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Resolving ambiguity: Broadening the consideration of risky decision making over adolescent development

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ABSTRACT

Popular culture often portrays adolescence as a period of peak risk-taking, but that developmental trend is not consistently found across laboratory studies. Instead, *meta*-analytic evidence shows that while adolescents take more risks compared to adults, children and adolescents actually take similar levels of risk. Furthermore, developmental trajectories vary across different measures of laboratory decision making and everyday risky behavior. Indeed, the psychological concept of "risk" is multifactorial, such that its different factors exhibit different developmental trajectories. Here, we examine how economic risk preference, or the propensity to gamble on uncertain outcomes with known probabilities, is distinct from economic ambiguity preference, or the propensity to gamble on uncertain outcomes with *unknown* probabilities – and how economic risk and ambiguity may differentially influence adolescent decision making. Economic ambiguity engages distinct neural mechanisms from economic risk – both in adults and adolescents – and differentially relates to everyday risk-taking. However, to date, it remains elusive how economic ambiguity aversion develops across adolescence, as the relative paucity of such work limits the conclusions that can be drawn. We propose that developmental research into adolescent decision making should consider economic ambiguity as a distinct component within the multifactorial construct of adolescent risk-taking. This will set the stage for future work on economic ambiguity preferences as an explanatory mechanism for behaviors beyond risk taking, such as learning and prosocial behavior.

Introduction

Risky behaviors are commonly thought to be endemic to adolescence, as seen in media portrayals of teenagers experimenting with alcohol and drugs, engaging in unprotected sex, and committing acts of vandalism. Many everyday reckless behaviors – such as binge drinking, drug use, and criminal activity – peak in late adolescence or early adulthood (Duell et al., 2018; Willoughby, Good, Adachi, Hamza, & Tavernier, 2013). Yet, laboratory studies of risky decision making indicate a different trajectory: as shown by a series of *meta*-analyses by Defoe et al. (2015), adolescents do take more risks compared to adults, but adolescents and children take equal levels

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of risk. The *meta*-analyses also found that risk-taking in early adolescents (11–13 year-olds) is comparable to that of children but greater than that of late adolescents (14–19 year-olds). Thus, the overall trajectory of risk-taking across development, at least as measured by experimental laboratory paradigms, suggests similarly high levels of risk-taking in childhood and early adolescence, followed by a decrease in mid-late adolescence through adulthood (Defoe, Dubas, Figner, & van Aken, 2015).

This discrepancy between everyday and laboratory measures of risky decision making may be due to contextual differences: the aspects of risk taking assessed in some laboratory tasks may differ from those encountered in everyday risk-taking situations, such that risk tolerance waxes or wanes depending on decision context (Chein, Albert, O'Brien, Uckert, & Steinberg, 2011; Defoe, Semon Dubas, & Romer, 2019; Li, 2017; Fairley, Parelman, Jones, & Carter, 2019; Pedroni et al., 2017). For instance, risk preferences that adolescents exhibit under the low social context and low arousal conditions found in some laboratory tasks might change under conditions of a social context (Chein et al., 2011; Gardner & Steinberg, 2005; Smith, Chein, & Steinberg, 2014) and/or increasing arousal (Albert & Steinberg, 2011; Figner, Mackinlay, Wilkening, & Weber, 2009; Somerville et al., 2019). Another, non-exclusive explanation is that laboratory tasks and everyday behaviors follow different developmental trajectories because they are not driven by the same underlying, unitary construct of risk preference (Frey, Pedroni, Mata, Rieskamp, & Hertwig, 2017). Through this lens, past developmental studies of "risk-taking" have yielded mixed findings because different studies with different paradigms measured fundamentally different types of risk preferences, which can take different developmental trajectories.

We adopt the latter perspective for this review, that risk-taking is not unitary but instead represents a multifactorial construct whose elements can be elicited separably in different contexts and different laboratory tasks. We will illustrate this view of risk-taking by specifically comparing decisions made under "risk", those with uncertain outcomes that have known probabilities, and decisions made under "ambiguity", those with uncertain outcomes that have unknown probabilities (Wakker, 2010). For clarity, we will hereafter refer to the former as "economic risk" and the latter as "economic ambiguity" to distinguish these formal definitions from the more colloquial application of "risk" to any form of decision making under uncertainty.[1]

Though there is a relative paucity of developmental studies of economic ambiguity, compared to developmental studies of economic risk, we will review the few available studies, which collectively suggest that economic risk and ambiguity are separable aspects of decision making with distinct developmental trajectories. Next, we will discuss the human functional magnetic resonance imaging (fMRI) studies in both developmental and adult samples, which suggest that assessments of economic risk and economic ambiguity rely on distinct neural mechanisms. Finally, we will offer some future directions for how a multifactorial view of risk-taking that considers economic risk and economic ambiguity as separate factors can better inform our understanding of how decision-making processes develop across different contexts and populations.

Disentangling economic risk and economic ambiguity

As noted by Defoe et al. (2015), our understanding of the development of risk-taking has been hampered by a lack of consensus as what "risk" entails. Different laboratory task paradigms represent risk in different ways, from probabilistic wheels of fortune (e.g., Burnett, Bault, Coricelli, & Blakemore, 2010; Ernst et al., 2004; Eshel, Nelson, Blair, Pine, & Ernst, 2007) to deciding whether to stop at or drive through a yellow light (e.g., Chein et al., 2011; Gardner & Steinberg, 2005). In their *meta*-analyses, Defoe et al. (2015) defined risk as uncertainty with outcome variability and operationalized greater risk as the choice featuring greater outcome variability – consistent with prior work showing that standardized measures of variation provide good accounts of risk sensitivity in humans and other animals (Weber, Shafir, & Blais, 2004). This allowed them to compare age differences in risk-taking across multiple tasks that varied in their format and reward structure.

In this review, we argue that even greater precision in our definition of risk – whether it involves known versus unknown outcomes and probabilities - could yield further insight into risk-taking across development. Economic risk specifically refers to decisions in which the exact outcome is uncertain, but the magnitude, valence, and probabilities of possible outcomes are known (Wakker, 2010). Outside of atypical contexts like gambling, everyday decisions rarely feature probabilities that are explicitly and precisely known by decision makers. Consider the example of an adolescent who is driving to a party and approaching an intersection just as the light turns red. The adolescent can either make a safe choice (waiting on the red light) or take a gamble (running the red light). Even if that decision were simplified to a small set of possible outcomes (e.g., arriving to the party late or on time; causing a traffic accident or not), the probabilities of these outcomes would be (largely) unknown (e.g., the chance of being on time if waiting or getting in a traffic accident if running the light). Thus, this example (like almost any everyday decision) should not be classified as involving economic risk and should instead be considered as involving economic ambiguity (Romer & Khurana, 2020).

Under this more precise delineation between economic risk and ambiguity, many laboratory paradigms that have been considered measures of risky decision making across development actually do not measure economic risk preferences. Outcome probabilities are not explicitly known in the Iowa Gambling Task (IGT) and its developmental variations, in which participants draw from decks of cards whose distributions of potential payoffs must be learned over time (Carlson, Zayas, & Guthormsen, 2009; Crone, Bunge, Latenstein, & van der Molen, 2005; Crone & van der Molen, 2007; Huizenga, Crone, & Jansen, 2007; Kerr & Zelazo, 2004; Prencipe et al., 2011; Smith, Xiao, & Bechara, 2012). In the Stoplight Task, participants must decide whether to drive through yellow light intersections with

[1] In keeping with its use in the developmental literature, we will continue to use the term "risk-taking" (without the "economic" modifier) throughout this review to refer to any form of decision making involving uncertainty, broadly construed.

an unknown probability of crashing (Chein et al., 2011; Gardner & Steinberg, 2005). And, in the Balloon Analog Risk Task (BART), participants inflate a balloon to earn points, with some unknown probability of the balloon popping and forgoing its earned points (Braams, van Duijvenvoorde, Peper, & Crone, 2015; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; MacPherson, Magidson, Reynolds, Kahler, & Lejuez, 2010). All of these tasks could be more accurately categorized as measuring preferences towards economic ambiguity, in which outcome probabilities and sometimes the potential outcomes themselves are unknown to the decision-maker. However, they also involve some aspect of learning about the underlying task dynamics through experience and thus cannot be considered measures of just economic ambiguity preference.

It is important to differentiate between measures of economic risk and ambiguity, as they represent separate factors that contribute to everyday risk-taking behavior. Economic risk and ambiguity share surface-level traits. They both represent decision preferences under uncertainty regarding what outcomes will be realized, and decision-makers often prefer a smaller but sure outcome to a probabilistic distribution of outcomes with a higher expected value (i.e. average outcome) – regardless of whether that distribution is known (risky) or unknown (ambiguous). Yet, research (largely featuring adult participants) has shown that economic risk and ambiguity are distinct constructs. For example, economic risk is typically preferred over economic ambiguity when expected value is held equal, a phenomenon called ambiguity aversion. In the classic Ellsberg paradox (Ellsberg, 1961), adult participants are asked about their willingness to bet money on drawing either a black or a red marble from one of two urns, each filled with both black and red marbles. One urn contains 50 black and 50 red marbles (economic risk), whereas the other urn contains 100 black and red marbles in an unknown ratio (economic ambiguity). As the average of all possible ratios for the economically ambiguous urn is 50:50, participants should be equally willing to bet on either urn if they consider economic risk and economic ambiguity similarly. Instead, regardless of which marble represents the winning color, most adults prefer to bet on the economically risky urn over the economically ambiguous one. This is considered a paradox because it means participants act as if the economically ambiguous urn simultaneously contains both fewer red *and* fewer black marbles than the economically risky urn – leading to a mathematical impossibility (Ellsberg, 1961; Tversky & Kahneman, 1992; von Gaudecker, van Soest, & WengstrÖm, 2011).

Ambiguity aversion has been replicated in adult populations (see Camerer & Weber, 1992; Trautmann & Van De Kuilen, 2015 for review) and even in monkeys (Hayden, Heilbronner, & Platt, 2010), although it varies across decision contexts and individuals, similarly to risk aversion (Kocher, Lahno, & Trautmann, 2018). Additional behavioral studies with adult participants support the idea that preferences for economic risk and ambiguity represent related but distinct decision-making factors. Some studies of adult decision making have found economic risk and ambiguity preferences to be correlated but non-identical (Abdellaoui, l'Haridon, & Paraschiv, 2011; Butler, Guiso, & Jappelli, 2014; Stanton et al., 2011; Dimmock et al., 2013; Dimmock et al., 2012). Other studies have found such correlations only under specific conditions: for losses but not gains (Lauriola & Levin, 2001), for gains but not losses (Chakravarty & Roy, 2009; Tymula, Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013), or only for those individuals with strong preferences for or against ambiguity (Lauriola, Levin, & Hart, 2007). Finally, several studies have reported no significant correlations between economic risk and ambiguity preferences (Blankenstein, Peper, Crone, & Van Duijvenvoorde, 2017; Cohen, Tallon, & Vergnaud, 2011; Curley, Yates, & Abrams, 1986; Di Mauro & Maffioletti, 2004; Hogarth & Einhorn, 1990; Huettel, Stowe, Gordon, Warner, & Platt, 2006; Levy, Snell, Nelson, Rustichini, & Glimcher, 2010). These results, while mixed, make clear that risk and ambiguity do not represent completely overlapping constructs (see Fig. 1).

For clarity in terminology, we note that the economically riskier choice can be defined as that with the greater outcome variability, and economic risk aversion is classified as choosing the less variable option (Defoe et al, 2015). Economic ambiguity aversion can be classified in a similar way (choosing the less variable option), along with consideration of how much probability information is available. As such, ambiguity aversion can be classified as follows: 1) In certain versus ambiguous gambles (Certain vs Ambiguous in Table 1), when the certain option is preferred over an ambiguous gamble, even when both have the same expected value or when the ambiguous gamble has a higher expected value. 2) In risky versus ambiguous gambles (Risky vs. Ambiguous in Table 1), when the risky gamble is preferred over an ambiguous gamble, even when both have the same expected value or when the ambiguous gamble has a higher expected value. And 3) In ambiguous versus ambiguous gambles (Ambiguous vs Ambiguous in Table 1), when the gamble that is less ambiguous (i.e. has less hidden probability and/or possible outcome information) is preferred over one than is more ambiguous, even when both have the same expected value or the more ambiguous gamble has the higher expected value. Furthermore, economic risk and ambiguity attitudes can be quantified in a few different ways. Some studies examine economic risk and ambiguity aversion as the proportion of choices for a less risky or ambiguous option, but such measures are difficult to compare across studies that offer participants different sets of choices to evaluate. Other studies apply a model-based approach in which the subjective utility of each choice option is modeled and individuals' economic risk and ambiguity attitudes are estimated. These attitudes reflect someone's general behavioral tendency to seek out, or shy away from, economic risk and ambiguity and can be compared across studies that use different choice sets (e.g., Gilboa & Schmeidler, 1989; Tymula et al., 2012).

In summary, economic risk and economic ambiguity are distinct forms of risk preference. However, despite the wealth of experimental research on the development of adolescent risky choice behavior (Defoe et al., 2015) and although the majority of adolescents' everyday risky decision making is characterized by economic ambiguity, relatively few studies have dissociated how behavior under economic risk and economic ambiguity changes throughout development.

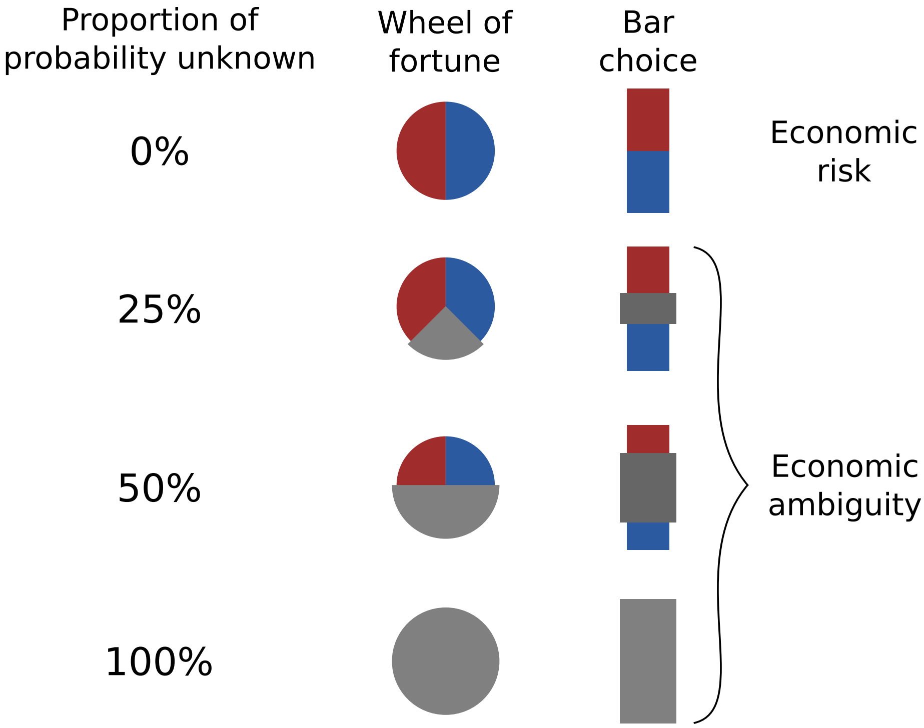

Fig. 1. Examples of commonly used stimuli to represent economic risk and varying levels of economic ambiguity. The red and blue sections represent probabilities of different outcomes, and the gray occluders represent probability information that is unknown to or hidden from participants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Economic risk and ambiguity preferences across development

In contrast to adult research, few studies have explicitly examined behavior under economic ambiguity in children and/or adolescents. While the *meta*-analyses on age differences in risky decision making by Defoe et al. (2015) included a comparison between description-based and experience-based tasks that was found to be statistically non-significant, few studies in those analyses explicitly included economic risk and ambiguity (except for Van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012 and Rakow and Rahim, 2010). Furthermore, such experience-based studies also engaged processes of learning, thus making it challenging to disentangle potential developmental changes in economic ambiguity preferences from changes in learning and memory abilities.

Hereafter, we review developmental studies that explicitly measured economic risk and ambiguity preferences independently of any opportunity to learn about the economically ambiguous gambles. Most such studies were published after 2015, and therefore not included in Defoe and colleagues' *meta*-analyses; the exception is Tymula et al. 2012, which was included as a measure of risky decision making per Defoe et al. 2015′s definition of risk as greater outcome variability. Table 1 provides details about the age range included, type of tasks and task characteristics, how risk and ambiguity preferences were assessed, and key results. In brief, this small body of research suggests that ambiguity aversion may be absent in childhood, and that children and adolescents may be more ambiguity-tolerant than adults. However, studies report different trajectories of age-related changes and distinct patterns associated with gains and losses. This lack of consensus makes it difficult to draw firm conclusions on the development of preferences under economic ambiguity. Still, the small number of published studies highlight the importance of considering economic ambiguity, in addition to economic risk, when assessing decision making across development.

Economic risk and ambiguity preferences in the gain domain

Developmental differences in ambiguity preferences were first reported by Tymula et al. (2012), who asked 33 adolescents (12–17 years) and 32 adults (30–50 years old) to make decisions between a sure gain and a uncertain lottery that was either economically risky (i.e., known probabilities) or economically ambiguous (i.e., hidden probabilities). They assessed risk and ambiguity aversion by creating models of subjective utility for both types of decisions, finding adolescents to be more risk-averse than adults (Tymula et al., 2012). However, the adolescents were less averse to ambiguity than adults – an intriguing finding potentially linked to drives for learning and exploration during this developmental phase (Tymula et al., 2012).

Subsequent work by Blankenstein and colleagues (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016) drew upon a continuous age range (10 to 25 years) and a larger sample (157 participants) to test linear and quadratic age-related changes in risk and ambiguity attitudes. Using a wheel-of-fortune task and subjective utility modeling to calculate preferences towards economic risk and

Table 1
Overview of developmental studies (in alphabetical order of the first author) examining the behavioral and neural representations of economic risk and economic ambiguity.

Study	N (f:m)	Age range (s)	Task(s)	Levels of ambiguity[1]	Choice presentation	Expected value differences	Gain / Loss	Calculation of risk and ambiguity preference	Developmental pattern	Relation with proxy of everyday risk-taking
Blankenstein et al. (2016).	157 (84:73)	10–25	WoF	25%, 50%, 75%, 100%	Certain vs. Ambiguous, Certain vs Risky	Gamble EV >, =, and < Certain EV	Gain	Subjective utility modelling of risk and ambiguity attitude	Risk attitudes were stable across age, ambiguity aversion increased with age	Ambiguity tolerance associated with more ARQ Reckless behavior
*Blankenstein, et al. (2018).	198 (94:104)	11–24	Simplified fMRI WoF	100%	Certain vs. Ambiguous, Certain vs Risky	Gamble EV > Certain EV	Gain	Proportion Risky and Ambiguous choices; Neural correlates of Risky vs Certain and Ambiguous vs Certain	Proportion Risky, but not Ambiguous, choices increased with age; Neural correlates of Risky and Ambiguous choices were stable across age.	ARQ Rebellious behavior associated with less DLPFC activation during reward processing following both risky and ambiguous gambling
*Blankenstein and van Duijvenvoorde (2019)	188 (100:88)	12–22	WoF, Simplified fMRI WoF	25%, 50%, 75%, 100% (behavioral task), 100% (fMRI task)	Certain vs. Ambiguous, Certain vs Risky	Behavioral: Gamble EV >, =, and < Certain EV fMRI:Gamble EV > Certain EV	Gain	Subjective utility modelling of risk and ambiguity attitude; Neural correlates of subjective value under risk and ambiguity	Risk seeking increased with age, ambiguity attitudes were stable across age. Neural correlates were independent of age.	NA
Braams, Davidow, and Somerville (2019)	99 (52:47)	12–22	Bar choice task	20%, 40%, 60%, 80%	Risky vs. Ambiguous, Risky vs Risky,	More variable EV >, =, < less variable EV (primarily >)	Gain	Choice of more variable gamble as a function of EV difference between gambles	Choosing the more variable gamble decreased with age, no clear changes in ambiguity preferences	NA
Braams, Davidow, and Somerville (2020) [preprint]	65 (32:33)	14–22	Bar choice fMRI task	20%, 40%, 60%, 80%	Certain vs. Ambiguous, Certain vs Risky	Gamble EV >, =, < Certain EV (mostly >)	Gain	Subjective utility modelling of risk and ambiguity attitude	Risk and ambiguity attitudes were stable across age. Neural correlates were stable across age.	NA
Fairley and Sanfey (2020)	172 (83:89)	12–17	Paper-and-pencil sequential Ellsberg paradigm	100%	Certain vs. Ambiguous, Certain vs Risky	Risky and Ambiguous EV > Certain EV	Gain	Switch point from choosing Risky/ Ambiguous gamble to choosing certain as certain gain incrementally increased	Risk and ambiguity aversion were stable across age in all participants. In boys only, risk aversion decreased with age and ambiguity aversion increased at trend level.	NA
Li, Brannon, and Huettel (2015)	74 (33:41)	8–9 and 19–27	Bar choice task, WTP	33%, 50%, 80%, 100%	Risky vs. Ambiguous, Ambiguous vs. Ambiguous,	Risky vs. Ambiguous: Risky EV >, =, and <	Gain	Proportion choices Risky vs. Ambiguous, proportion less	Children did not show ambiguity aversion while adults did	NA

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Table 1 (*continued*)

Study	N (f:m)	Age range (s)	Task(s)	Levels of ambiguity[1]	Choice presentation	Expected value differences	Gain / Loss	Calculation of risk and ambiguity preference	Developmental pattern	Relation with proxy of everyday risk-taking
					stated WTP for each Risky and Ambiguous gamble	Ambiguous EV; Ambiguous vs. Ambiguous: EV equal		Ambiguous vs. more Ambiguous, WTP for Risky vs. WTP for Ambiguous		
Li, Roberts, Huettel, and Brannon (2017)	62 (35:27)	5 and 18–31	Choice task with simple physical representations	100%	Risky vs. Ambiguous	Risky EV >, = , and < Ambiguous EV	Gain	Proportion choices Risky vs. Ambiguous	Children did not show ambiguity aversion while adults did	NA
Sutter, Kocher, Glätzle-Rützler, and Trautman (2013)	661 (358:303)	10–18	Sequential Ellsberg paradigm	100%	Certain vs. Ambiguous, Certain vs Risky	Risky and Ambiguous EV > Certain EV	Gain	Switch point from choosing Risky/ Ambiguous gamble to choosing certain as certain gain incrementally increased	Risk and ambiguity aversion were stable across age	Ambiguity tolerance associated with higher likelihood of smoking; Risk tolerance associated with higher BMI
**Tymula et al. (2012)	65 (34:31)	12–17 and 30–50	Bar choice task	24%,50%, 74%	Certain vs Ambiguous, Certain vs Risky	Gamble EV >, = , and < Certain EV	Gain	Subjective utility modelling of risk and ambiguity attitude	Adolescents were more ambiguity tolerant and less risk tolerant than adults	Ambiguity tolerance associated with more ARQ Reckless behavior
**Tymula et al. (2013)	135 (70:65)	12–17, 21–25, 30–50, 65–90	Bar choice task	24%,50%, 74%	Certain vs Ambiguous, Certain vs Risky	Gamble EV >, = , and < Certain EV	Gain and Loss[2]	Subjective utility modelling of risk and ambiguity attitude, separately for gains and losses	In losses, adolescents are similarly ambiguity tolerant as young and midlife adults, but less ambiguous averse than older adults	NA
Van den Bos and Hertwig (2017)	105 (53:52)	8–22	WoF	20%, 50%, 80%	Certain vs Ambiguous, Certain vs Risky	Assumed to vary	Gain and Loss[2]	Subjective utility modelling of risk and ambiguity attitude, separately for gains and losses	In gains, risk tolerance peaked in adolescence; ambiguity tolerance was stable. In losses, risk tolerance decreased with age and ambiguity tolerance peaked in adolescence	Ambiguity tolerance in losses associated with more ARQ Rebellious and Reckless behavior

Abbreviations: fMRI = functional magnetic resonance imaging; WoF = Wheel of Fortune; WTP = Willingness To Pay task; ARQ = Adolescent Risk Taking Questionnaire (Gullone, Moore, Moss, & Boyd, 2000); EV = Expected value; NA = Not Applicable.

* Participants in Blankenstein et al., 2019 (N = 188) are a subset of Blankenstein et al., 2018 (N = 198).

** Participants ages 12–17 and 30–50 in Tymula et al., 2012 were the same as those in Tymula et al., 2013.

1 Ambiguity levels indicate the proportion of probability information that was unknown to or hidden from the participant (see Fig. 1).

2 Gain and loss were studied separately, i.e., not mixed.

ambiguity, they found ambiguity aversion to show a moderate linear increase with age, supporting the categorical findings of Tymula et al. (2012). Blankenstein et al. (2016) also found that economic risk preferences were stable across age, which partially supports the *meta*-analytic finding that children and adolescents take equal levels of risk, but contrasts with the finding that children and adolescents take more risks compared to adults (Defoe et al., 2015). Taken together, these studies suggest that economic risk and ambiguity preferences exhibit different developmental trajectories – and that subjective utility modeling of economic risk preferences in monetary gambling tasks may reveal different developmental trends than other studies of risk-taking, broadly construed.

Additional work investigating ambiguity preferences in even younger children found that they, too, exhibited less ambiguity aversion compared to adults. In a child-friendly experiment that mimicked the procedures of Ellsberg (1961), Li and colleagues (Li, Roberts, Huettel, & Brannon, 2017) presented five-year-old children and young adults (18–31 years) with binary choices between economic risky and ambiguous stimuli. While adults were primarily ambiguity averse, children did not exhibit ambiguity aversion - a finding the authors also observed in older, 8-to-9-year old children (Li, Brannon, & Huettel, 2015). This work suggests that ambiguity aversion is not yet present in childhood, but the scarcity of data in very young children warrants further studying in this population. Measuring economic ambiguity preferences in young children is a challenging endeavor, as experimental tasks representing economic risk and ambiguity need to be comprehensible for this age group while still accurately measuring the construct of interest (e.g., using simple physical representations of economic risk and ambiguity; Li, Roberts, Huettel, and Brannon (2017). Furthermore, while older populations can self-report attitudes towards and propensity for engaging in everyday risky behaviors, such measures are not well-suited for young children, which impedes a translation from how laboratory choice maps onto everyday risk-taking behavior. Nonetheless, these findings offer a first glance into the early development of ambiguity aversion, suggesting that it is absent in childhood but present in adulthood.

Other studies, however, have not reported increases in ambiguity aversion from late childhood through adolescence, at least when considering decisions concerning potential gains. For instance, work by Blankenstein and van Duijvenvoorde (2019) in a different cross-sectional sample than Blankenstein et al. (2016) and over a more narrow age range (12–22, $n = 188$) found that economic ambiguity attitudes remained stable from 12 to 22 years, while economic risk-seeking increased linearly over that age range. These findings largely echo those of Van den Bos and Hertwig (2017), who found stable economic ambiguity preferences across ages 8 to 22 years in a cross-sectional sample of 105 participants, but an economic risk-tolerance peak between 12 and 14 years (van den Bos & Hertwig, 2017). Later work by Braams et al. (2019) measured the proportion of choices for more variable gambles as a function of expected value differences and economic ambiguity levels in 99 participants between 12 and 23 years. They found that choosing the more variable option decreased with age, except when ambiguity was low and the more variable gamble had a higher expected value, in which case no age differences were observed. Thus, although this study found overall decreases in choosing the more variable gamble across age, no pronounced age-related differences in preferences for economic ambiguity were observed (Braams et al., 2019). Furthermore, the same research group studied another sample of 65 participants aged 14 to 22, and found non-significant age effects in economic risk and ambiguity attitudes, using subjective utility modelling (Braams et al., 2020). Finally, a recent study of 172 adolescents aged 12 to 17 years using an Ellsberg paradigm found attitudes towards both economic risk and ambiguity to remain stable with age (Fairley & Sanfey, 2020), a finding also observed by Sutter et al. (2013).

In sum, the developmental trajectories of economic risk and ambiguity preferences in the gain domain remain inconclusive, perhaps due to differences in study paradigms or included age ranges. Some studies found that economic ambiguity aversion increases with age from childhood to adulthood (Tymula et al., 2012; Blankenstein et al., 2016; Li et al., 2015 & Li, Roberts, Huettel, & Brannon, 2017) while economic risk preferences remain constant (Blankenstein et al., 2016). Others reported stable economic ambiguity preferences but age-related differences in attitudes towards economic risk (Blankenstein & Van Duijvenvoorde, 2019; Van den Bos & Hertwig, 2017), and still others detected no age differences at all (Braams et al., 2019; Fairley & Sanfey, 2020; Sutter et al., 2013). Though the specific age-related findings are variable, the majority of the developmental evidence available suggests that economic risk and ambiguity may exhibit distinct developmental trajectories. Thus, although evidence remains mixed, such studies support our claim that economic ambiguity should be considered separately from economic risk when investigating the development of risk-taking, while highlighting the need for additional work to fully comprehend whether and how economic ambiguity preferences change with age.

Economic risk and ambiguity preferences in the loss domain

The aforementioned studies investigated economic risk and ambiguity involving potential gains. However, individuals' decision preferences may change under conditions involving losses (Tversky & Kahneman, 1981). For instance, developmental work has shown that, as individuals age from early adolescence to young adulthood, they become increasingly likely to choose a certain option in a gain frame and a risky option in a loss frame (Reyna & Farley, 2006). To date, however, very little is known on the developmental trajectories of ambiguity preferences for losses. Just two studies have explicitly studied economic risk and ambiguity preferences in the gain and loss domain – and those studies reported divergent findings. Van den Bos and Hertwig (2017) found that, for losses, economic risk tolerance decreased with age but economic ambiguity tolerance peaked around 16 years. This contrasted with the same study's finding that economic risk tolerance for gains peaked in adolescence while economic ambiguity tolerance for gains was stable across ages (van den Bos & Hertwig, 2017). Likewise, a study by Tymula et al. (2013) tested risk and ambiguity attitudes across the life span in both gain and loss contexts This study included the same adolescent and adult participants as in their previous work (Tymula et al., 2012). They found that adolescents, young adults, and midlife adults were similarly ambiguity neutral under losses, in contrast to the finding in the gain domain that adolescents were less ambiguity averse than adults (Tymula et al., 2012, Tymula et al. 2013). Although there are just two studies to date investigating the development of ambiguity preferences for losses, they highlight how moving from gains to losses can alter ambiguity preferences and their developmental trajectories, perhaps because shifting from gains to losses taps into a different factor of the multifactorial construct of risk.

Economic ambiguity preferences and self-reported risk-taking behavior

The majority of the aforementioned adolescent studies found economic risk and ambiguity preferences to be not significantly correlated in the gain domain (Blankenstein et al., 2016; Blankenstein & van Duijvenvoorde, 2019; Tymula et al., 2012; van den Bos & Hertwig, 2017) and in the loss domain (Tymula et al., 2013; van den Bos & Hertwig, 2017). These predominantly non-significant correlations suggest that economic risk and ambiguity preferences represent distinct aspects of (adolescent) risk-taking behavior - raising the question of whether attitudes towards economic risk and economic ambiguity differentially predict everyday risk taking.

Only a few studies directly comparing preferences towards economic risk and ambiguity also reported their relation with self-reported everyday risk-taking behavior in adolescents. Tymula et al. (2012) found that adolescents who self-reported more everyday reckless behavior (such as drinking and driving) as measured by the Adolescent Risk Taking Questionnaire (ARQ; Gullone, Moore, Moss, & Boyd, 2000) were more tolerant of economic ambiguity. In contrast, they found no relationship between attitudes toward economic risk and self-reported reckless behavior (or subscales measuring Thrill-seeking, Rebelliousness, and Antisocialness; Tymula et al., 2012). Furthermore, Sutter et al. (2013) found an − albeit weak − association between economic ambiguity preferences and smoking in 10 to 18 year-olds. The association between economic ambiguity attitude and everyday reckless behavior – and lack of association between economic risk attitude and everyday risk behavior – was also found by Blankenstein et al. (2016) and van den Bos & Hertwig (2017), although in the latter study this was observed in the loss domain only.

While these developmental studies found indices of everyday risk-taking to be associated with economic ambiguity tolerance, and not economic risk tolerance. Many studies with adult samples have found relations between economic risk preferences and everyday risk-taking propensity (see Frey, Pedroni, Mata, Rieskamp, & Hertwig, 2017; Levin & Hart, 2003). Thus, economic risk and ambiguity preferences may both relate to everyday risk-taking, but in different ways. For example, some everyday situations may call upon economic risk preferences (e.g., in situations where explicit probabilities are known, such as when deciding whether to take a medication with a known likelihood of adverse side effects) whereas other situations may call upon ambiguity preferences (e.g., in situations in which probabilities are largely unknown, such as deciding whether to jaywalk across a busy street). Future research may explicitly test these associations in a variety of task settings and across various risk-taking domains such as health-safety, recreational, ethical, social, and financial risks (Blankenstein et al., 2021; Blais & Weber, 2006; Weber et al., 2002) in order to better understand how economic risk and ambiguity may differentially predict decision making outside of the laboratory.

Need for further studies of economic risk and ambiguity preferences across development

The conclusions outlined in the previous sections – that economic risk and ambiguity preferences are largely distinct and differentially predict everyday risk-taking – suggest that decisions involving economic risk and ambiguity are supported by different underlying mechanisms. Yet the relatively few studies in developing samples that have explicitly dissected the development of decisions under economic risk and ambiguity have yielded inconsistent findings regarding exactly whether and how economic ambiguity preferences change across development and interact with changes in economic risk preferences. Moreover, other relevant task characteristics may influence developmental differences across studies. As Table 1 shows, studies included physical, computerized, and paper-and-pencil tasks to assess preferences towards economic risk and ambiguity. Furthermore, studies of economic ambiguity have varied in the range of included probabilities, whether probability information was completely or partially hidden, whether choices were between a gamble and a safe option or between two gambles; the amounts that could be won or lost, how choice options differed in expected value, and whether choices were hypothetical or incentive compatible (e.g., choices involving monetary outcomes resulted in gain or loss of participant payment). Each of these task parameters could influence decision preferences (Defoe et al., 2015), further underscoring the need for further, systematic investigation of economic ambiguity preferences in development.

In sum, more research is needed to clarify the developmental trajectory of economic risk and ambiguity preferences from (early) childhood to adulthood and their relations with risk-taking in everyday life, preferably including large samples, wider age ranges, longitudinal designs, and variations in task parameters. Nonetheless, although it remains elusive whether the observed peak in daily-life risk taking in adolescence is explained by a peak in ambiguity seeking preferences, a number of studies have found that individual differences in ambiguity seeking preferences correlate with everyday reckless behavior (Blankenstein et al., 2016; Sutter et al., 2013; Tymula et al., 2012; Van den Bos & Hertwig, 2017), suggesting that economic ambiguity preferences do relate to everyday decision making.

Neural mechanisms of economic risk and economic ambiguity

A large body of research within the field of neuroeconomics – combining insights from neuroscience, psychology, and economics – has studied the neural underpinnings of risky decision making with fMRI (Glimcher & Rustichini, 2004; Konovalov & Krajbich, 2019). It has been theorized that risk assessment recruits activity in multiple core components that either promote or discourage risk-taking. Research has resulted in key insights into which brain regions represent different aspects of the risky decision-making process (for reviews, see Knutson & Huettel, 2015; Mohr, Biele, & Heekeren, 2010; Platt & Huettel, 2008). As rough divisions of a complex process, evaluating *uncertainty* surrounding choices has been linked to activity in anterior insula (AI), dorsomedial prefrontal/anterior cingulate cortex (DMPFC/ACC), and ventrolateral prefrontal cortex (VLPFC; (Levy et al., 2010; Mohr et al., 2010), making *executive judgments* about probability and value has been related to dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC) activation (Huettel, Song, & McCarthy, 2005), and evaluating rewards has been linked to ventral striatum (VS), ventromedial prefrontal cortex (VMPFC) and orbitofrontal cortex (OFC) (Bartra, McGuire, & Kable, 2013; Delgado, 2007; Sescousse, Caldú, Segura, & Dreher, 2013).

While this body of work links different brain systems to different aspects of risky choices *in general,* relatively few studies have explicitly dissociated the neural correlates of economic risk and economic ambiguity. A recent functional magnetic resonance imaging *meta*-analysis has synthesized the few studies specifically examining distinct and common neurobiological substrates of decision making under economic risk and ambiguity (Poudel et al., 2020). The *meta*-analysis found that decision making under economic risk was related to activity in striatum and anterior cingulate cortex, while decision making under economic ambiguity was related to lateral prefrontal cortex (LPFC) and insula. Thus, these neuroimaging findings in adults further support the notion that economic risk and economic ambiguity draw upon distinct-making processes, which map onto core neural components of risky decision making.

Very few studies have explicitly tested the neural correlates of economic risk and economic ambiguity in developing samples. The few that have used fMRI to measure these activation patterns across development generally replicate findings from adult samples (Poudel et al., 2020). Blankenstein et al. (2018) presented 198 adolescents (11–24 years) with a simplified wheel-of-fortune fMRI paradigm that examined decision making under economic risk and economic ambiguity (Blankenstein, Schreuders, Peper, Crone, & van Duijvenvoorde, 2018). This study found that choosing to take economically risky gambles was prominently associated with PPC activation while choosing to take economically ambiguous gambles was related to DLPFC activation. A separate analysis of a subset of the sample (N = 188, 12–22 years) found VS and parietal cortex activation to positively correlate with increasing subjective value under economic risk (assessed with utility model-based risk attitudes), DLPFC and superior temporal gyrus activation to negatively correlate with increasing subjective value under economic ambiguity (assessed with utility model-based ambiguity attitudes), and DMPFC activation to negatively correlate with subjective value increases under both economic risk and ambiguity. This suggests that the neural representation of subjective value under economic risk and economic ambiguity has both shared and distinct components (Blankenstein & van Duijvenvoorde, 2019).

A recent, independent study of 69 participants between the ages of 14 and 22 years reached similar conclusions: trial-by-trial levels of economic risk correlated with increased activation in VS and ACC, while trial-by-trial levels of economic ambiguity correlated with increased activity in widespread regions including precuneus and superior frontal gyrus (Braams et al., 2020). Importantly, these three developmental fMRI studies found no age-related changes in the neural coding of economic risk and ambiguity, suggesting that such representations are stable throughout adolescent development (Blankenstein et al., 2018; Blankenstein & van Duijvenvoorde, 2019; Braams et al., 2020). Just as more developmental research is needed to understand the relationship between decision-making behaviors, more developmental neuroscience research is needed to examine neural representations of economic risk and economic ambiguity in a variety of decision contexts.

Collectively, fMRI research with adults indicates that economic risk and ambiguity have distinct neural mechanisms. The scant literature in developmental fMRI studies largely concurs with these findings, and additionally shows that the neural coding of economic risk and ambiguity is independent of age. Results to date suggest that the building blocks for the processing of economic risk and ambiguity are already neurally distinct and present in early adolescence and remain stable across development into adulthood. However, more developmental fMRI studies are needed to better understand how neural processes give rise to the mental processes that drive decision-making behavior, and what implications this has for how adolescents process ambiguity compared to children and adults.

Conclusion and future directions

In this review, we have outlined three lines of evidence suggesting that economic ambiguity should be considered independently from economic risk in studies of the development of decision making. First, a large body of behavioral studies with adults suggest that economic risk and ambiguity are separate, albeit related, constructs. Second, a more limited set of studies conducted in children and adolescents suggest that attitudes toward economic ambiguity develop along a distinct trajectory from that of economic risk. Third, human fMRI studies in both developmental and adult populations have found evidence that economic risk and ambiguity are distinctly represented in the brain. Taken together, these conclusions highlight the importance of taking a multifactorial view of risk-taking and the need for further work assessing the factor of economic ambiguity in the development of decision making.

Our understanding of economic ambiguity preferences across development should, of course, be bolstered by additional studies. Twelve studies (see Table 1) with sometimes conflicting findings are too few to draw firm conclusions – and additional studies that examine a broader age-range using more ways of representing economic ambiguity will improve our field's understanding of developmental trajectories. At a minimum, laboratory paradigms used to assess risk-taking should carefully determine whether they measure economic risk, economic ambiguity, or some combination of the two. As examples, many commonly used tasks like the IGT or BART involve initially unknown probabilities that are learned in the course of completing the task – and thus confound processes of economically risky and ambiguous decision making (Carlson et al., 2009; Crone et al., 2005; Crone & van der Molen, 2007; Huizenga et al., 2007; Kerr & Zelazo, 2004; Prencipe et al., 2011; Smith et al., 2012; for an excellent review on experienced-based risk taking, see Crone & Van Duijvenvoorde, under review, this issue).

We further suggest that laboratory studies explicitly investigate how decision making changes as choices start off economically ambiguous, with fully unknown probabilities, but become more economically risky as those probabilities are learned from experience. Nonhuman primate work has shown that monkeys become less ambiguity-averse and thus more willing to gamble as they increasingly learn about the ambiguous gambles' outcome probabilities via experience (Hayden et al., 2010), and extensive research with adult samples has demonstrated a "Description-Experience Gap", in which adults' decision preferences for identical gambles differ based on whether the gambles are economically risky (with outcomes and probabilities described) or initially ambiguous but with outcomes and probabilities that are eventually learned through experience (de Palma et al., 2014; Hertwig & Erev, 2009; Wulff, Mergenthaler-Canseco, & Hertwig, 2018; Camilleri and Newell, 2013). Such experience-based tasks may further our understanding of adolescents' everyday risk-taking, as they mirror how many everyday decisions are encountered and learned from (see Rosenbaum, Venkatraman, Steinberg, & Chein, 2018; Romer & Khurana, 2020, for review). To return to our example adolescent who is deciding whether to stop at or drive through an intersection just as the light turns red: This driving decision becomes increasingly less ambiguous as its probabilities become known to the decision-maker through learning, either via observation (e.g. watching other drivers run red lights with or without consequences), explicit instruction (e.g. being taught in a driving class to always stop at a red light), or personal experience (e.g. running red lights while driving and seeing what happens). Thus, it is important not only to distinguish between economic risk and ambiguity when assessing the development of decision making in the lab, but also to consider how attitudes towards everyday decisions interact with how decision probabilities are learned at different stages of development.

Novel studies of economic ambiguity preferences may also inform current influential frameworks of the study of risk-taking and its underlying mechanisms across adolescence, such as neurodevelopmental *imbalance models* and *fuzzy-trace theory* (for an overview and critical evaluation, see Defoe et al., 2015; Gladwin & Figner, 2015; Pfeifer & Allen, 2012). Neurodevelopmental imbalance models posit that the relatively protracted development of cognitive control in adolescence is overridden by heightened socio-affective processes, which fosters heightened risk-taking in adolescence compared to childhood and adulthood. Second, *fuzzy trace theory* distinguishes between the development of precise, computationally-driven reasoning about costs, benefits, and probabilities (i.e., verbatim-based decision-making modes), and heuristically-driven categorical decision making (i.e., gist-based decision-making modes; Reyna, 2012; Reyna & Rivers, 2008). Fuzzy trace theory suggests that with age, adolescents become increasingly able to use context-appropriate heuristics based on their increasing experience, resulting in adolescents engaging in less risk-taking compared to children, but more risk-taking compared to adults. Thus, these frameworks both provide theoretical accounts of how experiences shape risk-taking across development, but to date remain similarly constrained in interpretation by the fact that developmental literature carries many definitions for and examines many different underlying aspects of "risk-taking". Thus, this too calls for careful consideration of specific components underlying risk-taking.

There also remains much to be uncovered about the process through which economic risk and ambiguity are assessed, and how those processes may change across development. Behavioral choice tasks can indicate preferences, but not how such preferences arise. Work combining decision-making paradigms with process-tracing models such as eye-tracking (Kwak, Payne, Cohen, & Huettel, 2015) or mouse cursor tracking (Sullivan, Hutcherson, Harris, & Rangel, 2015; Sullivan et al., 2021) have been successfully used with developmental populations to provide further insight on the mental processes driving choice (Schulte-Mecklenbeck et al., 2017). Such methods could also be applied to compare the processes underlying economically risky and economically ambiguous decision making across development.

Finally, distinguishing economic risk and ambiguity and their associations with everyday decisions may also prove valuable beyond measures of risk-taking, such as our broader understanding of negative and positive socio-developmental trajectories (Crone & Dahl, 2012). The studies synthesized in this review included primarily population-based or typically-developing individuals. Interestingly, research suggests that adults with internalizing and externalizing disorders show aberrant attitudes towards economic ambiguity - but not economic risk. For instance, a study on adults with antisocial personality disorder revealed blunted economic ambiguity aversion but unaffected economic risk aversion, compared to healthy controls, particularly for those individuals characterized by impulsivity and aggression. Additionally, this blunted ambiguity aversion was correlated with higher frequency of criminal arrest (Buckholtz, Karmarkar, Ye, Brennan, & Baskin-Sommers, 2017). In contrast, prior research with adults with obsessive compulsive disorder (an internalizing disorder marked by extreme self-doubt and indecisiveness) showed heightened economic ambiguity aversion, but not economic risk aversion, compared with healthy controls (Pushkarskaya et al., 2015). This raises the question of whether adolescents with externalizing disorders (such as conduct disorder) display blunted ambiguity aversion, and whether adolescents with internalizing disorders (such as anxiety disorder) show heightened ambiguity aversion. These insights from a decision science perspective may further our understanding of positive and negative mental health development.

Relatedly, an intriguing avenue for future research is to study whether ambiguity may be related to positive behaviors, such as prosocial behavior (i.e., actions intended to benefit someone else). Recent research with adults has shown that ambiguity tolerance is predictive of prosocial behavior during trust and cooperative games (Vives & FeldmanHall, 2018), and future research may study whether ambiguity tolerance promotes prosocial behavior in developmental samples. In a similar vein, it has been suggested that ambiguity tolerance fosters learning and explorative behavior in adolescence (Tymula et al., 2012). It is important to examine the role that ambiguity aversion plays in these positive and negative behaviors. While extreme ambiguity tolerance may promote excessive everyday risk-taking and delinquent behavior, extreme ambiguity aversion may limit exploration, resulting in a lack of adaptive risk-taking (e.g. behaviors that foster experiential learning; Romer & Khurana, 2020) or other-oriented positive behavior. In fact, appropriate explorative behaviors are necessary for an adolescent to develop mature social goals and gain independence from parents (Crone & Dahl, 2012). In sum, the function of ambiguity aversion in adolescent development in the domains of adaptive/positive risk-taking behavior (Duell & Steinberg, 2019), prosocial behavior, and aspects of internalizing and externalizing behaviors are important avenues for future research.

Taken together, this review underscores that economic risk and economic ambiguity are distinct constructs with separate neural mechanisms that differentially impact everyday risk-taking behavior across adolescence. We acknowledge that the distinction between economic risk and ambiguity does not solely explain when and why heightened risk-taking may occur in adolescence, and the scant developmental literature on economic ambiguity needs to be bolstered with further studies. Nonetheless, we argue that a full consideration of risky decision making during adolescence will need a deeper understanding not just of economic risk, but also economic ambiguity.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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