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Review

Risks and rewards in adolescent decision-making

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Abstract

Adolescent decision-making has been characterized as risky, and a heightened reward sensitivity may be one of the aspects contributing to riskier choice-behavior. Previous studies have targeted reward-sensitivity in adolescence and the neurobiological mechanisms of reward processing in the adolescent brain. In recent examples, researchers aim to disentangle the contributions of risk- and reward-sensitivity to adolescent risk-taking. Here, we discuss recent findings of adolescent's risk preferences and the associated neural mechanisms. We highlight potential frameworks that target individual differences in risk preferences in an effort to understand adolescent risk-taking, and with an ultimate goal of leveraging undesirable levels of risk taking.

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Rewards, Risk taking, Adolescents, Individual differences, Social influence, Insula, Risk-return.

Introduction

Adolescence is a transitional life phase, marking the change from childhood to adulthood. It is a period in life known for changes in motivated, goal-directed behavior, and is associated with a heightened sensitivity to *rewards* and a greater tendency for *risk taking*. For instance, adolescents and young adults take more daily-life risks than children and adults [1]. Adolescents also rate themselves higher than children and adults on reward-drive [2], sensation-seeking [3], and show a heightened neural response to rewards [2,4,5]. This heightened reward-sensitivity may serve as a differential susceptibility marker that makes some adolescents more sensitive to the environment than others [6]. For instance, research found that adolescents with high compared to low neural activation to rewards conformed more to observed peer norms in both positive and negative directions [7]. This emphasis on potential rewards (e.g., money, power, acceptance) may also lead to risky decision-making by steering adolescents towards the high-reward, high risk options. The strong focus on studying adolescent reward-sensitivity, however, may have limited a developmental perspective on how adolescents process *risk*. Although correlated (and sometimes even conflated) with reward, risk preference is not the same as reward-sensitivity. In this concise review, we explore to what extent adolescent decision-making is related to changes in risk preferences and what neural mechanisms underlie adolescent risk-processing.

Measuring risk preference in adolescent risky decision-making

Risk has been defined in various ways, ranging from psychological definitions such as a potential danger or loss to more economic definitions such as a higher variance in outcomes [8]. The extent to which a person responds to risk and/or chooses the riskier option in their environment is called an individual's *risk preference*, also referred to as "risk attitude," "risk tolerance" or "sensitivity to risk" [9]. Individual's risk preferences have been related to real-world consequences, such as misbehavior in school and a lower likelihood to graduate [10], drug use, not wearing a seat-belt, or financial insecurity [11–13].

The measurement of risk preference knows two traditions. First, risk preferences have been *revealed* by using monetary lotteries in experimental studies examining how people make decisions under risk. Typically, people are asked to choose between options with explicitly stated risks and rewards (e.g., (A) do you prefer 45 Euro for sure, or (B) 100 dollar with a probability of .5?). A risk neutral person would follow the objectively calculated expected value when choosing between these options (hence choose B). A risk-averse person may overweigh the utility of the sure option over the riskier option (and

hence choose A). Another way in which risk preferences have been measured is by using *stated* preferences based on self-reports. Numerous questionnaires exist for adult and adolescent samples that also assess domain-specificity of risk taking (e.g., social, financial, recreational, health-safety). Findings indicate that even a one-shot question may result in reliable risk preferences (e.g., "would you describe yourself as someone who tries to avoid risks (risk-averse) or as someone who is willing to take risks (risk-prone)?") [12]. A recent study by Frey et al. [14] showed that self-reports outperformed behavioral risk-taking tasks in terms of reliability, retest-stability and validity. Moreover, in a latent-modeling approach a stable, "trait," factor emerged from self-reports that qualified as an overarching, domain-general risk preference, as well as a series of factors capturing (domain) specific aspects of risk preference. These findings indicate the importance of measurement when studying risk preference. In addition, they indicate that individual's risk preference comprises both general and domain-specific dimensions.

Even if risk preference is a stable trait, it may still show mean-level changes across development. Empirical evidence from large world-wide longitudinal studies suggest an increase in stated risk-seeking preferences in adolescence and early adulthood [1,15], followed by a decline across the adult lifespan [16,17]. However, variations in developmental changes may occur across different domains of risk taking (i.e., health-safety, recreational, social, ethical, and/or financial domains) [15,16]. Behavioral tasks have shown mixed findings regarding age differences in revealed risk preferences, with a meta-analysis showing a decrease in risk-seeking preferences from adolescence to adulthood [18]. It has been suggested that age differences in risk preferences might be moderated by specific task characteristics, including whether measures tap into learning, or cognitive functions [18,19].Thus, although findings are mixed depending on the measure used, risk preferences seem subject to developmental fluctuations.

Adolescent risk preference in context

Risk preference may also show elements of state specificity. With states we refer to relatively changeable variations around a person's mean risk preferences that may be associated with situational factors. One particular situation of interest to adolescence is a social context. Adolescence is considered a key period for social development with a social reorientation towards peers, and a heightened sensitivity towards meeting social needs [20–23]. Studies have included different social contexts to examine the impact on adolescent risky decision-making.

One particular context is *social observation*: in which a peer, friend, or other observes the behavior of the adolescent. Research has shown that adolescents risk preference increases when their choices are monitored by a peer [24–27] (but see [28–30]), while the mere presence of a peer was not sufficient to influence risky choice [24]. The effect of social observation on risk preference may be particularly salient in late adolescence [25], although the findings of a recent study suggests this particular developmental pattern is found only in more affective decision-contexts [24].

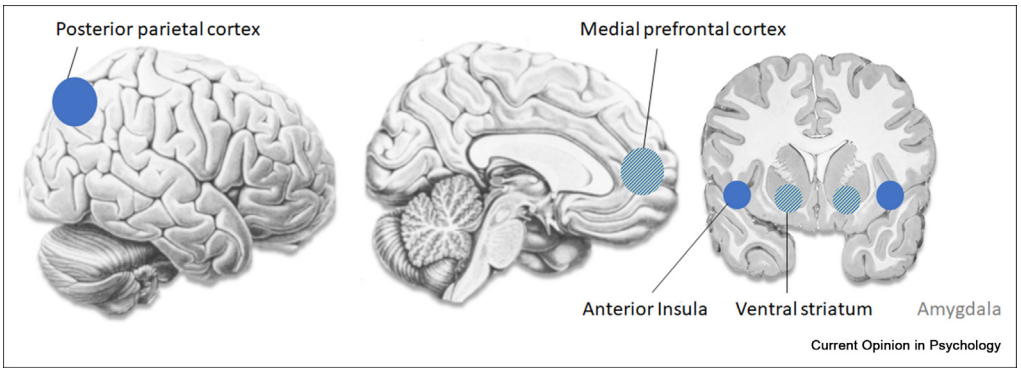
A different context is when adolescents are confronted with someone else's behavior. Recent research on *social influence* showed that when participants saw a previous participant select the risky option, their risk preference increased. A similar pattern, with risk preference decreasing, was observed for the condition in which participants saw a safe choice of a previous participant [31–36]. Some studies suggest that risk-promoting peers potentially have a larger influence [35], albeit less so in late adolescents [36]. Others state that safe-promoting peers weigh more heavily [33], and particularly in late adolescents [36]. Paradigm-specific differences may lead to some of these mixed findings. For instance, we may be more easily swayed by others if their risk preference is not too far away from our own risk preference. Clearly, the extent and conditions for "state" changes in risk preferences need to be further disentangled.

It has been suggested others influence our risk preference by adding to the subjective value of the presented options [33] and altering reward-related brain activation [27,37]. Alternatively, an interesting perspective is that adolescents may be more uncertain about their own preferences than adults, and hence depend more on what others do [38]. This resonates with studies showing that uncertainty about others' behavior increases rapidly in adolescence [39]. A longitudinal follow-up in this study [38], suggested that such a heightened uncertainty related to a more positive development of peer relations across adolescence. Taken together, these findings suggest adolescent's social susceptibility may be an opportunity for promoting positive behavior using peer influence and can be potentially adaptive in terms of strengthening friendships and relations [38,39]. These hypotheses will need to be addressed in future studies.

Risks in the adolescent brain

Developmental neuroimaging work has studied the functional neural correlates of rewards and risks, to gain a better understanding of the neural correlates underlying adolescents' risky decision-making (see Figure 1). Typically, these studies link an individual-difference measure, such as self-reports or indices of daily-life risk taking, to neural activation during a risky decision-making task. A large body of work shows that reward

Figure 1



Overview of brain regions related to risk processing (blue): Posterior parietal cortex, anterior insula, medial prefrontal cortex (MPFC), ventral striatum (VS), and amygdala (not shown in figure) have been related to risk processing. MPFC and VS additionally are related to reward processing (indicated with dashed colors).

anticipation and receipt increased neural activity in the ventral striatum and the medial prefrontal cortex (PFC), which are projection targets of midbrain dopamine neurons [40,41]. These findings raise the question of whether this same circuit might process risk preference [42].

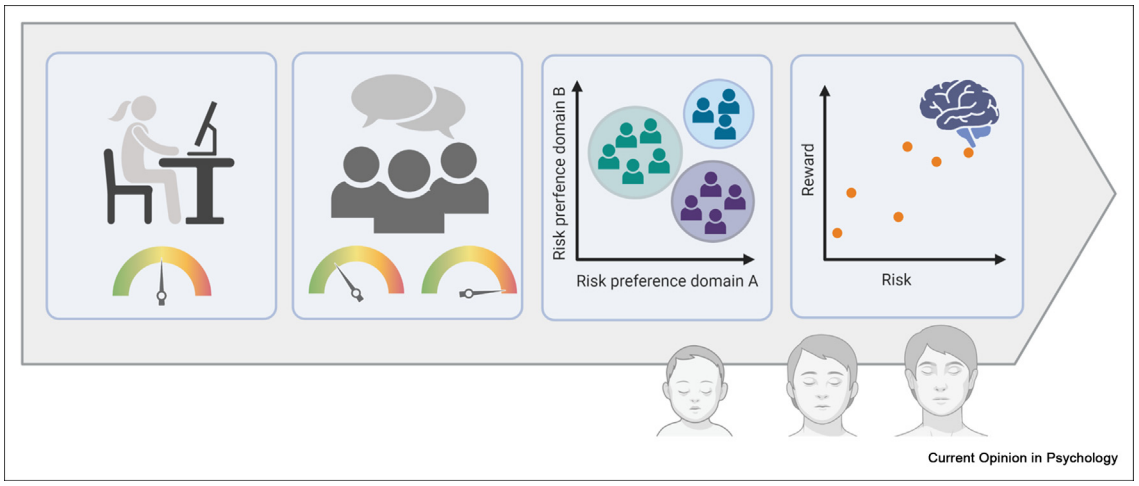
In adults, past functional neuroimaging studies have identified multiple brain regions associated with making decisions involving risk [43,44]: The (posterior) parietal cortex is thought to code probability [45] and its gray matter density has been related to individual differences in risk preference [46,47]. The ventral striatum is thought to reflect the potential of rewards for a giving option and may promote an approach-tendency towards risk. The (ventral) medial PFC integrates the (subjective) magnitude and probability of rewards for a risky option and controls the tendency to avoid or approach risks. For instance, functional connectivity of ventral medial PFC and action-related brain regions has shown to be higher in individuals with higher risk preferences [48]. Finally, activity in the amygdala and anterior insula would reflect the degree of risk and may promote risk-avoidance [43,45,49]. A recent meta-analysis supports these findings and highlights the insula as a crucial component of risk anticipation and processing, involved in coding known and unknown risks [44].

This key role of the insula is also confirmed in developmental studies of risk processing [50–52]. A study tracking parametric changes in risk in a risky-choice paradigm showed that adolescents versus children and adults exhibited heightened anterior insular risk activity to options of greater risk [53]. A larger developmental study (N = 256) confirmed that anterior insula activation scaled with parametric changes in risk [54]. Thus, risk-related brain regions typically found in adult studies, play a key role in developmental populations as well. Several recent studies showed that risk-related insula activation interacts with PFC regions and shuns adolescents from health-risk behaviors [55–57]. These findings indicate that risk engages brain regions that arewell-connected to brain regions associated with reward processing and valuation.

Opportunities for an individual difference perspective in adolescent risk processing

Several recent perspectives call for the need to characterizing individual differences in neurobiological development and cognition [58]. Particularly, the mixed findings of age-related changes in adolescent risk preferences may indicate these preferences differ profoundly between individuals [58,59]. One way to further understand developmental and individual differences in risk preferences is to use a model-based approach that formalizes the decision process. Where utility-based models present an integrated framework of value-based decision making, one of the few models disentangling the influence of risk and returns on risky decision-making is a risk-return framework. Risk-return models describe risky decision-making as a function of three variables: (1) the perceived return of available choice options (i.e., subjective expected value), (2) the perceived riskiness of those options (i.e., subjective outcome variability), and (3) the decision maker's attitude toward perceived risk—that is, his or her willingness to trade perceived risk for possible return [8,60]. One interesting suggestion from this body of work is that differences in perceptions are more influential than individual's willingness to take risk [60–62]. For instance, research on the COVID-19 pandemic showed that adults' risk perception (i.e., how risks are perceived) and risk preference (how likely one is to take risks) correlate positively to mitigation behaviors

Figure 2



Conceptual overview of risk processing research across four levels of information, examined across development from childhood to adulthood. From left to right, panel 1: Both revealed (e.g., experimental tasks and computational modeling) and stated (e.g., self-reports) measurements indicate an individual's risk preference, ranging from risk aversion, to risk neutrality, to risk seeking. Panel 2: Social context impacts risk preferences. Peers can sway an individual's risk preference (via influence or monitoring) towards risk seeking or risk aversion. Panel 3: Latent clustering techniques can capture individual differences and illustrate how individuals' group together depending on their risk preferences in several domains. Panel 4: Neuroimaging research reveals underlying mechanisms of risk processing. Although risks and rewards coincide, they may be related to distinct neural mechanisms that only partly overlap and both influence choice behavior. These four levels of information can each be examined across different age groups or longitudinally, to inform changes in risky choice across development. Note that these four levels of information are in no way exhaustive, and may be combined. For example, preferences can be examined as a function of social context, clustering approaches may be applied to neuroimaging research, etc. Created with BioRender.com.

concerning social distancing and hygiene [63]. Risk perceptions were, however, correlated with a larger number of mitigation practices. Since risk perceptions may also be more malleable than risk preferences, they are potentially an interesting target for adolescent policy and behavioral interventions.

An exciting approach to understand and quantify individual differences in risky decision-making is by examining heterogeneity within groups. Latent clustering approaches aim to find clusters of individuals that are described on the basis of a risk profile, i.e. a type of persons with a similar configuration of (multidimensional) risk preferences. A large-scale population study (N = 3123) used such a multidimensional cluster approach on self-reported risk data [64]. Findings showed four risk profiles that accounted for two thirds of participant (i.e., the "cautious," the "recreational adventurers," the "financial gamblers," and the "daredevils"). These approaches were shown to be associated with socio-demographic indicators, including age and gender. These clustering techniques have the potential to be extended to neuroimaging data (e.g. the studies by Becht et al., van Duijvenvoorde et al. [65,66] and a developmental longitudinal (i.e., latent change) perspective [67]. Ultimately, such analysis technics may foster greater specificity for certain groups of adolescents regarding behavioral interventions.

Conclusion

Although reward-sensitivity is integral to adolescent risky decision-making, we argue that a focus on risk broadens the perspective on adolescent behavior (see Figure 2). Here, we discuss recent findings on the measurement of risk preferences, the (social) context-specific influences on adolescents' risk preferences, and the associated brain regions involved in risk processing. A promising avenue that emerges from the work in this review is the potential to engage the social sensitivity of adolescents to steer decision-making, and the potential to embed models that target individual differences in multidimensional risk profiles. These renewed directions suggest that a perspective on risk sensitivity, in addition to adolescent reward-sensitivity, provide key insights to leverage undesirable levels of risk taking in young people and improve adolescents' health and wellbeing.

Author contributions

ACKvD: conceptualization, visualization, writing – original draft, writing – review & editing; JvH, NB: conceptualization, visualization, writing – review & editing.

Conflict of interest statement

Nothing declared.

Data availability

No data was used for the research described in the article.

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References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest

1. * Duell N, Steinberg L, Icenogle G, Chein J, Chaudhary N, Di Giunta L, Dodge KA, Fanti KA, Lansford JE, Oburu P, Pastorelli C, Skinner AT, Sorbring E, Tapanya S, Uribe Tirado LM, Alampay LP, Al-Hassan SM, Takash HMS, Bacchini D, Chang L: **Age patterns in risk taking across the world**. *J Youth Adolesc* 2018, **47**:1052–1072, https://doi.org/10.1007/s10964-017-0752-y.
This exceptional paper takes a multidimensional approach to study risk taking across various ages, cultures and areas of the world, finding largely overlapping results across the globe.

2. Braams BR, van Duijvenvoorde ACK, Peper JS, Crone EA: **Longitudinal changes in adolescent risk-taking: a comprehensive study of neural responses to rewards, pubertal development, and risk-taking behavior**. *J Neurosci* 2015, **35**: 7226–7238, https://doi.org/10.1523/JNEUROSCI.4764-14.2015.

3. Harden KP, Tucker-Drob EM: **Individual differences in the development of sensation seeking and impulsivity during adolescence: further evidence for a dual systems model**. *Dev Psychol* 2011, **47**:739–746, https://doi.org/10.1037/a0023279.

4. Schreuders E, Braams BR, Blankenstein NE, Peper JS, Güroğlu B, Crone EA: **Contributions of reward sensitivity to ventral striatum activity across adolescence and early adulthood**. *Child Dev* 2018, **89**:797–810, https://doi.org/10.1111/cdev.13056.

5. Silverman MH, Jedd K, Luciana M: **Neural networks involved in adolescent reward processing: an activation likelihood estimation meta-analysis of functional neuroimaging studies**. *Neuroimage* 2015, **122**:427–439, https://doi.org/10.1016/j.neuroimage.2015.07.083.

6. Crone EA, van Duijvenvoorde ACK: **Multiple pathways of risk taking in adolescence**. *Dev Rev* 2021, **62**, 100996, https://doi.org/10.1016/j.dr.2021.100996.

7. Telzer EH, Jorgensen NA, Prinstein MJ, Lindquist KA: **Neurobiological sensitivity to social rewards and punishments moderates link between peer norms and adolescent risk taking**. *Child Dev* 2021, **92**:731–745, https://doi.org/10.1111/cdev.13466.

8. *Who takes risks when and why?: Determinants of risk taking - bernd figner*. Elke U. Weber; 2011. https://journals.sagepub.com/doi/10.1177/0963721411415790.

9. Hertwig R, Erev I: **The description–experience gap in risky choice**. *Trends Cognit Sci* 2009, **13**:517–523, https://doi.org/10.1016/j.tics.2009.09.004.

10. Castillo M, Jordan JL, Petrie R: **Children's rationality, risk attitudes and field behavior**. *Eur Econ Rev* 2018, **102**:62–81, https://doi.org/10.1016/j.euroecorev.2017.12.002.

11. Caspi A, Houts RM, Belsky DW, Harrington H, Hogan S, Ramrakha S, Poulton R, Moffitt TE: **Childhood forecasting of a small segment of the population with large economic burden**. *Nat Human Behav* 2016, **1**:5, https://doi.org/10.1038/s41562-016-0005.

12. Dohmen T, Falk A, Huffman D, Sunde U, Schupp J, Wagner GG: **Individual risk attitudes: measurement, determinants, and behavioral consequences**. *J Eur Econ Assoc* 2011, **9**:522–550, https://doi.org/10.1111/j.1542-4774.2011.01015.x.

13. Moffitt TE, Arseneault L, Belsky D, Dickson N, Hancox RJ, Harrington H, Houts R, Poulton R, Roberts BW, Ross S, Sears MR, Thomson WM, Caspi A: **A gradient of childhood self-control predicts health, wealth, and public safety**. *Proc Natl Acad Sci USA* 2011, **108**:2693–2698, https://doi.org/10.1073/pnas.1010076108.

14. ** Frey R, Pedroni A, Mata R, Rieskamp J, Hertwig R: **Risk preference shares the psychometric structure of major psychological traits**. *Sci Adv* 2017, **3**, e1701381, https://doi.org/10.1126/sciadv.1701381.
This influential paper examined the general and domain-specific structure of risk preference using latent modeling by using an impressively large sample (N = 1507) with 39 different risk measures.

15. Blankenstein N, . van Hoorn J, Dekkers T, Popma A, Jansen B, Weber EU, Pollak Y, Figner B, Crone E, Huizenga HM, van Duijvenvoorde ACK: *Risk taking, perceived risks, and perceived benefits across adolescence: a domain-specific risk-return approach*. PsyArXiv; 2021, https://doi.org/10.31234/osf.io/wv26z.

16. Josef AK, Richter D, Samanez-Larkin GR, Wagner GG, Hertwig R, Mata R: **Stability and change in risk-taking propensity across the adult life span**. *J Pers Soc Psychol* 2016, **111**:430–450, https://doi.org/10.1037/pspp0000090.

17. Mata R, Josef AK, Hertwig R: **Propensity for risk taking across the life span and around the globe**. *Psychol Sci* 2016, **27**: 231–243, https://doi.org/10.1177/0956797615617811.

18. Defoe IN, Dubas JS, Figner B, van Aken MAG: **A meta-analysis on age differences in risky decision making: adolescents versus children and adults**. *Psychol Bull* 2015, **141**:48–84, https://doi.org/10.1037/a0038088.

19. Andreoni J, Di Girolamo A, List J, Mackevicius C, Samek A: **Risk preferences of children and adolescents in relation to gender, cognitive skills, soft skills, and executive functions**. *J Econ Behav Organ* 2020, **179**:729, https://doi.org/10.1016/j.jebo.2019.05.002. 472.

20. Crone EA, Dahl RE: **Understanding adolescence as a period of social–affective engagement and goal flexibility**. *Nat Rev Neurosci* 2012, **13**:636–650, https://doi.org/10.1038/nrn3313.

21. Blakemore S-J, Mills KL: **Is adolescence a sensitive period for sociocultural processing?** *Annu Rev Psychol* 2014, **65**: 187–207, https://doi.org/10.1146/annurev-psych-010213-115202.

22. Güroğlu B: **The power of friendship: the developmental significance of friendships from a neuroscience perspective**. *Child Dev. Perspect.* 2022, **16**:110–117, https://doi.org/10.1111/cdep.12450.

23. Tomova L, Andrews JL, Blakemore S-J: **The importance of belonging and the avoidance of social risk taking in adolescence**. *Dev Rev* 2021, **61**, 100981, https://doi.org/10.1016/j.dr.2021.100981.

24. * Somerville LH, Haddara N, Sasse SF, Skwara AC, Moran JM, Figner B: **Dissecting "peer presence" and "decisions" to deepen understanding of peer influence on adolescent risky choice**. *Child Dev* 2019, **90**:2086–2103, https://doi.org/10.1111/cdev.13081.
This elegant experimental study uses an ecologically valid paradigm and computational modelling to disentangle the impact of peer presence and peer decisions on adolescents' risky choice behavior.

25. Tymula A, Wang X: **Increased risk-taking, not loss tolerance, drives adolescents' propensity to choose risky prospects more often under peer observation**. *J Econ Behav Organ* 2021, **188**:439–457, https://doi.org/10.1016/j.jebo.2021.05.030.

26. Smith AR, Chein J, Steinberg L: **Peers increase adolescent risk taking even when the probabilities of negative outcomes are known**. *Dev Psychol* 2014, **50**:1564–1568, https://doi.org/10.1037/a0035696.

27. Chein J, Albert D, O'Brien L, Uckert K, Steinberg L: **Peers increase adolescent risk taking by enhancing activity in the**

brain's reward circuitry. *Dev Sci* 2011, **14**, https://doi.org/10.1111/j.1467-7687.2010.01035.x. F1–F10.

28. Tymula A: **An experimental study of adolescent behavior under peer observation: adolescents are more impatient and inconsistent, not more risk-taking, when observed by peers**. *J Econ Behav Organ* 2019, **166**:735–750, https://doi.org/10.1016/j.jebo.2019.08.014.

29. Tymula A, Whitehair J: **Young adults gamble less when observed by peers**. *J Econ Psychol* 2018, **68**:1–15, https://doi.org/10.1016/j.joep.2018.07.005.

30. Lorenz C, Kray J: **Explore with me: peer observation decreases risk-taking but increases exploration tendencies across adolescence**. *J Youth Adolesc* 2022, https://doi.org/10.1007/s10964-022-01608-2.

31. Blankenstein NE, Crone EA, van den Bos W, van Duijvenvoorde ACK: **Dealing with uncertainty: testing risk- and ambiguity-attitude across adolescence**. *Dev Neuropsychol* 2016, **41**:77–92, https://doi.org/10.1080/87565641.2016.1158265.

32. Braams BR, Davidow JY, Somerville LH: **Information about others' choices selectively alters risk tolerance and medial prefrontal cortex activation across adolescence and young adulthood**. *Dev. Cogn. Neurosci.* 2021, **52**, 101039, https://doi.org/10.1016/j.dcn.2021.101039.

33. Ciranka S, van den Bos W: **Social influence in adolescent decision-making: a formal framework**. *Front Psychol* 2019, **10**. https://www.frontiersin.org/article/10.3389/fpsyg.2019.01915.

34. Ciranka S, van den Bos W: **Social norms in adolescent risk engagement and recommendation**. *Br J Dev Psychol* 2021, **39**:481–498, https://doi.org/10.1111/bjdp.12369.

35. Reiter AMF, Suzuki S, O'Doherty JP, Li S-C, Eppinger B: **Risk contagion by peers affects learning and decision-making in adolescents**. *J Exp Psychol Gen* 2019, **148**:1494–1504, https://doi.org/10.1037/xge0000512.

36. Braams BR, Davidow JY, Somerville LH: **Developmental patterns of change in the influence of safe and risky peer choices on risky decision-making**. *Dev Sci* 2019, **22**, https://doi.org/10.1111/desc.12717.

37. . van Hoorn J, Shablack H, Lindquist KA, Telzer EH: **Incorporating the social context into neurocognitive models of adolescent decision-making: a neuroimaging meta-analysis**. *Neurosci Biobehav Rev* 2019, **101**:129–142, https://doi.org/10.1016/j.neubiorev.2018.12.024.

38. Reiter AMF, Moutoussis M, Vanes L, Kievit R, Bullmore ET, Goodyer IM, Fonagy P, Jones PB, Dolan RJ: **Preference uncertainty accounts for developmental effects on susceptibility to peer influence in adolescence**. *Nat Commun* 2021, **12**:3823, https://doi.org/10.1038/s41467-021-23671-2.

39. Ma I, Westhoff B, van Duijvenvoorde ACK: **Uncertainty about others' trustworthiness increases during adolescence and guides social information sampling**. *Sci Rep* 2022, **12**:7634, https://doi.org/10.1038/s41598-022-09477-2.

40. Haber SN, Knutson B: **The reward circuit: linking primate anatomy and human imaging**. *Neuropsychopharmacol. Off. Publ. Am. Coll. Neuropsychopharmacol.* 2010, **35**:4–26, https://doi.org/10.1038/npp.2009.129.

41. van Duijvenvoorde ACK, Peters S, Braams BR, Crone EA: **What motivates adolescents? Neural responses to rewards and their influence on adolescents' risk taking, learning, and cognitive control**. *Neurosci Biobehav Rev* 2016, **70**:135–147, https://doi.org/10.1016/j.neubiorev.2016.06.037.

42. Knutson B, Huettel SA: **The risk matrix**. *Curr. Opin. Behav. Sci.* 2015, **5**:141–146, https://doi.org/10.1016/j.cobeha.2015.10.012.

43. Mohr PNC, Biele G, Heekeren HR: **Neural processing of risk**. *J Neurosci* 2010, **30**:6613–6619, https://doi.org/10.1523/JNEUROSCI.0003-10.2010.

44. Wu S, Sun S, Camilleri JA, Eickhoff SB, Yu R: **Better the devil you know than the devil you don't: neural processing of risk and ambiguity**. *Neuroimage* 2021, **236**, 118109, https://doi.org/10.1016/j.neuroimage.2021.118109.

45. Preuschoff K, Bossaerts P: **Adding prediction risk to the theory of reward learning**. In *Reward decis. Mak. Corticobasal ganglia netw.* Malden: Blackwell Publishing; 2007:135–146.

46. Gilaie-Dotan S, Tymula A, Cooper N, Kable JW, Glimcher PW, Levy I: **Neuroanatomy predicts individual risk attitudes**. *J Neurosci* 2014, **34**:12394–12401, https://doi.org/10.1523/JNEUROSCI.1600-14.2014.

47. Grubb MA, Tymula A, Gilaie-Dotan S, Glimcher PW, Levy I: **Neuroanatomy accounts for age-related changes in risk preferences**. *Nat Commun* 2016, **7**, 13822, https://doi.org/10.1038/ncomms13822.

48. Rolls ET, Wan Z, Cheng W, Feng J: **Risk-taking in humans and the medial orbitofrontal cortex reward system**. *Neuroimage* 2022, **249**, 118893, https://doi.org/10.1016/j.neuroimage.2022.118893.

49. Kuhnen CM, Knutson B: **The neural basis of financial risk taking**. *Neuron* 2005, **47**:763–770, https://doi.org/10.1016/j.neuron.2005.08.008.

50. Barkley-Levenson EE, Van Leijenhorst L, Galván A: **Behavioral and neural correlates of loss aversion and risk avoidance in adolescents and adults**. *Dev. Cogn. Neurosci.* 2012, **3**:72–83, https://doi.org/10.1016/j.dcn.2012.09.007.

51. * Blankenstein NE, Schreuders E, Peper JS, Crone EA, van Duijvenvoorde ACK: **Individual differences in risk-taking tendencies modulate the neural processing of risky and ambiguous decision-making in adolescence**. *Neuroimage* 2018, **172**:663–673, https://doi.org/10.1016/j.neuroimage.2018.01.085.
This paper included a broad adolescent age range (8–27) and takes an individual-difference approach to examine how risk-sensitive brain regions scale with individual differences in risk sensitivity.

52. Smith AR, Steinberg L, Chein J: **The role of the anterior insula in adolescent decision making**. *Dev Neurosci* 2014, **36**:196–209, https://doi.org/10.1159/000358918.

53. * van Duijvenvoorde ACK, Huizenga HM, Somerville LH, Delgado MR, Powers A, Weeda WD, Casey BJ, Weber EU, Figner B: **Neural correlates of expected risks and returns in risky choice across development**. *J Neurosci* 2015, **35**:1549–1560, https://doi.org/10.1523/JNEUROSCI.1924-14.2015.
This paper combines computational modelling with fMRI to examine which brain regions scale parametrically with risk and return sensitivity, and how these patterns vary with age.

54. Korucuoglu O, Harms MP, Kennedy JT, Golosheykin S, Astafiev SV, Barch DM, Anokhin AP: **Adolescent decision-making under risk: neural correlates and sex differences**. *Cereb. Cortex N. Y. NY* 2020, **30**:2691–2707, https://doi.org/10.1093/cercor/bhz269.

55. Kim-Spoon J, Deater-Deckard K, Lauharatanahirun N, Farley J, Chiu PH, Bickel WK, King-Casas B: **Neural interaction between risk sensitivity and cognitive control predicting health risk behaviors among late adolescents**. *J. Res. Adolesc. Off. J. Soc. Res. Adolesc.* 2017, **27**:674–682, https://doi.org/10.1111/jora.12295.

56. Kim-Spoon J, Deater-Deckard K, Brieant A, Lauharatanahirun N, Lee J, King-Casas B: **Brains of a feather flocking together? Peer and individual neurobehavioral risks for substance use across adolescence**. *Dev Psychopathol* 2019, **31**:1661–1674, https://doi.org/10.1017/S0954579419001056.

57. Maciejewski D, Lauharatanahirun N, Herd T, Lee J, Deater-Deckard K, King-Casas B, Kim-Spoon J: **Neural cognitive control moderates the association between insular risk processing and risk-taking behaviors via perceived stress in adolescents**. *Dev. Cogn. Neurosci.* 2018, **30**:150–158, https://doi.org/10.1016/j.dcn.2018.02.005.

58. Foulkes L, Blakemore S-J: **Studying individual differences in human adolescent brain development**. *Nat Neurosci* 2018, **21**:315–323, https://doi.org/10.1038/s41593-018-0078-4.

59. Bjork JM, Pardini DA: **Who are those "risk-taking adolescents"? Individual differences in developmental neuroimaging research**. *Dev. Cogn. Neurosci.* 2015, **11**:56–64, https://doi.org/10.1016/j.dcn.2014.07.008.

60. Weber EU: **Risk attitude and preference**. *WIREs Cogn. Sci.* 2010, **1**:79–88, https://doi.org/10.1002/wcs.5.

61. Weber EU, Milliman RA: **Perceived risk attitudes: relating risk perception to risky choice**. *Manag Sci* 1997, **43**:123–144, https://doi.org/10.1287/mnsc.43.2.123.

62. Weber EU, Hsee C: **Cross-cultural differences in risk perception, but cross-cultural similarities in attitudes towards perceived risk**. *Manag Sci* 1998, **44**:1205–1217, https://doi.org/10.1287/mnsc.44.9.1205.

63. Kassas B, Morgan SN, Lai JH, Kropp JD, Gao Z: **Perception versus preference: the role of self-assessed risk measures on individual mitigation behaviors during the COVID-19 pandemic**. *PLoS One* 2021, **16**, e0254756, https://doi.org/10.1371/journal.pone.0254756.

64. Frey R, Duncan S, Weber EU: *Towards a typology of risk preference: four risk profiles describe two thirds of individuals in a large sample of the U.S. population*. PsyArXiv; 2020, https://doi.org/10.31234/osf.io/yjwr9.

65. Becht AI, Mills KL: **Modeling individual differences in brain development**. *Biol Psychiatr* 2020, **88**:63–69, https://doi.org/10.1016/j.biopsych.2020.01.027.

66. van Duijvenvoorde ACK, Whitmore LB, Westhoff B, Mills KL: **A methodological perspective on learning in the developing brain**. *Npj Sci. Learn.* 2022, **7**:12, https://doi.org/10.1038/s41539-022-00127-w.

67. Kievit RA, Brandmaier AM, Ziegler G, van Harmelen A-L, de Mooij SMM, Moutoussis M, Goodyer IM, Bullmore E, Jones PB, Fonagy P, Consortium NSPN, Lindenberger U, Dolan RJ: **Developmental cognitive neuroscience using latent change score models: a tutorial and applications**. *Dev. Cogn. Neurosci.* 2018, **33**:99–117, https://doi.org/10.1016/j.dcn.2017.11.007.