al., 2016; Toelch & Dolan, 2015; Tump et al., 2020). In a novel environment, using social information is beneficial because it informs individuals about good options without the potential dangers of trial and error learning[4] (Hoppitt & Laland, 2013; Mehlhorn et al., 2015; Todd & Brighton, 2016). In line with that, we show that agents who transition into the adolescent environment, in which they are maximally uncertain, use social information most. In addition, we show that combining their knowledge, social agents converge quicker on better options

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[4] *Social information is not always good and conformity can also lead to bad outcomes. We also find in our simulations that if there is too much conformity, this can lead to suboptimal outcomes.*

compared to searching for these alone. There are still some severe losses, and sometimes the agents followed a bad example, but overall "adolescent agents" benefited from following their peers. Since social learning allows individuals to avoid experiencing bad outcomes, conformity may be particularly strong for avoidance learning. Several studies have shown that adolescents may also be specifically sensitive to social information promoting risk-avoiding behaviour (Braams et al., 2019; Chung et al., 2020; Ciranka & van den Bos, 2019; Engelmann et al., 2012), which could reflect an adaptation to their uncertain ecology.

The social learning perspective also raises questions. If adolescent risk-taking can also be characterized by social learning and depends on uncertainty, identifying adolescents' uncertainties will help to understand where they are most likely to give in to peer pressure for two reasons. First, situations in which adolescents are uncertain about whether some behaviour is "worth the risk" will be those situations where they are most susceptible to peer influence. Second, uncertainty about others can influence adolescent risk-taking when social learning is not possible. This is because uncertainty itself is related to acute stress responses and arousal in humans when they anticipate negative outcomes (de Berker et al., 2016) or take risks (FeldmanHall et al., 2016). When adolescents find themselves observed by others, they more often anticipate negative outcomes, like being rejected or embarrassed than children or adults (Crone & Konijn, 2018; Pickett et al., 2004; Rodman et al., 2017; Somerville et al., 2013). Thus, their uncertainty about others' mental states in combination with their bias towards predicting negative social outcomes may contribute to adolescents' arousal which is, in turn, thought to nudge them into reward-sensitivity and risk-taking in social contexts (Shulman et al., 2016).

Limitations and extensions

Exploratory behaviour in our simulations not only reduces because the agents are learning but also because there is a finite set of options. In the real world, however, adults take on multiple roles that provide different opportunities and risks (Willoughby et al., 2013). Our choice not to consider different risky options for adults mimics the kinds of behaviours research on adolescent risk-taking is usually concerned with. The risks that adolescents engage in are hardly available for children and are novel for adolescents (Baumrind, 1987; Defoe et al., 2015, 2019), but all are have long been available to adults. For instance, the selected items on adolescent risk-taking questionnaires, mainly include activities related to substance abuse, risk driving, and sex (Gullone et al., 2000). These differences in risk-exposure and novelty can explain why adolescents exceptional risk-taking in the real-world (Steinberg et al., 2018) fails to replicate in laboratory tasks, where the "environment" is the same for everyone (Defoe et al., 2015, 2019). That is, the meta-analyses by Defoe et al (2015) suggest that children take equal risk compared to adolescents in laboratory tasks. This is in line with our model that predicts that as soon as the environment changes and novel risky options become available, risk-taking will increase. Related, different risks might be easier to explore at different times during development.

It is an empirical question whether options that become available to adults have the same potential for harm on the individual level, but clearly novel opportunities will arise. Simulations could integrate an ever-increasing set of options, by adding them later, resulting in another increase in exploratory behaviour, given that our agents' priors were the same for every new option. Thus, our model does not predict that adults would not take risks or explore anymore, but assumes risk-taking to be determined by the interaction with agents and their environment. By these means, the model can explain why risk-taking in certain areas significantly reduces across adolescence, presumably based on experience, while other risks for instance white collar crimes, which may be much more harmful to society than the risks adolescents take, have a much later peak (Benson & Kent, 2001, Willoughby et al., this issue). Furthermore, our model predicts that significant changes in adults' ecology stage will result in a new spike in exploration and social following behaviour. Although it is the common trope that adolescents will jump off the bridge if all their friends would do it, there is plenty of evidence of adults showing the same herding behaviour when there is uncertainty, for instance in real estate markets (Babalos et al., 2015) or cryptocurrencies (Coskun et al., 2020). More recently, following the Covid-19 outbreak, we have seen herding in hoarding of toilet paper in several countries around the world (Garbe et al., 2020; Kirk & Rifkin, 2020). Thus, when there is novelty and uncertainty, explorative or risky behaviour and social susceptibility will re-occur in adulthood. Exploring this in further studies based on sound intuitions about what type of affordances the adult environment provides will be most insightful.

Further, although agents can suffer losses in simulations, they could never get hurt or even die. Introducing this possibility would generate evolutionary dynamics, such as loss aversion, and would call for a using social information strategically, something adolescents are known to do (Chung et al., 2015; Ciranka & van den Bos, 2019). Generally, studies from across the biological and social sciences suggest that people use social information strategically; they are selective as to who they turn to for useful knowledge (Hoppitt & Laland, 2013). Developmental studies have shown that adolescents are more likely to rely on expert advice than adults when taking financial risks (Engelmann et al., 2012). On the other hand, peers might be a more important information source to adolescents when it comes to risk-perception (Knoll et al., 2015). It would be of great interest to study how decisions about when and whom to learn from, operate across adolescence specifically because the literature suggests that adolescents are exceptionally sensitive to social status (Yeager et al., 2018). Finally, the model assumes that all individuals initially have equal opportunities to benefit from the environment. In reality, parents' socioeconomic status influences the risks and opportunities that children are exposed to

(Frankenhuis et al., 2016; Worthman & Trang, 2018). It will be insightful to quantify how such inequalities impact risky behaviour during the adaptive mind's development.

Summary and Conclusion

The ecological approach has a long tradition in developmental (Bronfenbrenner, 1979) and decision science (Simon, 1956). It proposes that cognitive and motivational systems are shaped—by evolution or development—to take advantage of the external environment's structure (Gigerenzer & Gaissmaier, 2011; Todd & Brighton, 2016). Thus, to understand behaviour, it is necessary to understand the environment it occurs in. Here, we highlighted the role of learning and experience in this process. In the past decades, much research has focused on the adolescent mind's inner workings to understand the mechanisms behind adolescent risk-taking. Our agent-based models illustrate that exploration and adaptation to an uncertain environment itself can give rise to typical adolescent patterns in risk behaviour and peer influence without assuming developmental changes in internal drives. Although the claim that risk-taking may be adaptive is not new, we point out that models of adolescent risk-taking and peer influence, must integrate elements of learning, experience and the environment that adolescents *adapt to*. Such models would paint a fairer picture of adolescents, not just as individuals with unfinished brains and raging hormones, but as active learning agents who are exploring a new and uncertain world.

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6

Synthesis

„Perhaps all adolescence is a dialogue between Faust and Christ. We tremble on the brink of selling that part of ourselves that is real, unique, angry, defiant and whole for the rewards of attainment, achievement, success and the golden prizes of integration and acceptance; but we also in our great creating imagination, rehearse the sacrifice we will make: the pain and terror we will take from others' shoulders; our penetration into the lives and souls of our fellows; our submission to willingness to be rejected and despised for the sake of truth and love and, in the wilderness, our angry rebuttals of the hypocrisy, deception and compromise of a world which we see to be so false. There is nothing so self-righteous nor so right as an adolescent imagination."
– Stephen Fry, Moab is my Washpot (1990).

In my thesis, I investigated how adolescents are susceptible to social information when taking risks. In the following, I will highlight and discuss this dissertations' main findings and attempt to connect the dots between them.

Real-life risk-taking rises and laboratory risk-taking declines across adolescence.

One long-established narrative of adolescent decision-making is that they are exceptional risk-takers because the prospect of a reward allures adolescents more strongly than people in other developmental stages (Albert et al., 2013; Demos & Demos, 1969; Gullone et al., 2000; Hall, 1904; Spear, 2000; Steinberg, 2005). The notion of adolescent reward sensitivity is so prominent that it affected court decisions in the US (Steinberg, 2013), influenced government policies during the COVID-19 pandemic[5], and has a prolonged impact on interventions that aim to make adolescents healthier (Yeager et al., 2018). My research however provides evidence that an adolescent peak in reward sensitivity or risk-taking is not as ubiquitous as often thought. In line with a recent meta-analysis (Defoe, Semon Dubas, et al., 2019) adolescents took more risks than adults but fewer risks than children in the experiment that form the base of chapters 2 and 3. In chapter 4, adolescents self-reported a higher propensity

[5] https://www.nytimes.com/2020/06/15/opinion/coronavirus-college-safe.html

to take risks in real-life than children but did not report taking more risks than adults. In no empirical study of my dissertation have adolescents been outstanding risk-takers.

This begs the question why there is an increase in risky adolescent behaviour in the real world that fails to replicate, or even shows opposite developmental trends, in the experiment? Weak connections between experimental and real-life behaviour are not unique to adolescent risk-taking, but are also prominent in adults (Frey et al., 2017; Hertwig et al., 2019; Pedroni et al., 2017). Palminteri & Chevallier, (2018) suggested that this is because a risk-attitude, measured at one point in time in the experiment is merely the shaky manifestation of a weighted sum of many volatile factors that change at different frequencies. An individual's genotype may determine a stable, trait-like contribution to someone's risk-attitude. On a rapid timescale, risk attitudes may fluctuate randomly due to unpredictable external factors. Crucially, in between those extremes are slowly changing age-related factors or faster changing situational factors like hormonal rhythms and decision contexts respectively. If laboratory experiments like the ones in chapter 2 & 3 of this dissertation imply that risk-attitudes decrease with age, it is likely that other situational factors cause adolescents' risky behaviour in the real-world to increase or spike. There are two ways by which contextual variables could affect adolescents' risk-taking differently from adults and children. First, their reactions to different contexts may be distinct from children or adults. All chapters of my dissertation focussed on how a social context modifies adolescent risk-taking, but other aspects will be important to examine, too. For instance, past research implied that emotionally arousing situations may be among the modulators of adolescent risk-taking (Albert et al., 2013; Gardner & Steinberg, 2005;Rosenbaum et al., 2018; Steinberg, 2008). Second, adolescents might find themselves in risk-facilitating contexts more often than people in other age groups, a position I elaborate on in chapter 5.

In sum, my dissertations' results in combination with recent meta-analytic work (Defoe, Semon Dubas, et al., 2019) suggests that a single focus on adolescents' reward sensitivity is not enough to explain their risk-taking behaviour and contextual factors are likely more important.

Developmental research benefits from formal models.

There are different theories about why adolescents are supposedly more affected by social information than other age groups. The literature review I present in the introduction of chapter 2 identifies three theories that have guided the past years of research on adolescent social susceptibility in risk-taking. The first and maybe most influential theory is a dual systems model stating that adolescents become more sensitive to rewards when they are in a social context (Chein et al., 2011; Gardner & Steinberg, 2005; Shulman et al., 2016). The second states that adolescents are more distracted in social situations (Dumontheil, 2016). The third theory states that adolescents put a stronger weight on social signals in general (Blakemore & Mills, 2014). While all theories inspired a lot of research and some interventions (Bryan et al., 2019; Hansen & Graham, 1991; Liu et al., 2017; Yeager et al., 2018), in chapter 2, I pointed out that these theories are ill-specified. I argue that any behaviour in experiments or real-life could be consistent with either theory on adolescent social susceptibility in risk-taking. This is problematic because the theories assume different mechanisms behind risky behaviour and interventions that aim to improve adolescents' lives target these mechanisms. Thus, the lack of specificity in developmental theories is more than just a scientific controversy (Pfeifer & Allen, 2016; van den Bos et al., 2017). Ill-specified theories actively limit the potential of scientific theory to inform practitioners and, consequently, limit the positive impact that science could have on adolescents' quality of life.

To better negotiate between different theoretical standpoints, in chapter 2, I proposed a formal framework that maps them to precise mathematical equations. The formal approach I put forth in chapter 2 helps theory development on adolescent social susceptibility and risk-taking in two ways. First, putting a theory into formalism encourages researchers to think about the concrete cognitive processes implied by the theory. Second, formal models allow to be compared quantitatively, which is more objective than verbal post-hoc reasoning. Using machine learning methods (Caelen, 2017; Fawcett, 2006), I established that my formal models indeed make differential predictions in the context of monetary lotteries wherein risk-taking is usually studied experimentally. In chapters 2 and 3, I apply these models to three independent social risk-taking experiments and show in both chapters that children, adolescents and adults use social information strategically, depending on whether it is safe or risky. The formal approach in chapter 2 also provides evidence that safe social information has greater influence than risky social information. Asking why that is the case provides a starting point for future research.

Altogether, the formal approach in my dissertation allows to conclude that focussing on their undeveloped cognitive control when judging adolescents' social behaviours does not sufficiently credit how rational adolescents can be when they process social information.

A Bayesian standpoint provides novel insights into social development.

In chapter 2, I have demonstrated how important it is to specify a developmental theory formally. While this made a quantitative model comparison possible and established that adolescents pay attention to the content of social information, the expected utility framework I used (Chung et al., 2015) was agnostic about the learning mechanisms by which social information impacts behaviour. However, there is abundant evidence that social information use in humans and other animals can be described as a learning process, where social information is more impactful when people are more uncertain about how to decide (Bahrami et al., 2010; Behrens et al., 2008, 2009; Biele et al., 2011; De Martino et al., 2017; FeldmanHall et al., 2017; FeldmanHall & Shenhav, 2019; Melamed et al., 2019; Moutoussis et al., 2016; Toelch & Dolan, 2015). In chapter 3, I introduced an experiment that allowed me to manipulate the uncertainty that individuals encounter and examine how social impact changes as a function of uncertainty itself. At the same time, the experiment allowed keeping confounding factors that influence decisions under uncertainty, for instance experience (Hertwig et al., 2004; Hertwig & Erev, 2009) or feedback (Schultz et al., 1997; Stauffer et al., 2014) constant across individuals. I also introduced a Bayesian updating model of social influence and showed that adults indeed used social information more, when they were more uncertain and applied it to a developmental population.

With the model I could tease apart the weight that people assigned to social information from the impact social information had on their decisions. This is an essential feature because, from a Bayesian standpoint, there are two different possibilities by which beliefs can change in response to novel (social) information. The first possibility that has received some attention in the literature on social influence in adolescent risk-taking (Blakemore & Mills, 2014) is that there are interindividual differences in how strong people perceive the same social signal to be, where adolescents perceive social information to be more compelling. The second possibility, which has not received attention in the adolescent literature before, is peoples' uncertainty before observing social information. When people are uncertain, novel information has a greater impact on their beliefs (Bossaerts et al., 2019; Glassen & Nitsch, 2016; Mathys et al., 2014; Nassar et al., 2010; Rushworth & Behrens, 2008). In a social context this means that social information will have a greater impact on the beliefs of uncertain as compared to confident people even if social information is similarly important to them per se.

The results of chapter 3 imply that adolescence is not a developmental phase during which people put a particular weight on social information. In the experiment, developmental differences in susceptibility to social information could be fully explained with developmental differences in uncertainty. This provides evidence for a novel mechanism by which adolescent susceptibility to peer-influence in risk-taking should be understood. If adolescents are merely less certain about whether jumping off a bride is a bad idea, observing others doing the same will make them more likely to jump, too, not because they pursue specific social goals but simply because they learn from observation (Bandura, 1962). Suppose uncertainty is an important mediator of developmental differences in social information use, as chapter 3 implies. In that case, future research on peer influence in adolescent risk-taking needs to aim at identifying adolescents' uncertainties. Interventions will benefit from this, too, because knowing adolescents' uncertainties will also make it possible to help adolescents become more confident about their surroundings, which may decrease adolescents' probability to follow their peers when they jump off the metaphorical bridge.

In sum, using a novel task and computational model, I have shown that peoples social information use depends on their uncertainties. Developmental differences in uncertainty explained differences in how much social information impacted subjects' decisions, pointing to a previously overlooked mechanism by which peer influence operates across adolescence.

Social norms impact risk-taking differently across development.

When studying how decision-making in a social context develops, it is vital to be aware of the distinction between normative and informational social influences (Deutsch & Gerard, 1955; Toelch & Dolan, 2015). Informational social influence helps individuals to get a more accurate idea about the actual state of the world. Normative social influences serve to establish social relationships. Both have different effects on adolescent risk behaviour (van de Bongardt et al., 2015; Clark & Lohéac, 2007; Ragan, 2016).

The distinction between normative and informational social influence is also important to understand why social information use declined in chapters 2 and 3, whereas there was no particular age effect of social information in the subjects' self-reported risky behaviours of chapter 4. In chapters 2 and 3, an anonymous stranger provided subjects with advice about how to decide. In these cases, social influence is most likely "informational" (Rader et al., 2017). In contrast, in chapter 4, I asked subjects to think about how many others engaged in a particular risk behaviour, assessing their understanding of a social norm (Cialdini & Goldstein, 2004; McDonald & Crandall, 2015; Toelch & Dolan, 2015). I could show that the subjects' perception of the social norm about a risky behaviour was strongly related to their propensity to engage in the respective risk-behaviour. Therefore, the research in chapter 4 confirms, in line with research on preventing bullying or smoking in adolescents (Bryan et al., 2019; Yeager et al., 2018), that social norms are powerful mediators of peoples' risk-attitudes.

However, in chapter 4, there was no direct relationship between self-reported risk-taking, perception of social norms and the subjects' age, although it was argued that adolescents are especially susceptible to social norms (Blakemore & Mills, 2014; van Hoorn et al., 2017). Despite the absence of age-related differences in how important social norms were, I found evidence that adolescents considered risk-taking to be more normative than it was. The opposite was true for children, who thought that risk-taking was less normative. The finding that children and adolescents failed at accurately estimating risk-norms, but adults did not, could mean that younger people are simply more uncertain about risk-norms. Adults know better what to expect from others because they have learned and internalized the social norms of their culture (Cialdini & Goldstein, 2004; Schultz et al., 2018). If social norms are an essential correlate of risky behaviour that younger people misperceive, it is clear that seeking to understand adolescents' risky behaviours will benefit from first understanding how adolescents come to perceive the social norms surrounding them. This is a difficult task because it will also require understanding how social norms change from child to adulthood. For instance, children should not drink alcohol. In adults, drinking alcohol is normative (Spear, 2018). As adolescents are in the transition phase between child and adulthood (Blakemore, 2019; Nelson et al., 2005; van den Bos, 2013), drinking norms undergo a transition, which in all likelihood leaves them with some uncertainty about which drinking behaviour is appropriate and which is not. Whom they turn to for building their understanding of social norms about risky behaviour and when they are uncertain about which norms, will be fruitful research questions that can build on my dissertation's work.

In sum, I have shown that social norms are important mediators of people's propensity to take risks and normative social influence may have a different developmental trajectory as compared to informational social influence. Adolescents overestimate risk-norms which may contribute to their increased risk-taking behaviour in the real world.

Adolescents are active social agents.

Influential theories picture adolescent's social behaviour to be driven by their beliefs about others but often omit the fact that their own behaviour provides a social learning source for others as well (Albert et al., 2013; Blakemore & Mills, 2014; Rivers et al., 2008; Romer et al., 2014). Consequently, most of the literature on social influence in adolescent risk-taking is concerned with how plastic adolescents' behaviours are in the presence of social information. One may get the impression that young people are mostly passive bystanders and "find themselves" in a social context or "are sensitive to" social information (Albert et al., 2013; Blakemore, 2008; Blakemore & Mills, 2014; Chein et al., 2011; Romer & Hennessy, 2007; Steinberg, 2008; van Duijvenvoorde et al., 2016; van Hoorn et al., 2016). However, much of adolescents social behaviour might be motivated by sending a social signal (Krishnan-Barman & Hamilton, 2019), which comprises the latent goal of changing others' beliefs or behaviours. For instance, mimicking others builds affiliation, liking, and rapport between people (Chartrand & Bargh, 1999; Lakin & Chartrand, 2003). To increase belonging and being liked are major motivators for most people, and the need to belong is especially elevated during adolescence, which motivates their behaviour in many respects (Crone & Dahl, 2012).

Thus, a "social context" is a two-way street wherein there always is some sort of communication, and every behaviour sends some kind of social signal to others (Bliege Bird & Smith, 2005; Krishnan-Barman & Hamilton, 2019; Watzlawick & Beavin, 1967). In chapters 4 and 5, I took the explicit standpoint that adolescents are receivers and senders of social information. In chapter 4, I have shown that adolescents are more likely to be actively risk-approving by recommending risky behaviour more strongly than children or adults. Without a doubt, their propensity to recommend risky behaviours to others can in combination with their uncertainties add to the potential of adolescent risk-taking to escalate. However, my dissertation also demonstrated that adolescents' active contribution to others' risky behaviour is not necessarily a liability. In chapter 5 I have shown in theory how adolescents who explore an uncertain environment may benefit from being able to do both, send and receive social signals. I show that such exploration can result in harmful risky behaviours but social interactions can have great adaptive value. Such collective wisdom (Tump et al., 2018; Toyokawa et al., 2019) would be impossible if individuals would only receive social information. The developmental correlates of active social behaviour should be subject to future research projects.

Taken together, I present research showing that adolescents differ from people in other ages in the way they actively send social information, and may benefit from interacting with one another when they explore the world. These findings offer an important but understudied perspective towards adolescent social behaviour.

We need a model of the adolescent environment.

Many theories have been proposed to explain adolescents "heightened" risk-taking. Theoretical work has pointed to that adolescents might be peculiar by having an increased drive for exploration (Romer et al., 2017), low self-control and self-regulation (Botdorf et al., 2017; Steinberg et al., 2009), different reactions to culture and social context (Morgan et al., 2015), base their decisions on verbatim-based as opposed to gist-based intuitions (Reyna & Rivers, 2008), are tolerant to ambiguity (Tymula et al., 2012) or uncertainty (van den Bos & Hertwig, 2017), are especially susceptible to peer influence (Gardner & Steinberg, 2005) and so forth. As previously mentioned, the work outlined in chapters 2,3 and 4 in this dissertation casts, in agreement with a recent meta-analysis (Defoe, Semon Dubas, et al., 2019), doubt on the assumption that adolescents take more risks than adults (see also: Willoughby et al., 2013). However, objective measures like police records (Moffitt, 2018) or field observations (Steinberg et al., 2018), *do* tell a different story and hint to that at least in some respects, adolescents take more risks than adults or children in the real world.

In chapter 5 I attempt to explain why this is the case. I point out that the recent focus on the adolescent minds' inner working may have obscured researchers' attention to fact that not only adolescents' bodies and brains but also their environment undergoes pronounced changes (Baumrind, 1987; Blakemore, 2019). As evidenced by cross-cultural differences in adolescent risk-taking (Steinberg et al., 2018), the environment in which people grow up has an outsized influence on the development of an individuals' risk-taking propensity (Frankenhuis et al., 2016). Notwithstanding the research on environmental impact on adolescents' risk-taking, there is only little understanding of the environmental changes that people normatively encounter across development and how these changes impact decision-making. In chapter 5 I show that even perfectly rational learners will take some risks if they, like adolescents, transition from a relatively confined and safe "childhood" environment into the adolescent world of risks and opportunities (Dahl, 2004). I show that if we understand adolescents as agents in a novel environment which they have to explore, an adolescent increase of risky behaviour should be expected as normative behaviour. Thus, chapter 5 makes clear that a better model of adolescents' environments is needed if we want to understand why adolescents take risks in the real world.

Conclusion

When adults think about adolescents, they often think about reckless youngsters who cannot take care of themselves and always get themselves and their friends into trouble. The five studies in my dissertation unanimously disagree with this notion. In my research, neither have adolescents been exceptional risk takers, nor have they followed others' actions blindly without giving it a thought. Notably, my work provides no base to dispute that adolescents' cognitive processing undergoes pronounced changes. On the contrary, in all studies of my dissertation, behaviour or latent variables connected to risk-taking or social susceptibility continued to change across adolescence into young adulthood. However, most variables related to risky behaviour and social susceptibility changed linearly with age. I have further provided evidence that much of the development of social susceptibility might be attributed to greater uncertainties in younger people. I have shown that in theory, the mere combination of uncertainties that adolescents seek to reduce, and changes in the risks that adolescents are exposed to as compared to children or adults, could lead to the increase of adolescent risky-behaviour and susceptibility to peer pressure that they sometimes show in the real world. As such, my dissertation makes the case that adolescents' risky behaviour and their social susceptibility should be understood as a learning process, rather than a liability, that reduces uncertainty and helps them to adapt to the demands of the adult environment which they eventually need to navigate on their own. Thus, my dissertation work resonates with recent proposals that adolescents might be evolutionary equipped with a brain that facilitates exploration and (social) learning in order to generate meaningful novel experiences which they can rely on as independent adults in a complex society (Blakemore, 2019; Dahl et al., 2018; Gopnik et al., 2017; Worthman & Trang, 2018). Or as the neurobiologist Robert Sapolsky put it recently:

"There's a method to the madness of the teenage brain.[6]"

[6] https://nautil.us/issue/15/turbulence/dude-wheres-my-frontal-cortex

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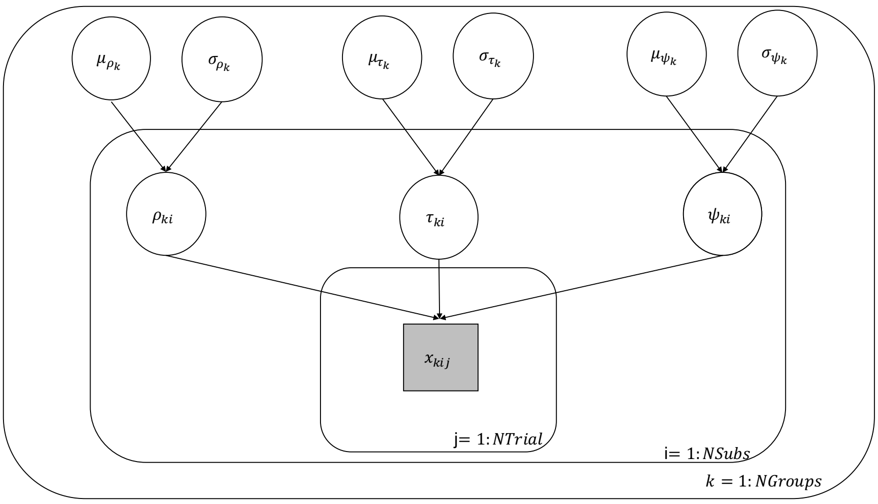
Supplementary Materials

Supplementary Material for Chapter 2

Hierarchical Models of social influence

The hierarchical Bayesian models we formulated had the following structure: We assumed subject level parameters to be sampled from hyper distributions that have uninformative priors. The asymmetric social influence model had two "social" parameters, one for safe and one for risky social information which are both treated exactly the same way as ψ and its hyper parameters.



Expected Utility Priors

$\mu_{\rho_k} \sim Gaussian(0,1)$,
$\mu_{\tau_k} \sim Gaussian(0,1)$,
$\sigma_{\rho_k} \sim Cauchy\ (0,5)$,
$\sigma_{\tau_k} \sim Cauchy\ (0,5)$,

Social Priors

$\mu_{\psi_k} \sim Gaussian(0,1)$,
$\mu_{\omega_k} \sim Gaussian(0,1)$,
$\mu_{\zeta_k} \sim Gaussian(0,1)$,

$\sigma_{\psi_k} \sim Cauchy\ (0,5)$,
$\sigma_{\omega_k} \sim Cauchy\ (0,5)$,
$\sigma_{\zeta_k} \sim Cauchy\ (0,5)$,

Subject-Level Parameters

$\rho_{ki} \sim Gaussian(\mu_{\rho_k}, \sigma_{\rho_k})$
$\tau_{ki} \sim Gaussian(\mu_{\tau_k}, \sigma_{\tau_k})$

$\psi_{ki} \sim Gaussian(\mu_{\psi_k}, \sigma_{\psi_k})$
$\omega_{ki} \sim Gaussian(\mu_{\omega_k}, \sigma_{\omega_k})$
$\zeta_{ki} \sim Gaussian(\mu_{\zeta_k}, \sigma_{\zeta_k})$

Observed Choices

$$USafe = \begin{cases} if\ advice = safe: Vsafe_j^{\rho_{ki}} + \psi_{ki} \\ else\ : Vsafe_j^{\rho_{ki}} \end{cases}$$

$$URisk = \begin{cases} if\ advice = risky: p_j * Vrisky_j^{\rho_{ki}} + \psi_{ki} \\ else: p_j\ * Vrisky_j^{\rho_{ki}} \end{cases}$$

$$x_{kij} \sim Bernoulli(\frac{1}{1+ e^{-(URisk - USafe\ * \tau_{ki})}})$$

Supplementary Figure S2.1: Graphical model of all models with priors used for simulations. The equations in observed choices correspond to Eq. 2.4 of the main text and shall be substituted with the other models, whereas the general structure of our hierarchical model and all priors remain the same for the respective parameters.

Model adjustments to account for ambiguity

Both studies reanalysed by us included an additional condition which we do not explicitly analyse in the main article. Both experiments examined social influence under two kinds of uncertainty: Risk and ambiguity. Risk refers to the fact that outcomes are probabilistic. Ambiguity refers to the explicit uncertainty *about* the outcome probabilities themselves and is often referred to as “known to be missing” information. This dimension of both studies is not relevant in order to generally motivate formal modelling which was the main focus of the present article. However, it can be argued that paying credit to this distinction might change the main articles qualitative conclusion that adolescents are more influenced by safety promoting social information. The line of argument is that ambiguity increases social influence, because it increases the uncertainty about what to choose. Additionally, adolescents have previously been reported to be tolerant to ambiguity (Tymula et al., 2012) and decide overly optimistic when faced with ambiguous choices. Optimism can result in more risky choices, especially when social information favours them.
In both reanalysed studies experiments ambiguity was achieved via covering the outcome indicators (Wheel of Fortune in Blankenstein et al., 2016 and Bars in Braams et al., 2019), in order to only disclose a 50/50 probability of winning to the participants. In both experiments, participants were told that the “real” probability was not 50/50, but the exact winning probability could be anywhere within the visual cover plus the proportion of the whole outcome indicator as seen by the participant.

Ambiguity Extension in Blankenstein et al. 2016

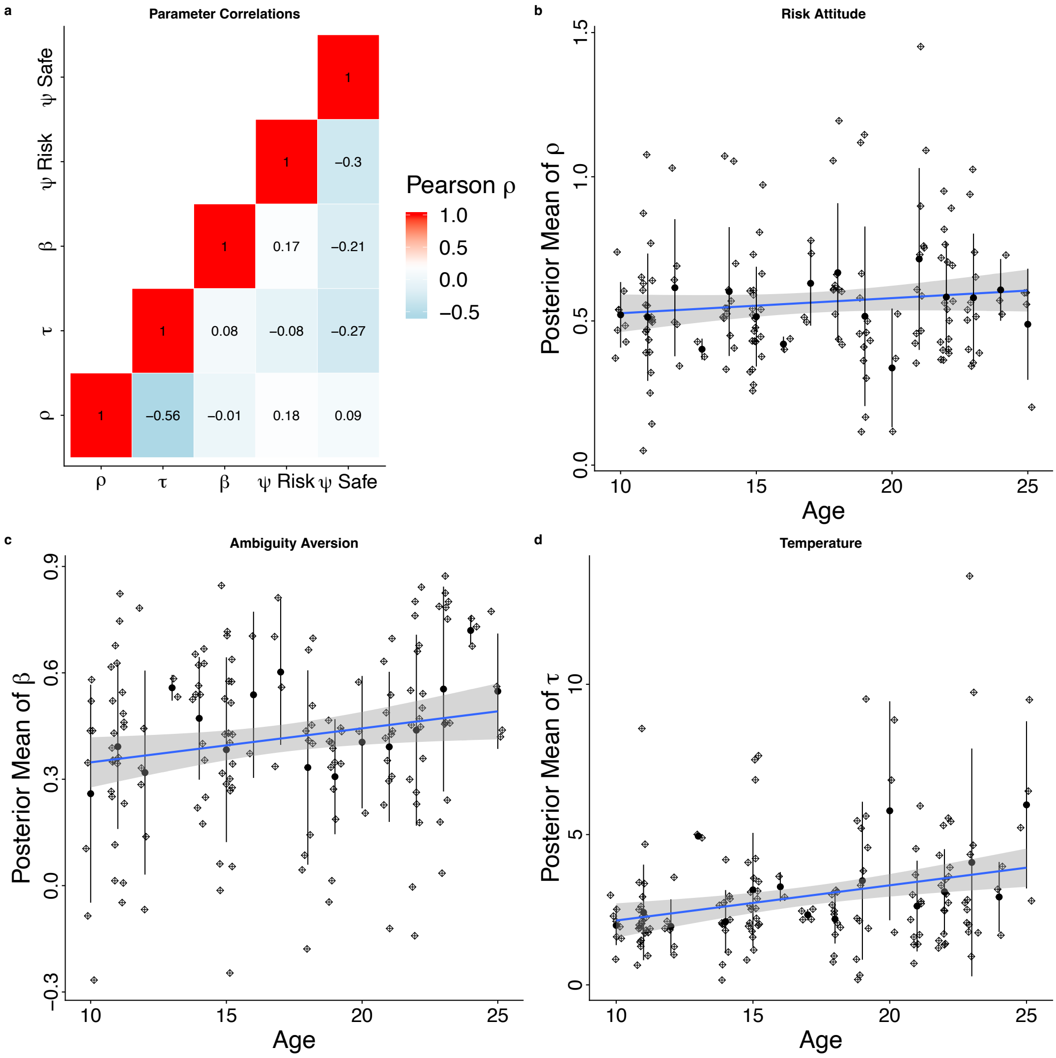
In order to account for this incomplete probability information in half of the trails of both experiment we adjusted out model for ambiguous trials to include a parameter capturing ambiguity attitude, which was orthogonal to the participants reward sensitvity or “risk attitude”. missing”. In Blankenstein et al. (2016), Between 25%, 50%, 75%, and 100% (In Braams et al. (2019), 20%, 40%, 60%, 80%) of the wheel of fortune (bars) was covered in these ambiguous conditions. In our computational models ambiguity is included as a scaling factor of the 50/50 probability information as follows:

Eq.S2.1 $$EU_{solo} = \left(\mathrm{p} * \beta * \frac{A}{2}\right) * (V)^{\rho} \ \forall \text{ Ambigous Trials,}$$

where β captures the weight of the ambiguity in the choice. β estimates larger than 0 are indicative of a pessimism meaning that the decision maker always treats ambiguous options as if ambiguity would reduce the chance of winning (Tymula et al., 2012).

Parameter estimates and correlations in Blankenstein et al. 2016

As parameter inference was not the focus of our main article our article and we had no hypothesis about the extent of these parameters we do not report them in the main text. However, it is notable that β is indeed only weekly correlated with the other parameter estimates. Furthermore, age trends in all parameters reported agree with these reported in the original study.



Supplementary Figure S2.2: Parameter inspection for Blankenstein et al. (2016). a) Correlations within the posterior mean of the parameter estimates obtained from inverting the asymmetric social influence model on the data shown in Blankenstein et al. (2016). b)-d): Individual parameters and age trends that were not shown in the main manuscript. Error bars denote the standard deviation.

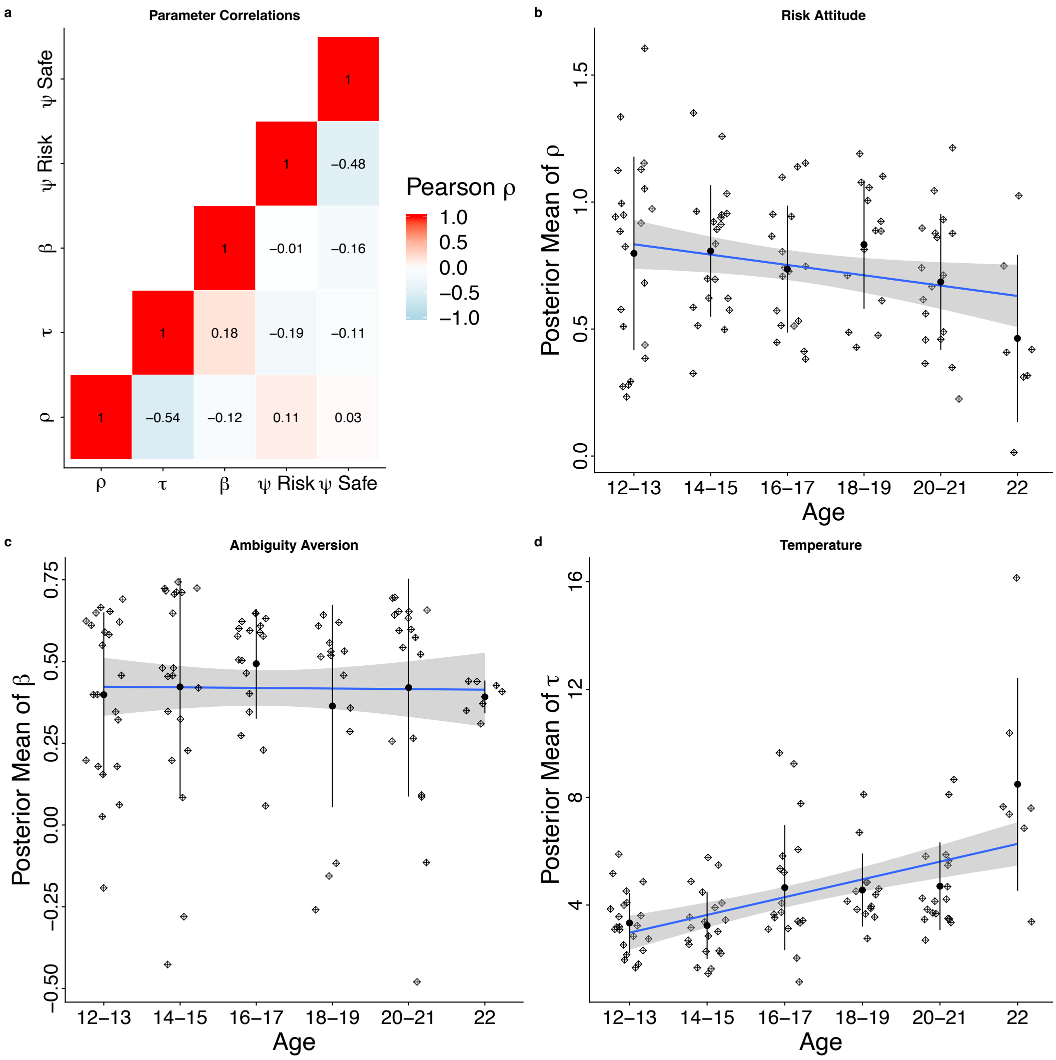
Ambiguity Extension in Braams et al. 2019

In this study, participants did not have a safe alternative to choose from, but decided between two differently risky gambles. Therefore, each options' utility was defined as:

Eq.S2.2 $$EU = \left(\mathrm{p} * \beta * \frac{A}{2}\right) * V^{\rho}{}_{high} + \left(1 - \left(\mathrm{p} * \beta * \frac{A}{2}\right)\right) * V^{\rho}{}_{low},$$

Where p denotes the probability to win the high value and ambiguity was accounted for with replacing p with the first term of the product in Eq 2.1.

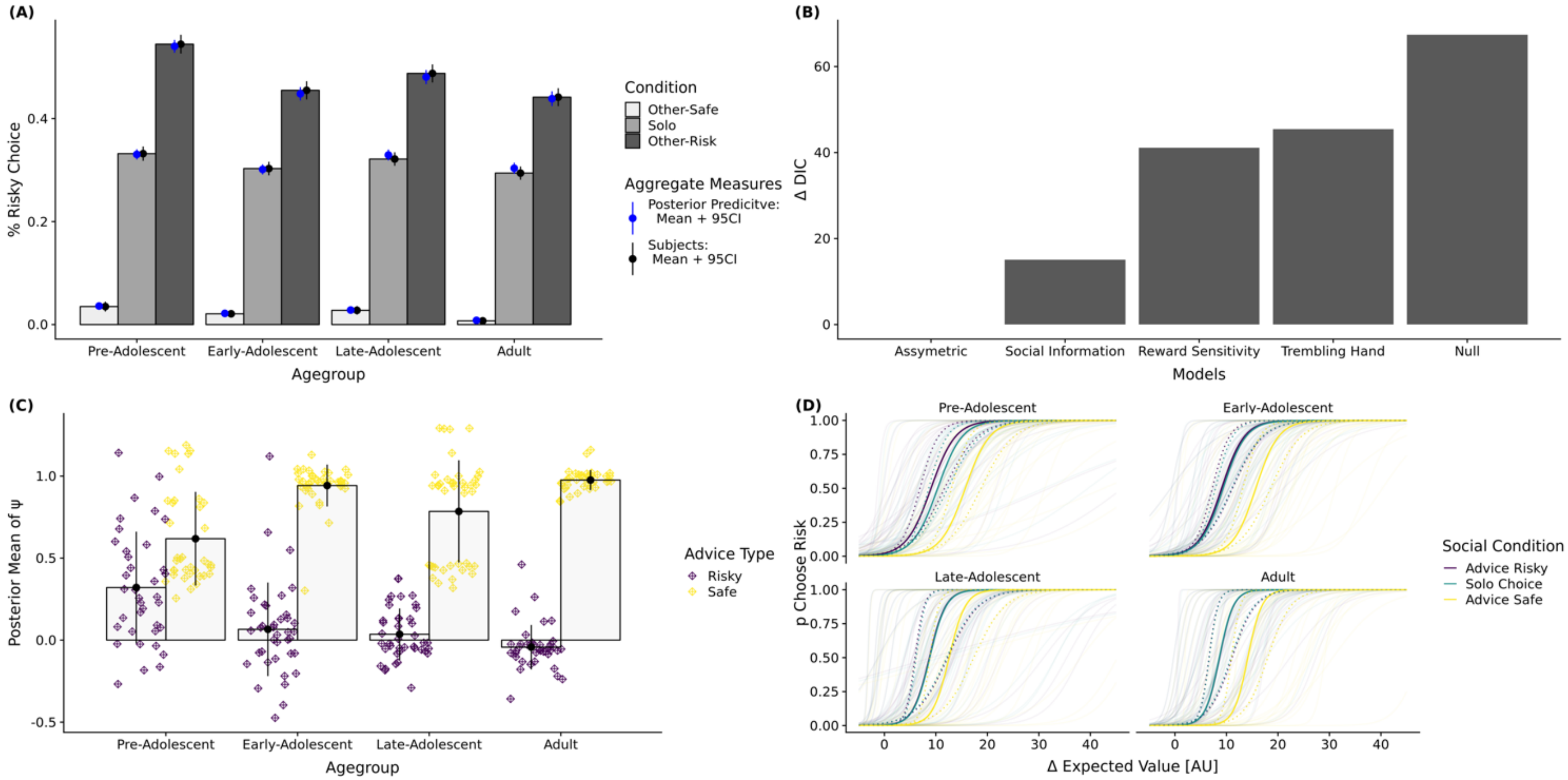
Parameter estimates and correlations in Braams et al. 2019



Supplementary Figure S2.3: Parameter inspection for Braams et al. (2019).

Analyzing only Risky Trails in Blankenstein et al. 2016

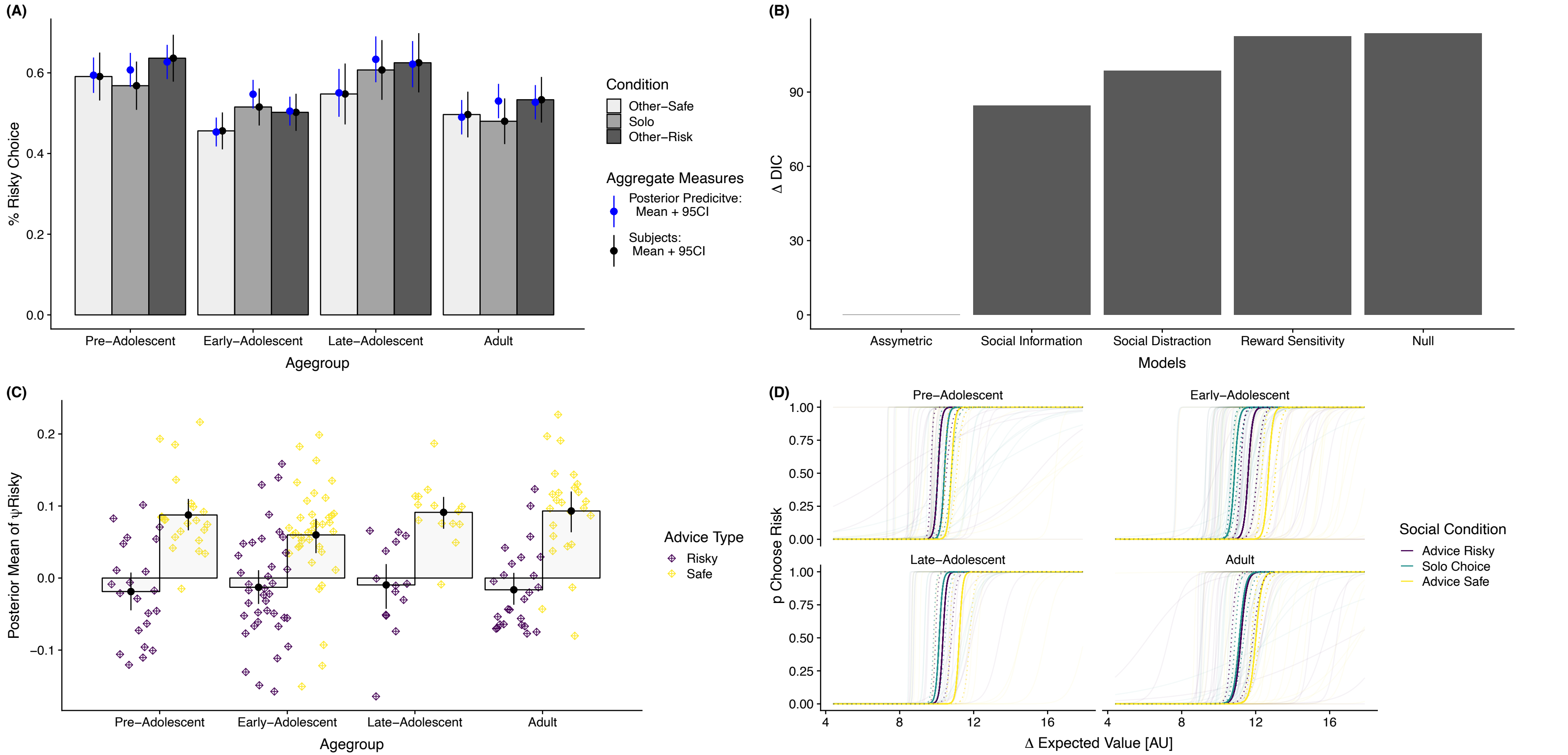
In what follows we show the results of analysing only risky trials in Blankenstein et al (2016). We did so because it is conceivable that ambiguity changes the amount of social influence. If this would be the case our reported results would be biased and would need to be interpreted even more cautiously. In the ambiguity extended models of Blankenstein et al (2016), which we presented in the main article Model comparison via DIC again identified the asymmetric social influence model as best fitting (Figure 2.4B) for the whole dataset. Here we investigated if subsetting the data and using only risky trials changed this model comparison. It did not. Using only expected utility models and only data that was subject to risky trials is consistent to the reports in the main article: all age groups made more risky decisions when social information was risky, and made more safe choices when social information was safe. Again, all subjects were stronger influenced by safe than by risky social information (Figure 4C). Like in the main text, we then performed Bayesian generalized linear regressions using age and quadratic age as predictor of the social model parameter estimates. We ran separate regression analysis on Ψ_{risk} and $\Psi_{safe,}$ treating them as separate dependent variables. In short: the qualitative results are exactly the same. We found that participants took risky advice less, the older they were ($\beta_{Age\text{-}Lin}$ = -1.5, CI = [-2,-1.1]) at the same time older participants took safe advice more (β_{AgeLin} = 1.2, CI = [0.8,1.7]). We also found adolescent specific effects as indicated by a quadratic contribution of age for following risky ($\beta_{AgeQuad}$= -0.5 CI = [-1,-0.1]) but no adolescent-specific effects on taking safe advice ($\beta_{AgeQuad}$= 0.5 CI = [-0.1,0.9]). In sum, participants of all ages are influenced by both safe and risky social information. In agreement with the original author's conclusions, we found that the impact of risky social information is strongest in youngest participants.



Supplementary Figure S2.4: Safe and Risky advice, only analyzing risky trials in Blankenstein et al. (2016). (A) Percent risky choice in Blankenstein et al. (2016), by age group and conditions. Black error bars represent the bootstrapped 95% confidence interval. Next to the mean and CI of the subjects' choices (black), we show simulations under the full posterior from the winning model' parameter estimates (blue). (B) Difference in DIC fit indices for the whole modelspace, using the winning model as a reference. (C) Posterior Parameter Estimates of ψrisk (purple) and ψsafe (yellow), binned by age group. (D) Predicted probability to choose the risky option given the difference in expected value of the gambles. Colored solid lines correspond to model predictions obtained by computing the mean of subject-level parameters in each age group. Colored dashed lines denote upper and lower confidence bounds obtained by computing the standard error of the posterior mean. Transparent lines refer to subject-level predictions.

Analyzing only Risky Trials in Braams et al 2019.

Subsetting the data in order to only analyze risk trials, yielded that the asymmetric advice model was best suited for the data. However, this procedure resulted in only 36 data points per subject therefore the regression results we report here can likely not be interpreted on a reasonable scale and we just report them here for completness. We find that most participants put higher weight on safety promoting social information (Figure 5C). To judge the statistical relevance of age this pattern, we performed Bayesian general linear regressions, again using age and quadratic age as predictor while treating Ψ_{risk} and Ψ_{safe} as separate dependent variables. We found that linear age was not a good predictor for using risky ($\beta_{AgeLin} = 0.0$, CI = [-0.1,0.1]) nor safe advice ($\beta_{AgeLin} = -0.1$ CI = [-0.1,0.2]). Also, quadratic age trends were not substantial for both risky ($\beta_{AgeQuad} = 0.0$ CI = [-0.1,0.2]) and or safe advice ($\beta_{AgeQuad} = -0.1$ CI = [-0.2,0.0]). In sum we find again that safe social information has a greater impact on choice than risky information, model comparison provides evidence that participants assign weight to risky and safe social information differentially.



Supplementary Figure S2.5: Safe and Risky advice, accounting for the ambiguity condition of Braams et al. (2019).

Supplementary Material for Chapter 3

Models:

A main focus of this work was to quantify how susceptibility to social influence under uncertainty develops across adolescence. To this end we developed a computational model which formalizes the assumption that social influence depends on individually experienced uncertainty (Toelch & Dolan, 2015). The model rests on three building blocks/assumptions.

First, there is risk attitude. We model risk attitude by borrowing concepts from expected utility theories (Schoemaker, 1982). According to expected utility, individual differences in reward sensitivity govern how likely individuals are to take risks. If individuals are highly sensitive to rewards, they will be more inclined to take a risk in order to obtain these rewards. Differences in reward sensitivity are usually modelled with a power function where lambda < 1 indicates risk aversion and lambda > 1 risk seeking:

$$U_i = V_i^{\lambda}. \tag{S3.1}$$

Where *U* describes the utility and *V* the objective value of gamble i. By examining how the values for λ differ across age groups we thus quantify how reward sensitivity develops. Second, inference and uncertainty. In the experience-based condition, subjects have to learn about the probability of obtaining a blue marble based on observing a sequence of draws of marbles from the jar. In the description based, uncertainties cannot be attributed to the learning process but directly relate to subjects' uncertainty about the utilities offered by each option. In both conditions however subjects are likely uncertain about the utility yielded by the current decision problem (Bach & Dolan, 2012; Blavatskyy, 2007; Castegnetti et al., 2020; Dayan et al., 1995; Friston, 2010; Moutoussis et al., 2016).

We estimate this uncertainty for a given decision problem with the parameter σ, which differs depending on whether the subject is asked to make decisions under risk or under uncertainty:

$$\phi_i \sim Beta\_Proportion(\mu_i, \zeta_i). \tag{S3.2}$$

μ denotes the mean of a beta distribution and describing the probability of winning (ratio of blue/red marbles) the depicted marble jar and ζ is the standard deviation of this distribution.

The conventional shape parameters of the beta distribution are then given by the reparameterization:

$$\alpha_i = \mu_i * \zeta_i^2, \tag{S3.4}$$

$$\beta_i = (1 - \mu_i) * \zeta_i^2 \tag{S3.5}$$

We then combine these two components, reward sensitivity and uncertainty, by multiplying the beta distribution with the utility of the gamble:

$$EU_i \sim Beta\left(\alpha_{solo_{ij}}, \beta_{solo_{ij}}\right) * U_i. \tag{S3.6}$$

This way, we are able to quantify individual uncertainty about the *utility* yielded by the risky option (figure 2) and can get an insight into the effect of these uncertainties on using social information and how this effect changes across development. Third, there is social influence where we formalize the following scenario: If someone observes risky social information, this will make them believe that the risky option is more advantageous than previously thought based on individual information alone. If someone observes safe social information it will make them believe that the risky option is less advantageous than previously thought. We model social influence as Bayesian updating. As shown in figure 2, higher prior uncertainty leads to a more pronounced difference between posterior (belief after observing social information) and prior (belief before observing social information).

$$\alpha_{social} = \begin{cases} \psi_{risky} * \alpha_i, & Risky\ Advice \\ \alpha_i, & Safe\ Advice \end{cases} \tag{S3.7}$$

$$\beta_{social} = \begin{cases} \beta_i, & Risky\ Advice \\ \psi_{safe} * \beta_i, & Safe\ Advice \end{cases} \tag{S3.8}$$

And the resulting utility distribution after observing social information is now given by:

$$EU_{social_i} \sim Beta\left(\alpha_{social_i}, \beta_{social_i}\right) * U_i. \tag{S3.9}$$

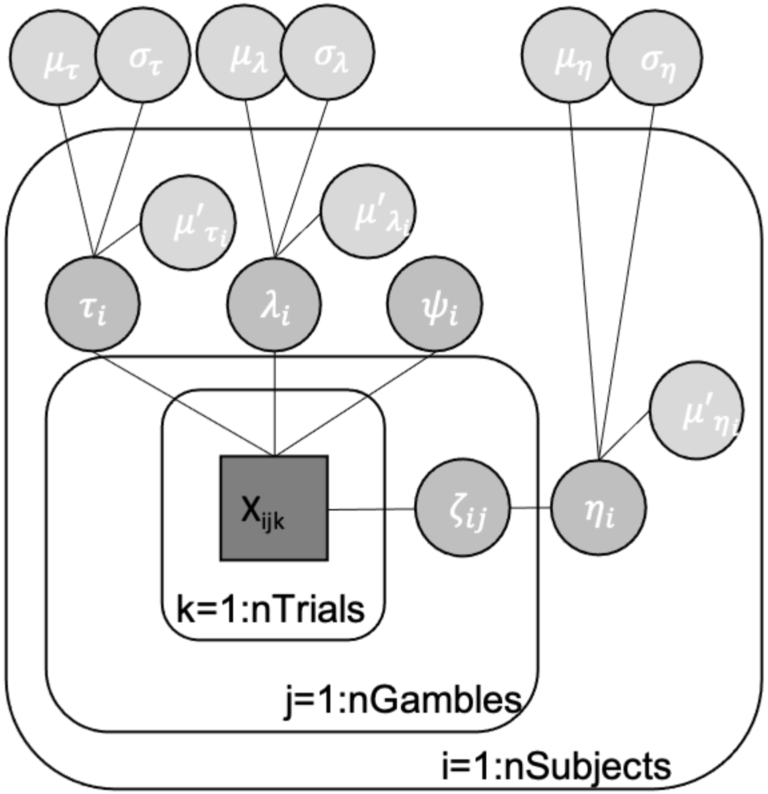
Differences in social information use are modelled with the parameter ψ. In our formulation, this parameter can take different values depending on whether social information is presented under risk or uncertainty and whether it advocates safe or risky choices. A null model which does not assume any changes in response to social information sets ψ to 1. The probability to choose risk, π, is then obtained by integrating over the posterior utility distribution, given social information, between the utility offered by the safe option and infinity:

$$\pi_{\mathrm{i}} = \begin{cases} \int_{\mathrm{U_{safe}}}^{\infty} \mathrm{EUsolo}\ , \ if\ condition == solo \\ \int_{\mathrm{U_{safe}}}^{\infty} \mathrm{EUsocial}\ , \ if\ condition == social \end{cases}. \tag{S3.10}$$

Finally, each choice is treated as a Bernoulli distributed random variable with probability parameter π.

$$choose_{risk_i} \sim Bernoulli(\pi_i). \tag{S3.11}$$

The elegance of this model is that it we integrate three mechanisms, known to develop through adolescence, namely: reward sensitivity, processing of uncertainty and social influence into one single cognitive model. The model was formulated in a hierarchical Bayesian way with the hierarchical parameter structure depicted in figure S3.1.



$$\mu \sim normal(0,1)$$
$$\sigma \sim cauchy(1,1)$$
$$\psi_{i_{risk/safe_{des/exp}}} \sim normal(1,1)$$
$$\tau_i = \exp(\mu_\tau + \mu'_{\tau_i} * \sigma_\tau)*5$$
$$\rho_i = \Phi(\mu_\lambda + \mu'_{\lambda_i} * \sigma_\lambda)*2$$
$$\eta_i = \Phi(\mu_\eta + \mu'_{\eta_i} * \sigma_\eta)*2$$
$$\zeta_{ij} = \begin{cases} \sim gamma(2,2), if\ description - based \\ \sqrt{\dfrac{nblue_{ij}^{\eta_i} * nred_{ij}{}^{\eta_i}}{\left(nblue_{ij}^{\eta_i} + nred_{ij}{}^{\eta_i} + 1\right) * \left(nred_{ij}^{\eta_i}\right)^2}}, otherwise \end{cases}$$
$$X_{ijk} \sim Bernoulli(\pi)$$

Figure S3.1 Graphical Model for the marble task. Hierarchy of parameters depend on subjects and condition. Subject level parameters are sampled from a unit normal distribution and are transformed into using non-centered parametrization in order to achieve efficient subject level parameter sampling. Φ denotes the unit normal cumulative distribution function

Alternative Models

Views of social influence during adolescent that provide an alternative to the uncertain utility model exist and have been prominent in the literature (Ciranka & van den Bos, 2019; Dumontheil, 2016; Shulman et al., 2016). One of these views is that a social context makes adolescents more sensitive towards rewards. We formalize this view by invoking a strictly positive, free parameter, ω, on the "reward sensitivity" part of each subjects' utility function, that occurs when social information is present:

$$U_{\mathrm{Social}} = V^{\lambda * \omega} \tag{S3.12}$$

Increased distraction has also been discussed as a mechanism determining adolescent decision-making under uncertainty. Therefore, we introduce another model which augments the probability to choose risk with a "trembling hand" error term, ϵ, that relates to the probability of guessing in a social context:

$$p_{\mathrm{choose\_risk\_social}} \sim \mathrm{Bernoulli}\left((1-\epsilon) * \pi + \frac{\epsilon}{2}\right). \tag{S3.13}$$

An alternative prior for the reward sensitivity model, which did not include ψ relates to the parameter ω:

$$\begin{gathered} \mu_{\omega} \sim \mathrm{normal}(1,1) \\ \sigma_{\omega} \sim \mathrm{cauchy}(1,1) \\ \omega_{\mathrm{i}} \sim \Phi\left(\mu_{\omega} + {\mu'}_{\omega} * \sigma_{\omega}\right) * 2 \end{gathered} \tag{3.14}$$

The prior for ζ in the distraction ("trembling hand") model was:

$$\epsilon_{\mathrm{i}} \sim \mathrm{normal}(0.1, 0.01) \tag{3.15}$$

Model comparison:

To assess whether increased distraction or reward sensitivity accounts for our subjects' choices better than the uncertain utility model, we performed an approximate leave one out cross validation on the likelihood surfaces of the full posterior.

Table S2.3 model comparison based on the expected log posterior predeictive density. The uncertain utility model depited in the main text in figure 1 describes the choices of our subjects considerably better than the alternative models considered

	elpd_diff	se_diff
Uncertain Utility	0	0
Reward Sensitvity	-413.3	87.3
Null	-908.3	104.6
Trembling Hand	-7279.3	242.2

Parameter Recovery

To establish that the parameters modes of the uncertain utility model are identifiable we re-fit the uncertain utility model to its own posterior predictions by simulating responses from full combinations with 10 equally spaced parameter values with following parameter boundaries: $\rho \in \{0 \ldots 2\}$; $\sigma_{\text{risk}} \in \{0 \ldots 0.2\}$, $\sigma_{\text{unc}} \in \{0 \ldots 0.2\}$, $\psi_{\text{risk}} \in \{0 \ldots 5\}$ $\psi_{\text{unc}} \in \{0 \ldots 5\}$.

Fitting of the parameter recovery was done using the L-BFGS algorithm for optimizing posterior modes in stan.

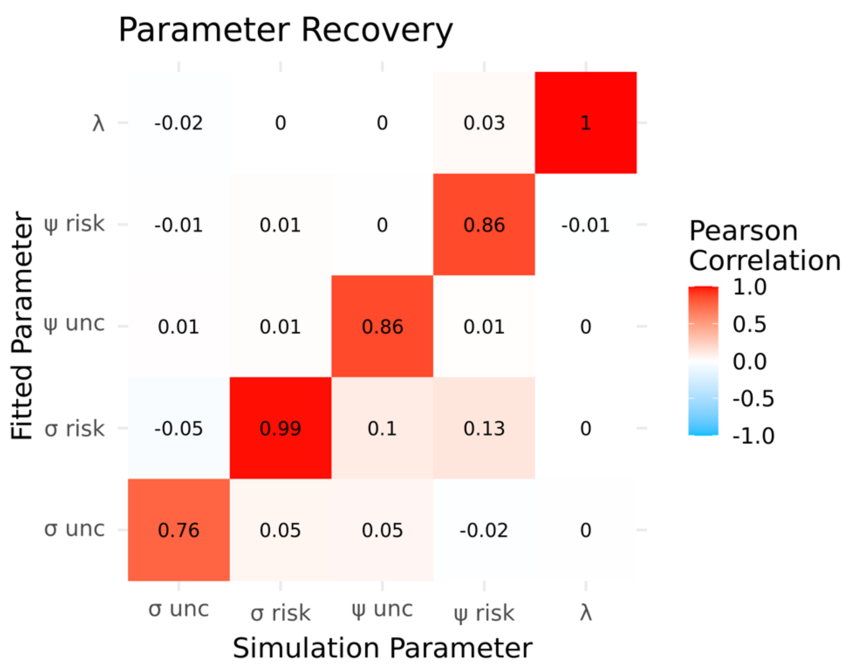


Figure S2.2: Parameter Recovery. Diagonal elements show the very high correlation between simulated and recovered parameters. The absence of strong spurious (off diagonal) correlations is an indication that our parameter estimates can be trusted.

Table S4.4: Willingness to engage. Shown are the item characteristics estimated on the base of our subjects' responses on the ARQ with all items. Blue are desirable, recreational behaviors, orange undesirable

Item	raw_alpha	std.alpha	G6(smc)	average_r	S/N	var.r	med.r
Overeating	0.75	0.77	0.82	0.13	3.3	0.02	0.11
Teasing people	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Cheating	0.77	0.77	0.83	0.14	3.4	0.02	0.12
Talking to Strangers	0.75	0.77	0.82	0.13	3.3	0.02	0.12
Sniffing Gas or Glue	0.76	0.77	0.83	0.14	3.3	0.02	0.12
Drinking	0.74	0.76	0.81	0.13	3.1	0.02	0.12
Smoking	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Getting Drunk	0.75	0.76	0.81	0.13	3.1	0.02	0.12
Drugs	0.75	0.76	0.82	0.13	3.1	0.02	0.12
Staying out late	0.74	0.76	0.82	0.13	3.1	0.02	0.11
Drinking and driving	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Stealing	0.75	0.76	0.82	0.13	3.1	0.02	0.11
Unprotected sex	0.76	0.77	0.83	0.14	3.3	0.02	0.12
Speeding	0.76	0.77	0.83	0.14	3.3	0.02	0.12
Biking without a helmet	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Leaving School	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Inline Skating	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Parachuteing	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Flying a Plane	0.75	0.76	0.82	0.13	3.2	0.02	0.11
Entering a competition	0.78	0.79	0.84	0.15	3.7	0.02	0.12
Martial Arts	0.76	0.77	0.83	0.14	3.4	0.02	0.12
Skiing	0.75	0.76	0.82	0.13	3.1	0.02	0.11

Table S4.5 :Willingness to recommend. Shown are the item characteristics estimated on the base of our subjects' responses on the ARQ with all items. Blue are desirable, recreational behaviors, orange undesirable

Item	*raw_alpha*	*std.alpha*	*G6(smc)*	*average_r*	*S/N*	*var.r*	*med.r*
Overeating	0.75	0.75	0.83	0.13	3.0	0.04	0.10
Teasing people	0.76	0.77	0.83	0.14	3.3	0.04	0.11
Cheating	0.75	0.75	0.82	0.13	3.0	0.04	0.10
Talking to Strangers	0.73	0.74	0.82	0.12	2.9	0.04	0.10
Sniffing Gas or Glue	0.76	0.76	0.83	0.13	3.2	0.04	0.11
Drinking	0.73	0.74	0.81	0.12	2.8	0.03	0.10
Smoking	0.74	0.74	0.82	0.12	2.9	0.04	0.10
Getting Drunk	0.72	0.73	0.80	0.12	2.7	0.03	0.10
Drugs	0.74	0.74	0.81	0.12	2.8	0.03	0.10
Staying out late	0.72	0.74	0.81	0.12	2.8	0.03	0.10
Drinking and driving	0.75	0.76	0.83	0.13	3.1	0.04	0.10
Stealing	0.73	0.74	0.81	0.12	2.8	0.03	0.10
Unprotected sex	0.75	0.76	0.83	0.13	3.1	0.04	0.11
Speeding	0.75	0.75	0.82	0.12	2.9	0.04	0.10
Biking without a helmet	0.76	0.76	0.83	0.13	3.2	0.04	0.10
Leaving School	0.75	0.76	0.83	0.13	3.1	0.04	0.11
Inline Skating	0.78	0.78	0.84	0.14	3.5	0.04	0.12
Parachuteing	0.77	0.77	0.84	0.14	3.4	0.04	0.11
Flying a Plane	0.76	0.77	0.84	0.13	3.3	0.04	0.11
Entering a competition	0.79	0.78	0.84	0.15	3.6	0.04	0.12
Martial Arts	0.76	0.77	0.84	0.14	3.3	0.04	0.11
Skiing	0.75	0.75	0.82	0.12	3.0	0.04	0.11

Table S3. Model comparison using leave one out cross validation for *desirable* risks. Models were compared with respect to their expected predictive density (elpd). In the model containing correlates of IQ and emotional intelligence (IQ_EQ_Linear_Quadratic), multiple imputation was used in 15 cases where CFT-20 and reading the mind in the eyes scores were missing completely at random due to computer problems.

Model	*se_diff*	*elpd_diff*
Linear_Quadratic	0.0	0.0
Linear	-5.6	4.0
IQ_EQ_Linear_Quadratic	-7.2	3.7
Quadratic	-15.3	5.8
NoAge	-19.5	7.2

Table S4. The same as table S3 but for *undesirable* risks

Model	*se_diff*	*elpd_diff*
Linear_Quadratic	0.0	0.0
Quadratic	-2.5	3.6
Linear	-2.5	2.7
IQ_EQ_Linear_Quadratic	-3.4	3.7
NoAge	-4.0	4.2

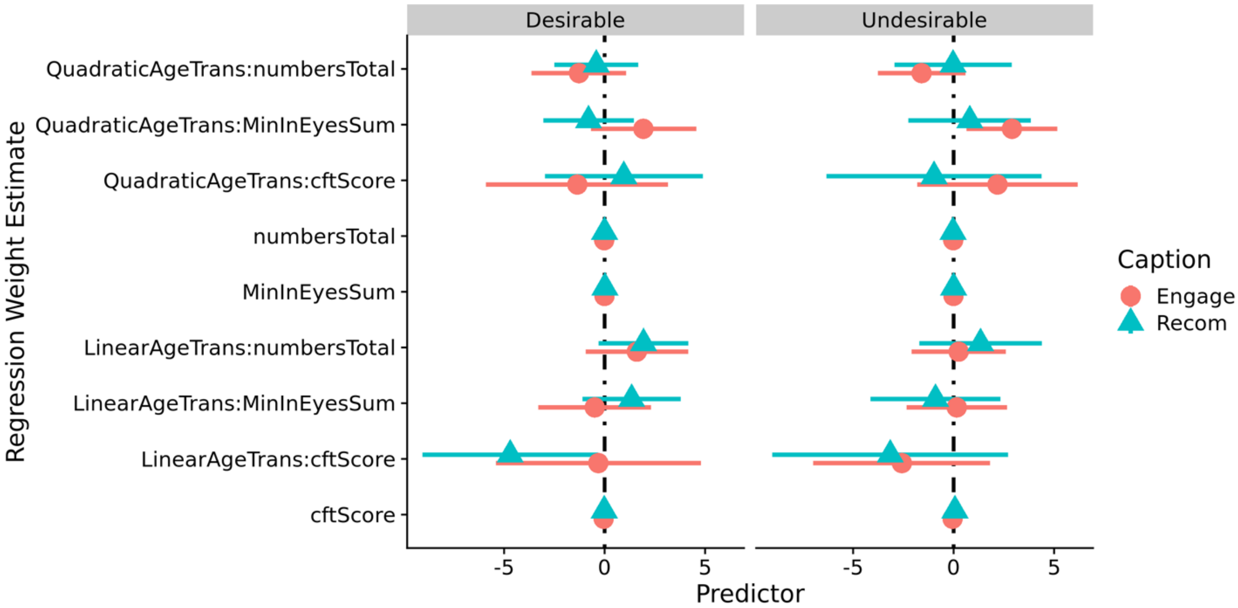


Figure S4.1. Posterior regression weights IQ, working memory and reading the mind in eye and their interactions with age for both, propensity to recommend (blue) and to engage (red). Shown are the 95% credible intervals of the posterior distributions of each regression weight that was not part of the best-fitting model, which we report in the main manuscript.

Supplementary Material for Chapter 5

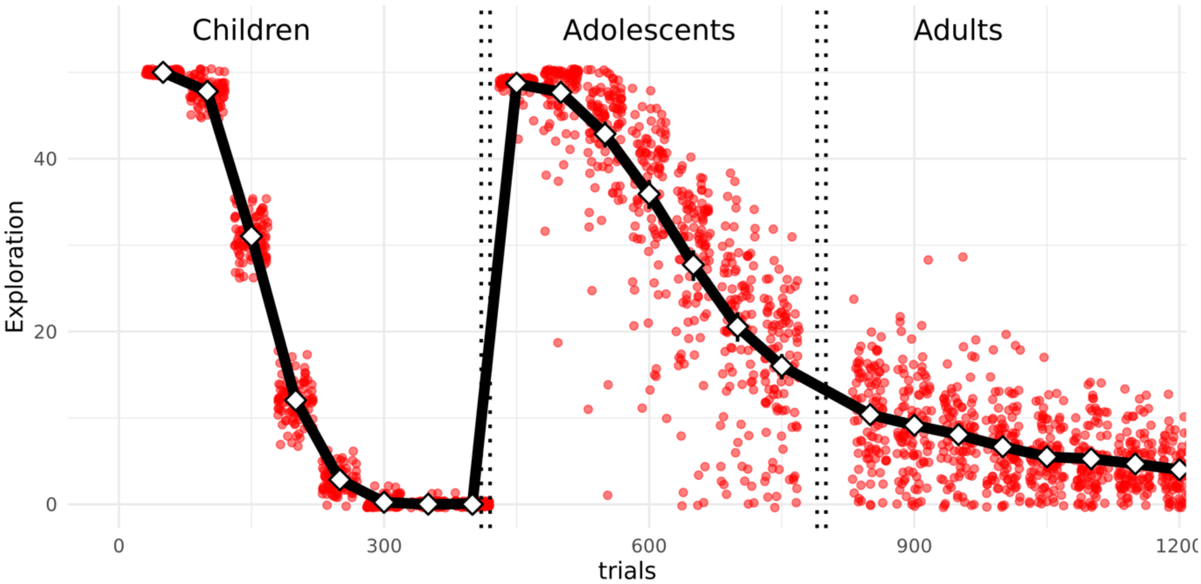


Figure S5.2: Exploration (y axis) by timepoints in the simulations (x-axis). Other than in the main manuscript exploration here was defined as sampling options about which the agent was uncertain ($\sigma > 38$). Such definition might be closer tot he intuitions about exploration, however it does not follow the definition of exploration that is often adopted in the literature. The pattern mirrors the one in the main text. Each shape denotes the average number of switches over the past 50 decisions per developmental stage. Small red shapes denote individual simulations, and large shapes cover the mean and bootstrapped 95%ci of the mean of all simulations. Explorative decisions are defined as the decision to switch from one to another option. While both, childhood and adolescence can be characterized by relatively high exploration, the adolescent environment leads agents to explore their environment for a prolonged time.

Data and code availability

The code to reproduce the results of chapter 2 can be found on:
https://github.com/NomisCiri/Social_Adolescence_Public

The data and code to reproduce the results of chapter 3 can be found on:
https://github.com/NomisCiri/Risk_Gaps

The data and code to reproduce the results of chapter 4 is still work in progress and has no public repository yet.

The data and code to reproduce the simulations of chapter 5 can be found on:
https://arc-git.mpib-berlin.mpg.de/ciranka/adaptiveadolescence

Statement of Contribution

The chapters 2-5 have been prepared with a co-author. In the following I clarify the authors' contributions to each chapter.

Chapter 2:

Simon Ciranka: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing

Wouter van den Bos: Conceptualization; Supervision; Writing – review & editing

Chapter 3:

Simon Ciranka: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing

Wouter van den Bos: Conceptualization; Supervision; Writing – review & editing

Chapter 4:

Simon Ciranka: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing

Wouter van den Bos: Conceptualization; Supervision; Writing – review & editing

Chapter 5:

Simon Ciranka: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing

Wouter van den Bos: Conceptualization; Supervision; Writing – original draft; Writing - review & editing

List of Manuscripts

Chapters 2-5 of this dissertation have been prepared with co-authors as manuscripts for peer reviewed journals.

Chapter 2:

Ciranka, S., & van den Bos, W. (2019). Social influence in adolescent decision-making: A formal framework. *Frontiers in Psychology*, *10*(AUG), 1915. https://doi.org/10.3389/fpsyg.2019.01915

Chapter 3:

Ciranka, S., & Bos, W. (in prep). Uncertainty explains social information use across adolescence. *This chapter is still under preparation for submission.*

Chapter 4:

Ciranka, S., & Bos, W. (2021). Social norms in adolescent risk engagement and recommendation. *British Journal of Developmental Psychology*, bjdp.12369. https://doi.org/10.1111/bjdp.12369

Chapter 5:

Ciranka, S., & Bos, W. (in press). Adolescent risk-taking in the context of exploration and social influence. *Developmental review*

Other Projects

Ciranka, S., & van den Bos, W. (2020). A Bayesian Model of Social Influence under Risk and Uncertainty. *Proceedings of the 42ndth Annual Conference of the Cognitive Science Society*. https://doi.org/10.31234/OSF.IO/MUJEK

Molleman, L., **Ciranka, S.,** & van den Bos, W. (under review in Nature Communictions). Social influence in adolescence as a double-edged sword. *PsyArXiv*. https://doi.org/10.31234/OSF.IO/GCBDF

Ciranka*, S., Linde-Domingo*, J., Padezhki, I., Wicharz, C., Wu, C., & Spitzer B. (submitted to Nature Human Behavior) Asymmetric learning facilitates human inference of transitive relations.

**shared first authors*

Declaration of Independent Work

I hereby declare that:

- I completed this doctoral thesis independently. Except where otherwise stated, I confirm that the work presented in this thesis is my own.
- Where information has been derived from other sources, I confirm that this has been indicated in the thesis.
- I have not applied for a doctoral degree elsewhere and do not have a corresponding doctoral degree.
- I have acknowledged the Doctoral Degree Regulations which underlie the procedure of the Department of Education and Psychology of Freie Universität Berlin, as amended on August 8th 2016.
- The principles of Freie Universität Berlin for ensuring good academic practice have been complied with.

Simon Ciranka
Berlin, 31. März 2021