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SPECIAL ISSUE/UNCERTAINTY

Aging, uncertainty, and decision making—A review

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Abstract
There is a great deal of uncertainty in the world. One common source of uncertainty results from incomplete or missing information about probabilistic outcomes (i.e., outcomes that may occur), which influences how people make decisions. The impact of this type of uncertainty may particularly pronounced for older adults, who, as the primary leaders around the world, make highly impactful decisions with lasting outcomes. This review examines the ways in which uncertainty about probabilistic outcomes is perceived, handled, and represented in the aging brain, with an emphasis on how uncertainty may specifically affect decision making in later life. We describe the role of uncertainty in decision making and aging from four perspectives, including 1) theoretical, 2) self-report, 3) behavioral, and 4) neuroscientific. We report evidence of any age-related differences in uncertainty among these contexts and describe how these changes may affect decision making. We then integrate the findings across the distinct perspectives, followed by a discussion of important future directions for research on aging and uncertainty, including prospection, domain-specificity in risk-taking behaviors, and choice overload.

Keywords Aging · Decision-making · Risk

The world is full of uncertainty. What are the chances my flight will be on time? What is the probability that my partner will be faithful? How likely is it that I'll get a year-end bonus, and how much will it be? All of this uncertainty undoubtedly affects how people make decisions. One common source of uncertainty arises due to incomplete or missing information about one or more probabilistic outcomes. Because most people tend to devalue, or discount, uncertain outcomes, this is an important consideration when making decisions; uncertain outcomes often lead to different behavior compared to when outcomes are certain.

There are several ways in which uncertainty is defined across the literature (see Table 1 for definitions of key terms). In this review, we focus on uncertainty about probabilistic outcomes, which is any time some information about the number, likelihood, and/or magnitude of probabilistic outcomes is unknown. While there are other areas of decision making that are potentially influenced by uncertainty (e.g., effort or temporal discounting), we focus on examining uncertainty that arises from probabilistic outcomes. Two of the most common ways that this type of uncertainty manifests are that of risk and ambiguity—two related but distinct concepts. Risk refers to situations where the probabilities of potential outcomes are known or easily estimated, but the person does not know the true outcome (also known as outcome uncertainty). An example of risk would be a coin toss. There is a 50/50 chance of the coin landing on heads or tails, but the person does not yet know the actual outcome of the coin toss, making the coin toss risky. The second way uncertainty manifests is through ambiguity, where the probabilities of potential outcomes are unknown. This is much more common in everyday life, where the exact likelihood of events often is unknown. An example of ambiguity would be a person not knowing the chances of getting a new job they just interviewed for. Because they do not know the actual outcome, nor the chances of each potential outcome, this uncertainty about how much uncertainty exists, or ambiguity, can be even more unsettling. In general, as people learn about their environments through experience, they move from states of ambiguity, where the probabilities are unknown, to risk, where they can estimate or even be certain of the probabilities of each outcome.

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Table 1 Definitions of key terms

Term	Definition	Example
Uncertainty	Information about the number, likelihood, and/or magnitude of probabilistic outcomes is unknown	Not knowing the chances that your flight will be on time
Risk	The probability of each possible outcome is known or easily estimated but the true outcome is unknown	A coin flip
Ambiguity	The probability of each possible outcome is unknown and the true outcome is also unknown	Chances of getting a job after an interview
Expected Uncertainty	A known amount of error in a familiar environment	Encountering traffic during rush hour but uncertainty about how long it will last
Unexpected Uncertainty	Changes in the environment that violate expectations	Encountering traffic mid-day due to unexpected road closure

Another relevant distinction regarding uncertainty is that of expected vs. unexpected uncertainty (Table 1). Expected uncertainty refers to a known amount of error in a familiar environment (Yu & Dayan, 2005). For example, predicting you will encounter traffic on your drive home from work during rush hour. While you may not know exactly how much traffic to expect or how long the journey will take (i.e., uncertainty), you anticipate this uncertainty to be present. Conversely, unexpected uncertainty describes changes in the environment that violate expectations, making us unable to accurately predict outcomes (Yu & Dayan, 2005): for example, encountering traffic in the middle of the day because of an unexpected road closure. Some authors also use the term volatility as a synonym for unexpected uncertainty, whereas others make a clear distinction between them. Bland and Schaefer (2012) define unexpected uncertainty as rare changes to the environment and volatility as frequent changes to the environment, which requires an individual to constantly update their predictions. Others use unexpected uncertainty to describe when a decision maker detects a change in the environment, whereas they use volatility to describe unexpected changes that occur regardless of whether the decision maker is aware (Soltani & Izquierdo, 2019). In this review, we will focus primarily on expected and unexpected uncertainty, rather than volatility, because these are more prominently featured across the literature, and there is more consensus on their definitions.

Despite there being so many unknowns in our environment, individuals still make countless decisions in their everyday lives. Current research indicates that individuals tend to make different choices when there is uncertainty compared with when the outcomes are certain. Because older adults often have less time and cognitive resources available, uncertainty may be particularly impactful for these individuals. For example, with less time in life remaining, recovering from a devastating loss in older age may be even more challenging. Thus, uncertainty about potential losses—such as market fluctuations—may elicit different responses from older and younger adults. Less time also means fewer opportunities for potential gains. Thus, this may result in age-related differences in response to uncertainty in the positive domain. This has serious implications for older adults, who, as the primary leaders in business, government, and healthcare, make many significant personal and collective decisions. Thus, due to the consequential nature of decisions made in later life, it is imperative to understand the ways in which uncertainty is perceived, handled, and represented in the aging mind and brain. In this review, we describe the role of uncertainty in decision making and aging from four perspectives: theoretical, self-report, behavioral, and neuroscientific. We end with some important directions for future research in this field including prospection, domain-specific decision making, and choice overload.

Age-related changes in uncertainty

Theoretical

A fundamental idea of the most prominent theoretical accounts of aging is that how individuals choose, plan, and implement goals changes across the lifespan. According to the Selection, Optimization and Compensation (SOC) model of lifespan development, individuals first select their goals and then optimize resources to reach them. As people age, they may need to compensate through substitutive resources to maintain functioning (Baltes & Baltes, 1990; Baltes & Smith, 2004). Similarly, the motivational theory of lifespan developments states that individuals strive to optimize the influence behavior has on the environment (i.e., primary control; Heckhausen & Schulz, 1999; Heckhausen et al., 2010). However, because the capacity for primary control decreases across the lifespan, there is a compensatory secondary control that increases in older adults. Both these theories focus on optimization—which can be particularly difficult to achieve in the face of uncertainty. Uncertainty introduces unknowns about what compensatory behaviors are needed to achieve the goal, as well as the potential outcomes and likelihood of taking each action. Furthermore, if there is unexpected uncertainty, this may require frequent shifts in strategies to achieve optimal outcomes. Because older adults tend to have a more difficult time with task-switching (Wasylyshyn et al., 2011), this adds yet another challenge. Thus, older individuals may have a harder time optimizing under uncertainty and therefore struggle to reach their optimization goals.

Based on the goal orientation perspective, age-related shifts in motivation result in changes to goal orientation and selection. While younger adults appear to strive for gains, middle-aged and older adults have been found to focus on maintenance and the avoidance of losses (Ebner et al., 2006; Freund & Ebner, 2005). This shift in goal orientation may lead to divergent decision strategies between age groups (Depping & Freund, 2011). For example, while someone in their 20s may be looking to advance their career and get promoted, someone in their 60s may be trying to hold their current position or even avoid losing their job. Uncertainty around these goals is likely to further influence what strategies an individual takes—the impact of which may depend on whether the goal focuses on gains or losses.

Other theories, such as the Socioemotional Selectivity Theory (SST), posit that age-related changes to goals and goal behavior are due to differences in emotion regulation and emotion processing in older age (Carstensen et al., 1999). The strength and vulnerabilities integration (SAVI) theory expounds on this idea by describing how cognitive and neural deficits may contribute to the positive role of emotion (Charles, 2010). A central theme across these two theories is that age-related changes in goal-directed behavior may be due to differences in future time perspective, that is, how expansively people see the future. As people get older, their time horizons (i.e., how much time is left) shrink. In turn, how they choose to make and act upon their goals also changes, often prioritizing more emotional and social goals over information-seeking goals. This change in future time perspective may have to do with uncertainty. A longer time horizon is inherently more unpredictable. Thus, as time horizons shrink, uncertainty may also decrease, meaning adults later in their lives should have less uncertainty than those in the decades prior. This may explain age-related differences in decision making under uncertainty. For example, because older and younger adults have vastly distinct time horizons, this is likely to influence behavior and give rise to divergent strategies for decisions such as investments and retirement planning.

Additionally, future time perspective may be particularly influenced by uncertainty regulation, that is, the idea that an individual self-regulates the amount of uncertainty present when creating and acting upon goals (Griffin & Grote, 2020; Grote & Pfrombeck, 2020). According to this view, individuals change their behavior depending on how they want to regulate the level of uncertainty, which ultimately affects their future time perspective, in a recursive loop. According to this framework, if older adults have less uncertainty than younger adults, then older adults may not need to be actively working to decrease uncertainty to the same degree.

In addition to the aging theories described above, there are several neuroscientific theories that point to changes to neuromodulatory systems that occur with age. They attempt to explain the age-related declines seen in dopaminergic (Braver & Barch, 2002), noradrenergic (Mather et al., 2016), and cholinergic (Schliebs & Arendt, 2006) functioning. Because these systems have been found to play significant roles in perceiving and responding to uncertainty (Dayan & Yu, 2006; Yu and Dayan, 200; Schultz et al., 1997; 2015), these may be particularly important when considering the role of uncertainty in decision making in the aging brain. We describe these theories in further detail throughout the Neuroscience section of this review.

Self-report

Uncertainty intolerance

Since the late 1900s, the concept of tolerance for uncertainty, or *uncertainty intoleranc*e, has increased in popularity. While the definition continues to be updated, it most commonly refers to the tendency to avoid uncertainty and the belief that unexpected future events are negative and should be avoided (Grenier et al., 2005). Uncertainty intolerance is typically measured through self-report measures that ask for beliefs about, emotional reactions to, and frequency of, behaviors to avoid or reduce, uncertainty. Scores on these measures have been found to be closely related to generalized anxiety disorder and excessive worry (Dugas et al., 2001; Dugas et al., 2005; Grenier et al., 2005), with increasing uncertainty intolerance preceding an increase in worry (Dugas et al., 2001).

However, uncertainty intolerance has seldom been studied in an aging context. Although older adults report worrying more about specific aspects of their lives such as health, family, and world issues (Hunt et al., 2003), frequency of worry generally decreases across adulthood with older adults worrying less than younger adults (Babcock et al., 2000, 2012; Brenes, 2006). This has been hypothesized to be partially due to older age groups seeing less value in worrying, and the idea that uncertainty intolerance also may be lower in older adults (Basevitz et al., 2008). However, aside from identifying a relationship between uncertainty intolerance and trait anxiety in older adults (Song & Li, 2019), there is little research on the association between uncertainty intolerance and aging beyond that.

Based on the theoretical perspectives discussed earlier including the SST and SAVI, it may be expected that older adults would have better uncertainty intolerance. That is, the shrinking time horizons may lead to less uncertainty about what the future holds, because the options become increasingly limited, which may lead to less worrying in general. Because emotion regulation strategy use in older adults tends to increase, this may help to reduce worrying in general, as well as uncertainty intolerance (Basevitz et al., 2008; Grote & Pfrombeck, 2020). Although uncertainty intolerance is assumed to be a relatively stable trait, because other personality-type traits have been seen to change in later life (Roberts et al., 2006), it is not yet clear how uncertainty intolerance may manifest in later life. Because high levels of worry are related to worse prospection and long-term decision making (Worthy et al., 2014), and older adults experience less worry and potentially less uncertainty intolerance, this may partially explain how older adults make decisions.

Risk tolerance

Risk tolerance—that is, willingness to accept risk—is another way to assess an individual's self-reported perception of, and response to, uncertainty. For several decades, risk tolerance was primarily assessed via an individual's financial portfolio, calculated as a proportion of a persons' risky assets to their total wealth. While one study found that older adults were less risk averse than younger adults, that is, an increased risk tolerance (Wang & Hanna, 1997), the majority of studies find that older adults actually show a decreased risk tolerance, as shown by a lower proportion of risky assets (Bonsang & Dohmen, 2015; Jianakoplos & Bernasek, 2006; Pålsson, 1996; Sharma & Chatterjee, 2021). This relationship between financial risk tolerance and age has been shown to be mediated by cognitive ability, suggesting that age-related change in cognition may be an integral component of this relationship (Bonsang & Dohmen, 2015; Sharma & Chatterjee, 2021).

While financial decisions are an obvious way to examine self-reported risky behaviors, risk tolerance also can be tested across other domains. One measure often used to study self-reported risk attitudes is the Domain-Specific Risk-Taking (DOSPERT) Scale, which assesses risk perceptions and behaviors across several domains (Weber et al., 2002). Roalf et al. (2012) found that older adults had less self-reported risk-taking attitudes and behaviors compared with younger adults in health/safety, recreation, and social domains. However, they found no age difference for financial or ethical behaviors. In contrast, also using the DOSPERT, Rolison et al. (2014) found that increased age was associated with less risky behavior for all domains, including financial and ethical, although the age-related trajectories of change were dependent on the specific domain. Thus, it appears that based on self-report measures, older adults report lower risk tolerance than younger adults across several, if not all, domains. This is further corroborated by a recent meta-analysis of longitudinal self-report data that finds a decreased propensity to take risks with increasing age that is not domain-specific (Liu et al., 2022).

Ambiguity intolerance

Ambiguity intolerance refers to the tendency to perceive ambiguity as negative and/or threatening (Budner, 1962; Frenkel-Brunswik, 1948). While originally synonymous with uncertainty intolerance, which focuses on behaviors that attempt to avoid uncertainty in the future, ambiguity intolerance refers to perceptions of, and reactions to, ambiguity in the current moment (Grenier et al., 2005). On the other end of the spectrum, ambiguity tolerance is the tendency to perceive ambiguous situations as desirable and/or challenging. An individuals' degree of tolerance/intolerance for ambiguity can be assessed through self-report measures, which ask participants to report their comfort level during various ambiguous situations (see Furnham & Ribchester, 1995 for a review).

To date, no studies have investigated age-related changes to self-reported ambiguity intolerance. If we believe that older adults report dealing with ambiguity similarly to uncertainty more generally, it may be the case that ambiguity tolerance increases with age. Alternatively, while there may be less ambiguity in older adults' lives, because they are used to having less ambiguity, it may impact their decisions even more severely. Then again, because self-reports of risk tolerance suggest older adults are less willing to accept risk, older adults also may perceive ambiguity as more negative. However, due to the absence of evidence in this area, we must rely on findings from behavioral work to compare how older and younger adults respond to situations of ambiguity.

Behavioral

Despite robust age-related decline seen across many facets of cognition (Park & Reuter-Lorenz, 2009), how older adults respond to risk does not appear to follow this general trend. In behavioral studies, risky decision making often is tested in the laboratory by asking participants to choose between two or more hypothetical choices, often with varying levels of risk. Because the literature is mixed, findings from meta-analyses, which use evidence across several independent studies, and large-scale studies are helpful in determining if there is an effect. In a meta-analysis with 29 studies ($N = 4{,}093$), Mata et al. (2011) found no overall difference between younger and older adults in description-based (i.e., not experienced) risky decision making. Moreover, using survey data from an extremely large sample ($N = 147{,}118$) across the world, Mata et al. (2016) found only a small age-related difference in propensity for risk taking such that older age is associated with slightly less risk-taking. A follow-up meta-analysis by Best and Charness (2015; N = 3,232), which examined choices between risky and sure outcomes, also found age differences for positively, but not negatively, framed items such that older adults were less risk-seeking. This trend also was observed in a large sample by Rutledge et al. (2016; N = 25,189); they found a small age-related difference in risk-taking for gains, but not losses, when choosing between safe and risky options where older adults were once again less likely to choose the risky option. Thus, it appears as though there may only be slight age-related changes in risky decision making, which may be limited to the positive domain.

Yet, it is unlikely that these findings reflect the whole story. These meta-analyses incorporate mixed evidence concluding there is little to no overall age effect on risky decision making overall. There are indeed many instances where more moderate differences have been documented. In this section, we describe three cases where age-related differences in decision making do arise—decisions under certainty, ambiguity, and from experience—and how uncertainty plays a role in each.

Certainty

Certainty appears to play a special role in cognition. Both inside and outside of the laboratory, there are instances when an individual must make a choice between one option that is the safe, sure option where the outcome is known and another that is uncertain. Mather et al. (2012) found that decision making did not differ between younger and older adults when given two risky options, but performance did diverge for decisions between one risky and one certain outcome. That is, older adults were more risk averse in the gain condition (greater preference for sure gains) and more risk seeking in the loss condition (greater avoidance of sure losses), showing a stronger “certainty effect” than younger adults (Mather et al., 2012). This implies that older adults, compared with younger adults, may give greater negative weight to potentially uncertain outcomes when making decisions. These findings would also explain why Rutledge et al. (2016), which compared certain and uncertain outcomes, indeed found an age-related difference, albeit small, such that older adults were more risk averse than younger adults for potential gains. Moreover, this finding has been replicated by O’Brien and Hess (2019), who also found that older adults were more likely to avoid a sure loss compared to younger adults. Thus, it seems (un)certainty is highly important for age-related differences in decision making.

One potential explanation for this preference for certainty in older age is due to the increased cognitive resources required to process uncertainty (O’Brien & Hess, 2019; Pachur et al., 2017; Zilker et al., 2020). According to this hypothesis, individuals who have less cognitive resources may opt for the sure option more often due to decreased complexity. Indeed, Pachur et al. (2017) found evidence in support of this with an association between cognitive ability and the processing of probability information such that better cognition in older adults was related to higher decision quality in the loss domain. Further support comes from Zilker et al. (2020), who found that by reducing option complexity, thereby lowering the cognitive demand required for the task, age-related differences in risk attitude disappeared.

Ambiguity

Overall, humans tend to dislike ambiguity, that is, outcomes with unknown probabilities, and tend to choose non-ambiguous options more often than those that are ambiguous. This is referred to as “ambiguity aversion.” The existence of age-related differences in ambiguity are not yet clear. For example, Tymula et al. (2013) tested varying degrees of ambiguity and found that ambiguity aversion occurred for both younger and older adults for potential gains, but only in older adults for potential losses. Furthermore, Sproten et al. (2018) found that while ambiguous gambles are chosen less often than risky gambles for both older and younger adults, older adults were more likely than younger adults to gamble under ambiguity, demonstrating less ambiguity aversion. Thus, older adults appear to show ambiguity aversion in both positive and negative domains, but may do so to a less extent than younger adults. This may be related to cognitive resources—more ambiguity means more uncertainty, but it also means that there is less information to process, making these options easier to work with.

One of the most popular ways to study ambiguity is using the Iowa Gambling Task, which starts with ambiguous choices where the probabilities of outcomes are unknown but uncertainty is reduced through experiential sampling so that choices eventually reflect risky decisions. Wood et al. (2005) found that older adults do learn to perform optimally on this task but may use different strategies than younger adults. They found that older adults apply equal weights to gains and losses, where younger adults are more influenced by the losses. This follows a shift from growth promotion to loss prevention seen in older age, where there is a decreased sensitivity to expected value (Chen et al., 2014; Weller et al., 2011). Additionally, older, but not younger, adults’ choices are dependent on recent experience, rather than the maximum expected value (Wood et al., 2005). This may be because it requires less memory capacity, a common characteristic of older adults, to remember only the most recent events, as opposed to all of the previous experiences in the task. Zamarian et al. (2008) also found that while older and younger adults perform similarly on a risky decision-making task (i.e., probabilities are known), older adults show poorer performance than younger adults on the Iowa Gambling Task, where they must learn the outcomes over time to reduce ambiguity. This may be due in part to age-related deficits in learning abilities (see Decisions from Experience for more detail). There also appears to be substantial individual differences in older adults' ability to handle ambiguity as between 25% and 40% of older adults show impairments on the Iowa Gambling Task, whereas the rest remain unimpaired (Denburg et al., 2005, 2006, 2007). Taken together, older adults seem to avoid ambiguity less than younger adults, but they are not necessarily better at dealing with (or learning from) that ambiguity.

Decisions from experience

Just like in the Iowa Gambling Task, there are many cases in real-world decision making where an individual starts off with a great deal of ambiguity about outcomes, but over time, learns about the likelihood of those outcomes and that alters their subsequent decisions. Through this process of experiential sampling, the amount of uncertainty is reduced. Whereas the Mata et al. (2011) meta-analysis reported no age-related differences decisions from description, as described above, they did find age-related differences in risky behavior for decisions from experience, although the specific direction of these effects was task dependent. This is likely related to the finding that learning from probabilistic feedback slows with age (Lighthall et al., 2013; Seaman et al., 2014, 2015). Thus, it is perhaps unsurprising that age-related differences are found in decisions from experience, that is, those where the outcomes are experienced, rather than just described.

Eppinger and Kray (2011) have posited that these changes in learning may reflect age-related deficits in the ability to build representations of ambiguous outcomes. Furthermore, neural representation of the prediction errors during probabilistic learning is reduced in older adults (Samanez-Larkin et al., 2014). This contrasts with the representation of reward outcome, which does not require learning, and was found to remain stable across adulthood. Using computational modeling, Nassar et al. (2016a, b) more broadly proposes that this deficit is due to an insufficient representation of uncertainty in older adults and a diminished capacity to use uncertainty to learn.

When considering age-related differences in decisions from experience, it is important to recognize that older adults have lived longer and thus have had more experiences than individuals younger than them. This means that when older adults make decisions from experience, there may be less reliance on learning because they are more likely to have encountered similar situations in the past. Having repeated experiences also may decrease levels of uncertainty such that older adults experience less uncertainty than a younger adult in their position, even for the same event.

Neuroscience

When examining the neural mechanisms of uncertainty, this is primarily done in the context of prediction error. Prediction error refers to the neural response that occurs when there is a discrepancy between expected and actual outcomes (Schultz, 2015; Schultz et al., 1997). Positive prediction error occurs when an event is better than predicted, whereas negative prediction error occurs when an event is worse than predicted. For both types, the larger the error, the larger the difference between expectation and reality. Prediction error also is scaled by outcome uncertainty (Tobler et al., 2005). That is, uncertainty, such as the variability in possible outcomes, modifies the magnitude of the prediction error. Under conditions of high uncertainty, prediction error is larger, whereas under conditions of low uncertainty, prediction error is smaller. Prediction error is at its largest the first time a person encounters something unexpected. However, through learning and experience, as they come to know what to expect, this reduces prediction error. Prediction error often is modeled through reinforcement learning models and is used to examine how errors influence subsequent decisions and maximize rewards (Chowdhury et al., 2013; O'Doherty et al., 2003).

Evidence suggests that prediction error originates in the dopaminergic neurons of the midbrain but can be observed in regions in which there are dopamine projections, including the ventral striatum and medial frontal cortex (D'Ardenne et al., 2008; Schultz, 2007). Prediction error in the brain can be detected by tracking levels of dopamine, as well as other neuromodulators, such as noradrenaline and acetylcholine, all of which are affected by aging. Experts also use neuroimaging techniques, such as fMRI and EEG, to quantify prediction error. In this section, we review the literature of age-related changes in prediction error in specific neuromodulators and across multiple methods.

Dopamine

Scientists have long known that dopamine is related to reward processing. After initially testing the activity of dopamine neurons in nonhuman primates and eventually humans, they found that providing a reward causes dopamine neurons to fire (Schultz et al., 1997). However, they found that it was not just the reward itself being coded but rather the deviation, or error, between the expected and actual reward (Montague et al., 1996; Schultz et al., 1997). The idea that this change in dopamine activity, which occurs as a function of prediction error, is referred to as the reward prediction error theory of a dopamine function (Schultz et al., 1997, 2015).

There is substantial evidence that during normal aging, there is a marked loss in dopamine receptors (i.e., D1 and D2) and transporters (i.e., DAT; Juarez et al., 2019; Karrer et al., 2017; see Braver & Barch, 2002 and Bäckman et al., 2006; 2009 for reviews), leading to the dopamine hypothesis of aging. In its strongest form, this hypothesis suggests that age-related changes in cognition are mediated by age-related changes in dopamine function, and this hypothesis has been extended to prediction errors. Specifically, age-related differences in prediction error, especially during reinforcement learning, are thought to be a result of age-related decline in dopamine function (Eppinger et al., 2013; Hämmerer & Eppinger, 2012; Nieuwenhuis et al., 2002). In support of this idea, increasing dopamine through pharmacological intervention (i.e., administration of L-DOPA) is associated with greater prediction error in younger adults (Pessiglione et al., 2006) and restored prediction errors in older adults (Chowdhury et al., 2013). As a result, many believe that age-related changes in dopamine functioning lead to the age deficits observed in reinforcement learning, which are particularly pronounced under conditions of uncertainty (Eppinger et al., 2011). However, the original hypotheses about large age-related declines in dopamine function were built on small, cross-sectional studies (Karrer et al., 2017). It is notable that more recent studies with larger sample sizes (Seaman et al., 2019) and longitudinal samples (Karalija et al., 2022) have estimated much smaller age-related decreases of dopamine in the striatum, a region associated with prediction errors (D'Ardenne et al., 2008; Schultz, 2007).

Of note, some studies have examined the direct effect of periods of uncertainty on levels of dopamine, rather than using prediction error as a proxy. This work has found that reward uncertainty is correlated with gradual activity in dopaminergic midbrain neurons (Fiorillo et al., 2003) that is distinct from dopamine responses to reward and reward-prediction (Schultz, 2007). However, there is substantially less research in this area and prediction-error is far more commonly studied regarding uncertainty.

Noradrenaline

Noradrenaline (also known as norepinephrine) is a neurotransmitter primarily associated with arousal but is thought to also play a role in related processes, such as attention, sleep, motivation, and stress. During states of arousal, noradrenaline is released from the locus coeruleus, where it is created and distributed to the cortex through axonal projections (Berridge & Waterhouse, 2003). Recent evidence suggests that situations with uncertainty lead to increased levels of arousal and thus noradrenaline (Lavín et al., 2014; Preuschoff et al., 2011). Yu and Dayan (2005) found that the reverse also is true such that by experimentally increasing noradrenaline, the degree of uncertainty also increased. They further specify that noradrenaline neuronal activity is specifically related to unexpected, as opposed to expected, uncertainty (Dayan & Yu, 2006; Yu & Dayan, 2005). This increase in noradrenaline may be related to learning from decision making. For example, Devauges and Sara (1990) found that a noradrenaline agonist, which increases the firing rate of noradrenaline, improved the speed of learning rule changes in rats. Noradrenaline also may play a major role in decisions of whether to explore vs. exploit (Aston-Jones & Cohen, 2005). Exploration occurs when uncertainty (particularly unexpected uncertainty) is high, such as when someone may be unsure about the state of their environment or when things are volatile. This may lead them to explore to better understand what has (or has not) changed to optimize their decisions. In contrast, exploitation occurs when uncertainty (particularly unexpected uncertainty) is low. Here, an individual has already figured out the environment and knows what the best option is to maximize reward.

Like dopamine, there are significant age-related changes in the noradrenergic system (Grudzien et al., 2007; Mitsis et al., 2009; Wilson et al., 2013). Specifically, there are structural and functional changes to the locus coeruleus, which result in reduced noradrenergic neuron activity (Berridge & Waterhouse, 2003; Mather et al., 2016). There also is an age-related decrease in connectivity between the locus coeruleus and the frontoparietal networks (Lee et al., 2018). Some hypothesize that the deficit in older adults' ability to learn under conditions of uncertainty may be linked to the function of the locus coeruleus-norepinephrine system. However, this has yet to be tested empirically (Nassar, Bruckner, & Eppinger, 2016a).

Acetylcholine

Acetylcholine is a neuromodulator that has been associated with arousal and various cognitive functions including attention, learning, and memory (for a review, see Hasselmo & Sarter, 2011). It has been found to be linked to situations where there is expected uncertainty (Phillips et al., 2000; Yu & Dayan, 2005). Both human and animal work suggests that cholinergic responses are scaled by the degree of uncertainty and thus are important for computing prediction error and learning from feedback (Hangya et al., 2015; Puigbò et al., 2020). Similar to what was found with levels of noradrenaline, Phillips et al. (2000) found that increasing acetylcholine in rodents altered uncertainty-seeking behaviors, such as choosing to explore or exploit. Yu and Dayan (2005) then tested this effect in humans and found that acetylcholine was indeed released during conditions of expected, but not unexpected, uncertainty. Thus, it appears that while noradrenaline and acetylcholine play similar roles in dealing with uncertainty, noradrenaline is associated with unexpected uncertainty, whereas acetylcholine is linked to expected uncertainty. Furthermore, Yu and Dayan (2005) hypothesized that the noradrenergic and cholinergic systems interact during conditions of uncertainty and that acetylcholine might set the threshold for noradrenaline signaling. Other work suggests that acetylcholine may mediate dopamine signaling by increasing firing rates (Belkaid & Krichmar, 2020; Naudé et al., 2016). Thus, the cholinergic system may influence uncertainty in more ways than one, including the modulation of other neuromodulators.

The cholinergic system is related to aging such that during normal aging, there appears to be a gradual decline in cholinergic functioning (Schliebs & Arendt, 2006, 2011). A loss of cholinergic neurons in the basal forebrain has also been identified, which becomes more substantial during diseases, such as Alzheimer's or related dementias. According to the cholinergic hypothesis, this decrease in acetylcholine may, in part, cause the decline in learning and memory typically seen in dementia (Bartus et al., 1982; Dumas & Newhouse, 2011). However, it is likely a combination of these neuromodulators contribute to the documented age-related differences.

Functional magnetic resonance imaging

In what is called the "affect-integration-motivation" (AIM) framework, Samanez-Larkin and Knutson (2015) propose the specific brain regions and neural circuits that work together to promote choice. According to AIM, positive affective responses (i.e., the anticipation of gains) are associated with the dopamine neurons of the ventral tegmental area (VTA) that project to the nucleus accumbens and the rest of the ventral striatum. Negative affective responses (i.e., the anticipation of losses) are related to the noradrenergic neurons of the locus coeruleus that project to the anterior insula. These dopaminergic and noradrenergic neurons then send signals to the medial prefrontal cortex (mPFC), where responses can be integrated with information from other sources. Finally, these neurons provide the motivation to act through projections into the premotor areas—primarily through glutamatergic neurons (Samanez-Larkin & Knutson, 2015). Because of the significant role the dopaminergic and noradrenergic pathways play in prediction error, as described previously, uncertainty is likely to be represented in the signals of both the affect and integration components of the AIM framework.

Functional magnetic resonance imaging (fMRI) evidence supports the idea that prediction error responses are associated with these brain regions, often measured via blood-oxygen-level-dependent (BOLD) signal. For example, BOLD activity in the VTA—a hypothesized source of dopamine for affective responses—and the ventral striatum—one of the primary targets of dopaminergic projections for affective responses—have indeed been found to be related to positive prediction error (D'Ardenne et al., 2008; Jocham et al., 2011; Pessiglione et al., 2006). Further evidence suggests that BOLD activity in the ventromedial prefrontal cortex (vmPFC)—an area proposed to be associated with response integration—also is correlated with reward prediction error (Jocham et al., 2011). Similar relationships have been found in the noradrenergic system between BOLD activity in the anterior insula and prediction error in the negative domain (Fazeli & Büchel, 2018). These findings support the idea that uncertainty, at least when measured via prediction error, may influence the affect and integration processes used during decision making.

Two notable studies have shown age-related differences in the neural representation of prediction error such that older adults have reduced BOLD activity in both the ventral striatum and the vmPFC (Eppinger et al., 2013; Samanez-Larkin et al., 2014). Chowdhury et al. (2013) found irregular representation of expected reward in the nucleus accumbens of older adults, which led to an incomplete prediction error, in older, but not younger, adults. They also found that replacement of dopamine in low baseline dopamine older individuals restored prediction errors. This age-related reduction in prediction-error representation seems to be independent of neural representation of the reward outcome (Samanez-Larkin et al., 2014) and subjective value (Seaman et al., 2018), which do not reliably differ between older and younger adults.

Electroencephalogram

Scientists also use electroencephalogram (EEG) to study electrical activity on the scalp that corresponds to specific events or stimuli—that is, an event-related potential (ERP). In the context of uncertainty, one of the major responses that occurs is error-related negativity (ERN). Like prediction error, the ERN is elicited in the brain when an individual sees an outcome, such as a gain or loss, that is different than expected (Holroyd & Coles, 2002). Thus, it can be used as a proxy to study the neural underpinnings of uncertainty, especially unexpected uncertainty and volatility, where the reward or outcome is continuously changing. The ERN is also heavily dependent on the mesencephalic dopamine system and is thought to originate in the anterior cingulate cortex (ACC) of the medial prefrontal cortex (mPFC), which is proposed to have variety of functions regarding error processing including signaling unexpectedness, predicting the likelihood of outcomes, detecting volatility, and processing feedback from learning situations (Holroyd & Coles, 2002; see Alexander & Brown, 2011 for a review).

As mentioned in previous sections, dopamine functioning deficits in older age have consequences for cognitive processing, especially learning (Bäckman et al., 2006, 2010; Braver & Barch, 2002). In studies that have examined age-related differences in ERN, older adults showed reduced ERN responses (Eppinger et al., 2008; Mathalon et al., 2003; Niessen et al., 2017; Nieuwenhuis et al., 2002). According to Eppinger and Kray (2011), this may be due to a reduced ability to create representations of ambiguous outcomes. In concordance with Nieuwenhuis et al. (2002)'s account of altered error processing in older age, older adults also learn less from the errors that elicit ERNs. This also is found in feedback-related negativity responses (FRN), which reflect a prediction error to feedback, rather than reward (Miltner et al., 1997). Older adults similarly demonstrate reduced responses and deficits in learning from these types of feedback-related errors (Eppinger et al., 2008). Collectively, the neuroscience evidence suggests that older adults may have lower magnitude and/or less precise neural representations of uncertainty, which contribute to the age-related differences in learning and decision-making behavior described above.

Intersection of perspectives

We find evidence across the four perspectives that uncertainty influences decision making in aging adults. From a theoretical lens, we see that during older age, goals often shift toward more social and emotional priorities and/or with an increased focus on loss avoidance. How these goals are implemented also changes, often necessitating the use of compensatory mechanisms to optimize achievement. While there is a lack of evidence from self-reported uncertainty intolerance in an aging context, because older adults have been found to experience less worry and demonstrate increased use of positive emotion regulation strategies, they may avoid conditions of uncertainty less than their younger counterparts. Thus, with less time left, older adults may be experiencing less uncertainty in general, although when it is present, it may cause increased problems. Behavioral work indicates that certainty, and therefore uncertainty, impacts decisions, as shown by older adults yielding a stronger certainty effect than younger adults. However, the remaining evidence suggests that the effects of uncertainty may depend on how it is manifested—i.e., conditions of risk and ambiguity do not appear to impact older adults in the same way. Neuroscientific data suggest that any differences that do arise may be related to a change in uncertainty representation and/or neuromodulatory functioning.

When we look specifically at risk, self-report and behavioral data appear to be in conflict. While self-reported risk tolerance has been seen to decrease (i.e., older adults report being less risk tolerant across most, if not all, domains), there is little evidence for age-related changes in risky behavior seen in the laboratory (Frey et al., 2021). Therefore, although older adults may report taking less risks in later life, they appear to be making similar decisions to younger adults, at least when tested in the laboratory. It may be the case that older adults are less accurate in their self-reports, thereby indicating that they are less risk tolerant than they are. Alternatively, the risky decision-making tasks used in the laboratory may not be sensitive enough to detect differences in how individuals take risks in their everyday lives (e.g., with their financial portfolios).

Nonetheless, ambiguity has been seen to yield age-related differences in behavior. This is likely related to learning, which often is required to reduce ambiguity of situations and is found to be impaired with increased age. Thus, learning deficits often seen in later life may give rise to the differences in choice behavior under conditions of uncertainty. This is further supported by neuroscientific evidence—that is, neuromodulatory functioning that supports learning also decreases with age. Alas, because self-reported tolerance for ambiguity has not been studied within older adults, we are unable to compare behavioral evidence of ambiguity aversion to that of self-reported ambiguity intolerance. It is possible that the same discrepancy between self-report and behavioral evidence arises for ambiguity that is seen for risk.

Lastly, it is important to note the strong likelihood that the association between uncertainty and aging is valence-specific—that is, different for positive (i.e., gains) and negative (i.e., losses) outcomes. There is substantial evidence that finds enhanced emotional processing abilities (e.g., attention, memory) for positive, compared with negative, information in older age, in what is called the "the positivity effect" (Mather & Carstensen, 2005; see Reed et al., 2014 for a meta-analysis). Thus, this change may explain why some of the evidence described in this review was not consistent for both gains and losses. For example, the evidence that older adults show a small decrease in risky behavior was only the case for positively framed items. Whereas younger adults tend to focus only on losses when learning from ambiguity, older adults use a different strategy—similarly weighting both gains and losses. Furthermore, reductions in both affective and neural sensitivity have been found for loss, but not gain, anticipation in older adults (Samanez-Larkin et al., 2007), which may be a result of valence-specific, age-related changes in neural circuitry (Samanez-Larkin & Knutson, 2015). Collectively, these studies suggest that there may be preferential processing of gains compared with losses, but more research is needed to clarify the magnitude of this difference.

Future directions

In this review, we have described evidence of the influence of uncertainty on decision making in the aging brain. However, several unanswered questions remain. Below, we describe a few areas that we feel are understudied with regards to uncertainty, aging, or both and would be particularly beneficial to the field.

Prospection

People often use episodic simulations of possible events to make predictions about the future, create goals, plan actions, and make decisions. The group of processes related to future thinking is called prospection. This includes processes such as predicting future feelings (i.e., affective forecasting) or imagining the future (i.e., episodic future thinking). These prospective abilities appear to be important for mental health, with inaccurate predictions of the future related to more negative well-being and poorer mental health outcomes (MacLeod, 2016; Roepke & Seligman, 2016). Prospection also plays an important role in decision making such that the anticipation of future motivations, emotions, and cognitive processes may influence the subjective value given to each choice (Pezzulo & Rigoli, 2011). Assumably, uncertainty about the future plays a major role in these prospection processes. It may be the case that uncertainty makes prospection more challenging as individuals need to simulate a greater number of potential future outcomes and actions. As a result, increased uncertainty could result in less accurate prospection.

In older age, some prospection abilities have been seen to remain constant, or even improve, whereas other abilities decline. For example, older adults' predictions of future feelings are just as accurate (Kim et al., 2008) or even better (Nielsen et al., 2008; Scheibe et al., 2011) than younger adults. Coupled with older adults' relative preservation of emotional processing (see Mather, 2012 for a review), the hypothesized decline in levels of uncertainty in older age, discussed in earlier sections, may partially explain the absence of an age-related decline in affective forecasting accuracy. However, older adults' episodic future thoughts have been found to be less detailed and specific compared with their younger counterparts (Addis et al., 2008). Because of an established link between remembering the past and imagining the future (Schacter & Madore, 2016), episodic memory deficits seen in older adults may cause increased uncertainty in the past representations. This could then lead to increased uncertainty, and thus less specificity, about the future. Nevertheless, there is relatively little research in this area. Future work should examine how older adults may differ from younger adults in how they use prospection when making decisions and what role uncertainty plays in these processes.

Domain-specificity

The majority of extant decision-making research focuses on financial decision making. This is due to the quantitative nature of these decisions, as well as their ability to be adapted to a laboratory task and setting. Evidence from the domain-specific risk-taking scale (DOSPERT) suggests that risk perception and risk-taking behavior depends on the type of decision an individual is making (Blais & Weber, 2006; Shou & Olney, 2020). This may be especially relevant for uncertainty, which may arise from different sources depending on the domain. For example, for social decisions, the uncertainty primarily lies in what other people may be feeling and how they may act. In contrast, for health decisions, the uncertainty may come from the potential outcomes of a medical procedure, which might include some with very serious consequences (e.g., death). Thus, this uncertainty might differentially affect decisions across distinct domains.

Evidence suggests that this divergence in risk perception between domains continues into older age, with unique age-related trajectories for each domain (Rolison et al., 2014). They found that risk-taking tendencies for financial and social decision making declined rather steeply, whereas decreases in health and ethical risk-taking behavior occurs more gradually. Additionally, Hanoch et al. (2018) found age-related differences in medical decision making, with less passive risk taking and a lower likelihood to accept medical treatment. Yet, this work is typically done using the DOSPERT or related self-report methods. While there is some evidence that subjective measures of risk behavior may predict risk behavior, this may not be true when ambiguity is introduced (Rolison & Pachur, 2017). Therefore, because uncertainty may cause self-report measures to be less predictive of behavior, and thus less reliable, it is imperative to look closer at the role uncertainty plays both across the lifespan and in domains other than financial.

Multiple options

Many of the tasks used to study decision making in the laboratory use between two and four choices, each with a limited number of outcomes. Yet, in the real world, the number of options to choose from drastically increases in most situations. For example, when choosing a medical treatment plan, there often are several options to consider, each with their own advantages and disadvantages. Additionally, for each of the possible choices, there are various potential outcomes. This yields a tremendous amount of uncertainty. In what is frequently called "choice overload" or "the overchoice effect," individuals, somewhat paradoxically, appear to dislike having too many options (Chernev et al., 2015; but see Scheibehenne et al., 2010). Research shows that in situations with choice overload, people have higher negative emotions and lower motivation and satisfaction (Chernev et al., 2015; Iyengar & Lepper, 2000; Schwartz et al., 2002).

However, older adults have been seen to show less of the negative consequences of choice overload compared with younger adults and adolescents (Misuraca et al., 2016). This may be due to the higher level of experience and knowledge that older adults possess. One study found that only individuals with low, but not high, knowledge about retirement and investing were negatively affected by having too many options (Morrin et al., 2012). Additionally, there is evidence that increased uncertainty and number of choices increases complexity and therefore will require more cognitive resources (Chernev et al., 2015; Scheibehenne et al., 2010). While one may assume that this may make the task even more difficult for older adults, a number of studies have found that older adults often use different, often simpler, strategies when making decisions to avoid depleting cognitive resources (Mata et al., 2007; Tanius et al., 2009). However, the absence of overchoice effect in older adults is understudied and not yet understood. Research in this area will help us to understand under what conditions older adults make the best decisions that lead to the most satisfaction and least amount of regret.

Conclusions

We reviewed how uncertainty about probabilistic outcomes manifests in older age by using evidence across four perspectives: theoretical, self-report, behavioral, and neuroscientific. Taken together, the evidence from the theoretical accounts and self-report measures indicate that uncertainty is likely reduced and/or avoided less in older age, although it may be particularly harmful to goal optimization when uncertainty does arise. While self-report studies indicate that older adults are less risk tolerant than their younger peers, meta-analyses on behavioral data suggest that there are little to no overall age-related changes to risky decision making. In contrast, there appears to be substantial behavioral evidence of age-related differences for other types of uncertainty, such as conditions of ambiguity and decisions from experience, both of which are likely related to deficits in learning that accompany aging. According to the neuroscientific evidence, older adults may have lower magnitude and/or less precise neural representations of uncertainty, which may stem from age-related changes to the neuromodulatory system and contribute to these age-related differences in learning and decision-making. Across all four perspectives, there is support for the idea that positive and negative outcomes may yield distinct choice patterns across the adult lifespan, which should be considered when interpreting related work. Future work that focuses on prospection, domain-specific decisions, and many choice alternatives may help us to better understand how uncertainty affects decision making in the aging brain. More broadly, research in this area will help to explain how the aging population, despite having limited time and cognitive resources remaining, are able to make decisions under conditions of uncertainty.

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References

Addis, D. R., Wong, A. T., & Schacter, D. L. (2008). Age-related changes in the episodic simulation of future events. *Psychological Science, 19*(1), 33–41. https://doi.org/10.1111/j.1467-9280.2008.02043.x

Alexander, W. H., & Brown, J. W. (2011). Medial prefrontal cortex as an action-outcome predictor. *Nature Neuroscience, 14*(10), 1338–1344. https://doi.org/10.1038/nn.2921

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28*, 403–450.

Babcock, R. L., Laguna, L. B., Laguna, K. D., & Urusky, D. A. (2000). Age differences in the experience of worry. *Journal of Mental Health and Aging, 6*(3), 227–235.

Babcock, R. L., MaloneBeach, E. E., Hou, B., & Smith, M. (2012). The experience of worry among young and older adults in the United States and Germany: A cross-national comparison. *Aging & Mental Health, 16*(4), 413–422. https://doi.org/10.1080/13607863.2011.615736

Bäckman, L., Nyberg, L., Lindenberger, U., Li, S. C., & Farde, L. (2006). The correlative triad among aging, dopamine, and cognition: Current status and future prospects. *Neuroscience and Biobehavioral Reviews, 30*(6), 791–807. https://doi.org/10.1016/j.neubiorev.2006.06.005

Bäckman, L., Lindenberger, U., Li, S. C., & Nyberg, L. (2010). Linking cognitive aging to alterations in dopamine neurotransmitter functioning: recent data and future avenues. *Neuroscience & Biobehavioral Reviews, 34*(5), 670–677. https://doi.org/10.1016/j.neubiorev.2009.12.008

Baltes, P. B., & Baltes, M. M. (1990). Psychological perspectives on successful aging: The model of selective optimization with compensation. In P. B. Baltes & M. M. Baltes (Eds.), *Successful aging: Perspectives from the behavioral sciences* (pp. 1–34). Cambridge University Press. https://doi.org/10.1017/CBO9780511665684.003

Baltes, P. B., & Smith, J. (2004). Lifespan psychology: From developmental contextualism to developmental biocultural co-constructivism. *Research in Human Development, 1*(3), 123–144. https://doi.org/10.1207/s15427617rhd0103_1

Bartus, R. T., Dean, R. L., Beer, B., & Lippa, A. S. (1982). The cholinergic hypothesis of geriatric memory dysfunction. *Science, 217*(4558), 408–414. https://doi.org/10.1126/science.7046051

Basevitz, P., Pushkar, D., Chaikelson, J., Conway, M., & Dalton, C. (2008). Age-Related Differences in Worry and Related Processes. *The International Journal of Aging and Human Development, 66*(4), 283–305. https://doi.org/10.2190/AG.66.4.b

Belkaid, M., & Krichmar, J. L. (2020). Modeling uncertainty-seeking behavior mediated by cholinergic influence on dopamine. *Neural Networks, 125*, 10–18. https://doi.org/10.1016/j.neunet.2020.01.032

Berridge, C. W., & Waterhouse, B. D. (2003). The locus coeruleus–noradrenergic system: Modulation of behavioral state and state-dependent cognitive processes. *Brain Research Reviews, 42*(1), 33–84. https://doi.org/10.1016/S0165-0173(03)00143-7

Best, R., & Charness, N. (2015). Age differences in the effect of framing on risky choice: A meta-analysis. *Psychology and Aging, 30*(3), 688–698. https://doi.org/10.1037/a0039447

Blais, A.-R., & Weber, E. U. (2006). A Domain-Specific Risk-Taking (DOSPERT) scale for adult populations. *Judgment and Decision Making, 1*(1), 33–47.

Bland, A., & Schaefer, A. (2012). Different varieties of uncertainty in human decision-making. *Frontiers in Neuroscience, 6*, 85. https://doi.org/10.3389/fnins.2012.00085

Bonsang, E., & Dohmen, T. (2015). Risk attitude and cognitive aging. *Journal of Economic Behavior & Organization, 112*, 112–126. https://doi.org/10.1016/j.jebo.2015.01.004

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews, 26*(7), 809–817. https://doi.org/10.1016/s0149-7634(02)00067-2

Brenes, G. A. (2006). Age differences in the presentation of anxiety. *Aging and Mental Health, 10*(3), 298–302. https://doi.org/10.1080/13607860500409898

Budner, S. (1962). Intolerance of ambiguity as a personality variable. *Journal of Personality, 30*, 29–59.

Carstensen, L. L., Isaacowitz, D. M., & Charles, S. T. (1999). Taking time seriously: A theory of socioemotional selectivity. *American Psychologist, 54*(3), 165–181. https://doi.org/10.1037/0003-066X.54.3.165

Charles, S. T. (2010). Strength and vulnerability integration: A model of emotional well-being across adulthood. *Psychological Bulletin, 136*(6), 1068–1091. https://doi.org/10.1037/a0021232

Chen, Y., Wang, J., Kirk, R. M., Pethtel, O. L., & Kiefner, A. E. (2014). Age differences in adaptive decision making: The role of numeracy. *Educational Gerontology, 40*(11), 825–833. https://doi.org/10.1080/03601277.2014.900263

Chernev, A., Böckenholt, U., & Goodman, J. (2015). Choice overload: A conceptual review and meta-analysis. *Journal of Consumer Psychology, 25*(2), 333–358. https://doi.org/10.1016/j.jcps.2014.08.002

Chowdhury, R., Guitart-Masip, M., Lambert, C., Dayan, P., Huys, Q., Düzel, E., & Dolan, R. J. (2013). Dopamine restores reward prediction errors in old age. *Nature Neuroscience, 16*(5), 648–653. https://doi.org/10.1038/nn.3364

D'Ardenne, K., McClure, S. M., Nystrom, L. E., & Cohen, J. D. (2008). BOLD responses reflecting dopaminergic signals in the human ventral tegmental area. *Science, 319*(5867), 1264–1267. https://doi.org/10.1126/science.1150605

Dayan, P., & Yu, A. J. (2006). Phasic norepinephrine: A neural interrupt signal for unexpected events. *Network: Computation in Neural Systems, 17*(4), 335–350. https://doi.org/10.1080/09548980601004024

Denburg, N. L., Tranel, D., & Bechara, A. (2005). The ability to decide advantageously declines prematurely in some normal older persons. *Neuropsychologia, 43*(7), 1099–1106. https://doi.org/10.1016/j.neuropsychologia.2004.09.012

Denburg, N. L., Recknor, E. C., Bechara, A., & Tranel, D. (2006). Psychophysiological anticipation of positive outcomes promotes advantageous decision-making in normal older persons. *International Journal of Psychophysiology, 61*(1), 19–25. https://doi.org/10.1016/j.ijpsycho.2005.10.021

Denburg, N. L., Cole, C. A., Hernandez, M., Yamada, T. H., Tranel, D., Bechara, A., & Wallace, R. B. (2007). The orbitofrontal cortex, real-world decision making, and normal aging. *Annals of the New York Academy of Sciences, 1121*(1), 480–498. https://doi.org/10.1196/annals.1401.031

Depping, M. K., & Freund, A. M. (2011). Normal aging and decision making: The role of motivation. *Human Development, 54*(6), 349–367. https://doi.org/10.1159/000334396

Devauges, V., & Sara, S. (1990). Activation of the noradrenergic system facilitates an attentional shift in the rat. *Behavioural Brain Research, 39*, 19–28. https://doi.org/10.1016/0166-4328(90)90118-X

Dugas, M. J., Gosselin, P., & Ladouceur, R. (2001). Intolerance of uncertainty and worry: Investigating specificity in a nonclinical sample. *Cognitive Therapy and Research, 25*(5), 551–558. https://doi.org/10.1023/A:1005553414688

Dugas, M. J., Hedayati, M., Karavidas, A., Buhr, K., Francis, K., & Phillips, N. A. (2005). Intolerance of uncertainty and information processing: Evidence of biased recall and interpretations. *Cognitive Therapy and Research, 29*(1), 57–70. https://doi.org/10.1007/s10608-005-1648-9

Dumas, J. A., & Newhouse, P. A. (2011). The cholinergic hypothesis of cognitive aging revisited again: Cholinergic functional compensation. *Pharmacology Biochemistry and Behavior, 99*(2), 254–261. https://doi.org/10.1016/j.pbb.2011.02.022

Ebner, N. C., Freund, A. M., & Baltes, P. B. (2006). Developmental changes in personal goal orientation from young to late adulthood: From striving for gains to maintenance and prevention of losses. *Psychology and Aging, 21*(4), 664–678. https://doi.org/10.1037/0882-7974.21.4.664

Eppinger, B., & Kray, J. (2011). To choose or to avoid: Age differences in learning from positive and negative feedback. *Journal of Cognitive Neuroscience, 23*(1), 41–52. https://doi.org/10.1162/jocn.2009.21364

Eppinger, B., Kray, J., Mock, B., & Mecklinger, A. (2008). Better or worse than expected? Aging, learning, and the ERN. *Neuropsychologia, 46*(2), 521–539. https://doi.org/10.1016/j.neuropsychologia.2007.09.001

Eppinger, B., Hämmerer, D., & Li, S.-C. (2011). Neuromodulation of reward-based learning and decision making in human aging. *Annals of the New York Academy of Sciences, 1235*(1), 1–17. https://doi.org/10.1111/j.1749-6632.2011.06230.x

Eppinger, B., Schuck, N. W., Nystrom, L. E., & Cohen, J. D. (2013). Reduced striatal responses to reward prediction errors in older compared with younger adults. *Journal of Neuroscience, 33*(24), 9905–9912. https://doi.org/10.1523/JNEUROSCI.2942-12.2013

Fazeli, S., & Büchel, C. (2018). Pain-related expectation and prediction error signals in the anterior insula are not related to aversiveness. *Journal of Neuroscience, 38*(29), 6461–6474. https://doi.org/10.1523/JNEUROSCI.0671-18.2018

Fiorillo, C. D., Tobler, P. N., & Schultz, W. (2003). Discrete coding of reward probability and uncertainty by dopamine neurons. *Science, 299*(5614), 1989–1902.

Frenkel-Brunswik, E. (1948). Intolerance of ambiguity as an emotional perceptual personality variable. *Journal of Personality, 18*, 108–143.

Freund, A. M., & Ebner, N. C. (2005). The aging self: Shifting from promoting gains to balancing losses. In W. Greve, K. Rothermund, & D. Wentura (Eds.), *The adaptive self: Personal continuity and intentional self-development* (pp. 185–202). Hogref & Huber Publishers.

Frey, R., Richter, D., Schupp, J., Hertwig, R., & Mata, R. (2021). Identifying robust correlates of risk preference: A systematic approach using specification curve analysis. *Journal of Personality and Social Psychology, 120*(2), 538–557. https://doi.org/10.1037/pspp0000287

Furnham, A., & Ribchester, T. (1995). Tolerance of ambiguity: A review of the concept, its measurement and applications. *Current Psychology, 14*(3), 179–199. https://doi.org/10.1007/BF02686907

Grenier, S., Barrette, A.-M., & Ladouceur, R. (2005). Intolerance of uncertainty and intolerance of ambiguity: Similarities and differences. *Personality and Individual Differences, 39*, 593–600. https://doi.org/10.1016/j.paid.2005.02.014

Griffin, M. A., & Grote, G. (2020). When is more uncertainty better? A model of uncertainty regulation and effectiveness. *Academy of Management Review, 45*(4), 745–765. https://doi.org/10.5465/amr.2018.0271

Grote, G., & Pfrombeck, J. (2020). Uncertainty in aging and lifespan research: Covid-19 as catalyst for addressing the elephant in the room. *Work, Aging and Retirement, 6*(4), 246–250. https://doi.org/10.1093/workar/waaa020

Grudzien, A., Shaw, P., Weintraub, S., Bigio, E., Mash, D. C., & Mesulam, M. M. (2007). Locus coeruleus neurofibrillary degeneration in aging, mild cognitive impairment and early Alzheimer's disease. *Neurobiology of Aging, 28*(3), 327–335. https://doi.org/10.1016/j.neurobiolaging.2006.02.007

Hämmerer, D., & Eppinger, B. (2012). Dopaminergic and prefrontal contributions to reward-based learning and outcome monitoring during child development and aging. *Developmental Psychology, 48*(3), 862–874. https://doi.org/10.1037/a0027342

Hangya, B., Ranade, S. P., Lorenc, M., & Kepecs, A. (2015). Central cholinergic neurons are rapidly recruited by reinforcement feedback. *Cell, 162*(5), 1155–1168. https://doi.org/10.1016/j.cell.2015.07.057

Hanoch, Y., Rolison, J. J., & Freund, A. M. (2018). Does medical risk perception and risk taking change with age? *Risk Analysis, 38*(5), 917–928. https://doi.org/10.1111/risa.12692

Hasselmo, M. E., & Sarter, M. (2011). Modes and models of forebrain cholinergic neuromodulation of cognition. *Neuropsychopharmacology, 36*(1), 52–73. https://doi.org/10.1038/npp.2010.104

Heckhausen, J., & Schulz, R. (1999). Selectivity in life-span development: Biological and societal canalizations and individuals' developmental goals. In J. Brandtstädter & R. M. Lerner (Eds.), *Action & self-development: Theory and research through the life span* (pp. 67–103). Sage Publications, Inc. https://doi.org/10.4135/9781452204802.n3

Heckhausen, J., Wrosch, C., & Schulz, R. (2010). A motivational theory of life-span development. *Psychological Review, 117*(1), 32–60. https://doi.org/10.1037/a0017668

Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109*(4), 679–709. https://doi.org/10.1037/0033-295X.109.4.679

Hunt, S., Wisocki, P., & Yanko, J. (2003). Worry and use of coping strategies among older and younger adults. *Journal of Anxiety Disorders, 17*(5), 547–560. https://doi.org/10.1016/S0887-6185(02)00229-3

Iyengar, S. S., & Lepper, M. R. (2000). When choice is demotivating: Can one desire too much of a good thing? *Journal of Personality and Social Psychology, 79*(6), 995–1006. https://doi.org/10.1037/0022-3514.79.6.995

Jianakoplos, N. A., & Bernasek, A. (2006). Financial risk taking by age and birth cohort. *Southern Economic Journal, 72*(4), 981–1001. https://doi.org/10.1002/j.2325-8012.2006.tb00749.x

Jocham, G., Klein, T. A., & Ullsperger, M. (2011). Dopamine-mediated reinforcement learning signals in the striatum and ventromedial prefrontal cortex underlie value-based choices. *Journal of Neuroscience, 31*(5), 1606–1613. https://doi.org/10.1523/JNEUROSCI.3904-10.2011

Juarez, E. J., Castrellon, J. J., Green, M. A., Crawford, J. L., Seaman, K. L., Smith, C. T., Dang, L. C., Matuskey, D., Morris, E. D., Cowan, R. L., Zald, D. H., & Samanez-Larkin, G. R. (2019). Reproducibility of the correlative triad among aging, dopamine receptor availability, and cognition. *Psychology and Aging, 34*(7), 921–932. https://doi.org/10.1037/pag0000403

Karalija, N., Johansson, J., Papenberg, G., Wåhlin, A., Salami, A., Köhncke, Y., Brandmaier, A. M., Andersson, M., Axelsson, J., Riklund, K., Lövdén, M., Lindenberger, U., Bäckman, L., & Nyberg, L. (2022). Longitudinal dopamine D2 receptor changes and cerebrovascular health in aging. *Neurology*. https://doi.org/10.1212/WNL.0000000000200891

Karrer, T. M., Josef, A. K., Mata, R., Morris, E. D., & Samanez-Larkin, G. R. (2017). Reduced dopamine receptors and transporters but not synthesis capacity in normal aging adults: A meta-analysis. *Neurobiology of Aging, 57*, 36–46. https://doi.org/10.1016/j.neurobiolaging.2017.05.006

Kim, S., Healey, M. K., Goldstein, D., Hasher, L., & Wiprzycka, U. J. (2008). Age differences in choice satisfaction: A positivity effect in decision making. *Psychology and Aging, 23*(1), 33–38. https://doi.org/10.1037/0882-7974.23.1.33

Lavín, C., San Martín, R., & Rosales Jubal, E. (2014). Pupil dilation signals uncertainty and surprise in a learning gambling task. *Frontiers in Behavioral Neuroscience, 7*, 218. https://doi.org/10.3389/fnbeh.2013.00218

Lee, T.-H., Greening, S. G., Ueno, T., Clewett, D., Ponzio, A., Sakaki, M., & Mather, M. (2018). Arousal increases neural gain via the locus coeruleus–noradrenaline system in younger adults but not in older adults. *Nature Human Behaviour, 2*, 356–366. https://doi.org/10.1038/s41562-018-0344-1

Lighthall, N. R., Gorlick, M. A., Schoeke, A., Frank, M. J., & Mather, M. (2013). Stress modulates reinforcement learning in younger and older dults. *Psychology and Aging, 28*(1), 35–46. https://doi.org/10.1037/a0029823

Liu, Y., Bagaïni, A., Son, G., Kapoor, M., & Mata, R. (2022). Life-course trajectories of risk-taking propensity: A coordinated analysis of longitudinal studies. *The Journals of Gerontology: Series B*, gbac175. https://doi.org/10.1093/geronb/gbac175

MacLeod, A. K. (2016). Prospection, well-being and memory. *Memory Studies, 9*(3), 266–274. https://doi.org/10.1177/1750698016645233

Mata, R., Schooler, L. J., & Rieskamp, J. (2007). The aging decision maker: Cognitive aging and the adaptive selection of decision strategies. *Psychology and Aging, 22*(4), 796–810. https://doi.org/10.1037/0882-7974.22.4.796

Mata, R., Josef, A. K., Samanez-Larkin, G. R., & Hertwig, R. (2011). Age differences in risky choice: A meta-analysis. *Annals of the New York Academy of Sciences, 1235*(1), 18–29. https://doi.org/10.1111/j.1749-6632.2011.06200.x

Mata, R., Josef, A. K., & Hertwig, R. (2016). Propensity for risk taking across the life span and around the globe. *Psychological Science, 27*(2), 231–243. https://doi.org/10.1177/0956797615617811

Mathalon, D. H., Bennett, A., Askari, N., Gray, E. M., Rosenbloom, M. J., & Ford, J. M. (2003). Response-monitoring dysfunction in aging and Alzheimer's disease: An event-related potential study. *Neurobiology of Aging, 24*(5), 675–685. https://doi.org/10.1016/S0197-4580(02)00154-9

Mather, M. (2012). The emotion paradox in the aging brain. *Annals of the New York Academy of Sciences, 1251*(1), 33–49. https://doi.org/10.1111/j.1749-6632.2012.06471.x

Mather, M., & Carstensen, L. L. (2005). Aging and motivated cognition: The positivity effect in attention and memory. *Trends in Cognitive Sciences, 9*(10), 496–502. https://doi.org/10.1016/j.tics.2005.08.005

Mather, M., Mazar, N., Gorlick, M. A., Lighthall, N. R., Burgeno, J., Schoeke, A., & Ariely, D. (2012). Risk preferences and aging: The "certainty effect" in older adults' decision making. *Psychology and Aging, 27*(4), 801–816. https://doi.org/10.1037/a0030174

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory.

Behavioral and Brain Sciences, 39, e200. https://doi.org/10.1017/S0140525X15000667

Miltner, W. H., Braun, C. H., & Coles, M. G. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: Evidence for a "generic" neural system for error detection. *Journal of Cognitive Neuroscience, 9*(6), 788–798. https://doi.org/10.1162/jocn.1997.9.6.788

Misuraca, R., Teuscher, U., & Faraci, P. (2016). Is more choice always worse? Age differences in the overchoice effect. *Journal of Cognitive Psychology, 28*(2), 242–255. https://doi.org/10.1080/20445911.2015.1118107

Mitsis, E. M., Cosgrove, K. P., Staley, J. K., Bois, F., Frohlich, E. B., Tamagnan, G. D., Estok, K. M., Seibyl, J. P., & van Dyck, C. H. (2009). Age-related decline in nicotinic receptor availability with [^{123}I]5-IA-85380 SPECT. *Neurobiology of Aging, 30*(9), 1490–1497. https://doi.org/10.1016/j.neurobiolaging.2007.12.008

Montague, P., Dayan, P., & Sejnowski, T. (1996). A framework for mesencephalic dopamine systems based on predictive Hebbian learning. *The Journal of Neuroscience, 16*(5), 1936–1947. https://doi.org/10.1523/JNEUROSCI.16-05-01936.1996

Morrin, M., Broniarczyk, S. M., & Inman, J. J. (2012). Plan format and participation in 401(k) plans: The moderating role of investor knowledge. *Journal of Public Policy & Marketing, 31*(2), 254–268. https://doi.org/10.1509/jppm.10.122

Nassar, M. R., Bruckner, R., & Eppinger, B. (2016a). What do we GANE with age? *Behavioral and Brain Sciences, 39*. https://doi.org/10.1017/S0140525X15001892

Nassar, M. R., Bruckner, R., Gold, J. I., Li, S.-C., Heekeren, H. R., & Eppinger, B. (2016b). Age differences in learning emerge from an insufficient representation of uncertainty in older adults. *Nature Communications, 7*(1), 11609. https://doi.org/10.1038/ncomms11609

Naudé, J., Tolu, S., Dongelmans, M., Torquet, N., Valverde, S., Rodriguez, G., Pons, S., Maskos, U., Mourot, A., Marti, F., & Faure, P. (2016). Nicotinic receptors in the ventral tegmental area promote uncertainty-seeking. *Nature Neuroscience, 19*(3), 471–478. https://doi.org/10.1038/nn.4223

Nielsen, L., Knutson, B., & Carstensen, L. L. (2008). Affect dynamics, affective forecasting, and aging. *Emotion, 8*(3), 318–330. https://doi.org/10.1037/1528-3542.8.3.318

Niessen, E., Fink, G. R., Hoffman, H. E. M., Weiss, P. H., & Stahl, J. (2017). Error detection across the adult lifespan: Electrophysiological evidence for age-related deficits. *Neuroimage, 152*, 517–529. https://doi.org/10.1016/j.neuroimage.2017.03.015

Nieuwenhuis, S., Ridderinkhof, K. R., Talsma, D., Coles, M. G. H., Holroyd, C. B., Kok, A., & van der Molen, M. W. (2002). A computational account of altered error processing in older age: Dopamine and the error-related negativity. *Cognitive, Affective, & Behavioral Neuroscience, 2*(1), 19–36. https://doi.org/10.3758/CABN.2.1.19

O'Brien, E. L., & Hess, T. M. (2019). Differential focus on probability and losses between young and older adults in risky decision-making. *Aging, Neuropsychology, and Cognition, 27*(4), 532–552. https://doi.org/10.1080/13825585.2019.1642442

O'Doherty, J. P., Dayan, P., Friston, K., Critchley, H., & Dolan, R. J. (2003). Temporal difference models and reward-related learning in the human brain. *Neuron, 38*, 329–337.

Pachur, T., Mata, R., & Hertwig, R. (2017). Who dares, who errs? Disentangling cognitive and motivational roots of age differences in decisions under risk. *Psychological Science, 28*(4), 504–518. https://doi.org/10.1177/0956797616687729

Pålsson, A.-M. (1996). Does the degree of relative risk aversion vary with household characteristics? *Journal of Economic Psychology, 17*(6), 771–787. https://doi.org/10.1016/S0167-4870(96)00039-6

Park, D. C., & Reuter-Lorenz, P. A. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*(1), 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Pessiglione, M., Seymour, B., Flandin, G., Dolan, R. J., & Frith, C. D. (2006). Dopamine-dependent prediction errors underpin reward-seeking behaviour in humans. *Nature, 442*(7106), 1042–1045. https://doi.org/10.1038/nature05051

Pezzulo, G., & Rigoli, F. (2011). The value of foresight: How prospection affects decision-making. *Frontiers in Neuroscience, 5*, 79. https://doi.org/10.3389/fnins.2011.00079

Phillips, J. M., McAlonan, K., Robb, W. G. K., & Brown, V. J. (2000). Cholinergic neurotransmission influences covert orientation of visuospatial attention in the rat. *Psychopharmacology, 150*(1), 112–116. https://doi.org/10.1007/s002130000437

Preuschoff, K., 't Hart, B., & Einhauser, W. (2011). Pupil dilation signals surprise: Evidence for adrenaline's role in decision making. *Frontiers in Neuroscience, 5*, 115. https://doi.org/10.3389/fnins.2011.00115

Puigbò, J.-Y., Arsiwalla, X. D., González-Ballester, M. A., & Verschure, P. F. M. J. (2020). Switching operation modes in the neocortex via cholinergic neuromodulation. *Molecular Neurobiology, 57*(1), 139–149. https://doi.org/10.1007/s12035-019-01764-w

Reed, A. E., Chan, L., & Mikels, J. A. (2014). Meta-analysis of the age-related positivity effect: Age differences in preferences for positive over negative information. *Psychology and Aging, 29*(1), 1–15. https://doi.org/10.1037/a0035194

Roalf, D. R., Mitchell, S. H., Harbaugh, W. T., & Janowsky, J. S. (2012). Risk, reward, and economic decision making in aging. *The Journals of Gerontology: Series B, 67B*(3), 289–298. https://doi.org/10.1093/geronb/gbr099

Roberts, B. W., Walton, K. E., & Viechtbauer, W. (2006). Patterns of mean-level change in personality traits across the life course: A meta-analysis of longitudinal studies. *Psychological Bulletin, 132*(1), 1–25. https://doi.org/10.1037/0033-2909.132.1.1

Roepke, A. M., & Seligman, M. E. P. (2016). Depression and prospection. *British Journal of Clinical Psychology, 55*(1), 23–48. https://doi.org/10.1111/bjc.12087

Rolison, J. J., & Pachur, T. (2017). How well do we know our inner daredevil? Probing the relationship between self-report and behavioral measures of risk taking. *Journal of Behavioral Decision Making, 30*(2), 647–657. https://doi.org/10.1002/bdm.1979

Rolison, J. J., Hanoch, Y., Wood, S., & Liu, P.-J. (2014). Risk-taking differences across the adult life span: A question of age and domain. *The Journals of Gerontology: Series B, 69*(6), 870–880. https://doi.org/10.1093/geronb/gbt081

Rutledge, R. B., Smittenaar, P., Zeidman, P., Brown, H. R., Adams, R. A., Lindenberger, U., Dayan, P., & Dolan, R. J. (2016). Risk taking for potential reward decreases across the lifespan. *Current Biology, 26*(12), 1634–1639. https://doi.org/10.1016/j.cub.2016.05.017

Samanez-Larkin, G. R., & Knutson, B. (2015). Decision making in the ageing brain: Changes in affective and motivational circuits. *Nature Reviews Neuroscience, 16*(5), 278–289. https://doi.org/10.1038/nrn3917

Samanez-Larkin, G. R., Gibbs, S. E. B., Khanna, K., Nielsen, L., Carstensen, L. L., & Knutson, B. (2007). Anticipation of monetary gain but not loss in healthy older adults. *Nature Neuroscience, 10*(6), 787–791. https://doi.org/10.1038/nn1894

Samanez-Larkin, G. R., Worthy, D. A., Mata, R., McClure, S. M., & Knutson, B. (2014). Adult age differences in frontostriatal representation of prediction error but not reward outcome. *Cognitive, Affective, & Behavioral Neuroscience, 14*(2), 672–682. https://doi.org/10.3758/s13415-014-0297-4

Schacter, D. L., & Madore, K. P. (2016). Remembering the past and imagining the future: Identifying and enhancing the contribution of episodic memory. *Memory Studies, 9*(3), 245–255. https://doi.org/10.1177/1750698016645230

Scheibe, S., Mata, R., & Carstensen, L. L. (2011). Age differences in affective forecasting and experienced emotion surrounding the 2008 US presidential election. *Cognition & Emotion, 25*(6), 1029–1044. https://doi.org/10.1080/02699931.2010.545543

Scheibehenne, B., Greifeneder, R., & Todd, P. M. (2010). Can there ever be too many options? A meta-analytic review of choice overload. *Journal of Consumer Research, 37*(3), 409–425. https://doi.org/10.1086/651235

Schliebs, R., & Arendt, T. (2006). The significance of the cholinergic system in the brain during aging and in Alzheimer's disease. *Journal of Neural Transmission, 113*(11), 1625–1644. https://doi.org/10.1007/s00702-006-0579-2

Schliebs, R., & Arendt, T. (2011). The cholinergic system in aging and neuronal degeneration. *Behavioural Brain Research, 221*(2), 555–563. https://doi.org/10.1016/j.bbr.2010.11.058

Schultz, W. (2007). Behavioral dopamine signals. *Trends in Neurosciences, 30*(5), 203–210. https://doi.org/10.1016/j.tins.2007.03.007

Schultz, W. (2015). Neuronal reward and decision signals: From theories to data. *Physiological Reviews, 95*(3), 853–951. https://doi.org/10.1152/physrev.00023.2014

Schultz, W., Dayan, P., & Montague, P. R. (1997). A neural substrate of prediction and reward. *Science, 275*(5306), 1593–1599.

Schwartz, B., Ward, A., Monterosso, J., Lyubomirsky, S., White, K., & Lehman, D. R. (2002). Maximizing versus satisficing: Happiness is a matter of choice. *Journal of Personality and Social Psychology, 83*(5), 1178–1197. https://doi.org/10.1037/0022-3514.83.5.1178

Seaman, K. L., Howard, D. V., & Howard, J. H., Jr. (2014). Adult Age Differences in Learning on a Sequentially Cued Prediction Task. *The Journals of Gerontology: Series B, 69*(5), 686–694. https://doi.org/10.1093/geronb/gbt057

Seaman, K. L., Howard, D. V., & Howard, J. H. (2015). Adult age differences in subjective and objective measures of strategy use on a sequentially cued prediction task. *Aging, Neuropsychology, and Cognition, 22*(2), 170–182. https://doi.org/10.1080/13825585.2014.898736

Seaman, K. L., Brooks, N., Karrer, T. M., Castrellon, J. J., Perkins, S. F., Dang, L. C., Hsu, M., Zald, D. H., & Samanez-Larkin, G. R. (2018). Subjective value representations during effort, probability and time discounting across adulthood. *Social Cognitive and Affective Neuroscience, 13*(5), 449–459. https://doi.org/10.1093/scan/nsy021

Seaman, K. L., Smith, C. T., Juarez, E. J., Dang, L. C., Castrellon, J. J., Burgess, L. L., San Juan, M. D., Kundzicz, P. M., Cowan, R. L., Zald, D. H., & Samanez-Larkin, G. R. (2019). Differential regional decline in dopamine receptor availability across adulthood: Linear and nonlinear effects of age. *Human Brain Mapping, 40*(10), 3125–3138. https://doi.org/10.1002/hbm.24585

Sharma, M., & Chatterjee, S. (2021). Cognitive functioning: An underlying mechanism of age and gender differences in self-assessed risk tolerance among an aging population. *Sustainability, 13*(4), 2361. https://doi.org/10.3390/su13042361

Shou, Y., & Olney, J. (2020). Assessing a domain-specific risk-taking construct: A meta-analysis of reliability of the DOSPERT scale. *Judgment and Decision Making, 15*(1), 112–134.

Soltani, A., & Izquierdo, A. (2019). Adaptive learning under expected and unexpected uncertainty. *Nature Reviews Neuroscience, 20*(10), 635–644. https://doi.org/10.1038/s41583-019-0180-y

Song, Y., & Li, B. (2019). Locus of control and trait anxiety in aged adults: The mediating effect of intolerance of uncertainty. *International Journal of Mental Health and Addiction, 17*(1), 13–21. https://doi.org/10.1007/s11469-017-9860-x

Sproten, A. N., Diener, C., Fiebach, C. J., & Schwieren, C. (2018). Decision making and age: Factors influencing decision making under uncertainty. *Journal of Behavioral and Experimental Economics, 76*, 43–54. https://doi.org/10.1016/j.socec.2018.07.002

Tanius, B. E., Wood, S., & Hanoch, Y. (2009). Aging and choice: Applications to Medicare Part D. *Judgment and Decision Making, 4*(1), 92–101.

Tobler, P. N., Fiorillo, C. D., & Schultz, W. (2005). Adaptive coding of reward value by dopamine neurons. *Science, 307*, 1643–1645. https://doi.org/10.1126/science.1105370

Tymula, A., Rosenberg Belmaker, L. A., Ruderman, L., Glimcher, P. W., & Levy, I. (2013). Like cognitive function, decision making across the life span shows profound age-related changes. *Proceedings of the National Academy of Sciences, 110*(42), 17143–17148. https://doi.org/10.1073/pnas.1309909110

Wang, H., & Hanna, S. D. (1997). Does risk tolerance decrease with age? *Financial Counseling and Planning, 8*(2), 27–32. https://doi.org/10.2139/ssrn.95489

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and Task Switching: A Meta-Analysis. *Psychology and Aging, 26*(1), 15–20. https://doi.org/10.1037/a0020912

Weber, E. U., Blais, A.-R., & Betz, N. (2002). A domain-specific risk-attitude scale: Measuring risk perceptions and risk behaviors. *Journal of Behavioral Decision Making, 15*, 263–290.

Weller, J. A., Levin, I. P., & Denburg, N. L. (2011). Trajectory of risky decision making for potential gains and losses from ages 5 to 85. *Journal of Behavioral Decision Making, 24*(4), 331–344. https://doi.org/10.1002/bdm.690

Wilson, R. S., Nag, S., Boyle, P. A., Hizel, L. P., Yu, L., Buchman, A. S., Schneider, J. A., & Bennett, D. A. (2013). Neural reserve, neuronal density in the locus coeruleus, and cognitive decline. *Neurology, 80*(13), 1202–1208. https://doi.org/10.1212/WNL.0b013e3182897103

Wood, S., Busemeyer, J., Koling, A., Cox, C. R., & Davis, H. (2005). Older adults as adaptive decision makers: Evidence from the Iowa Gambling Task. *Psychology and Aging, 20*(2), 220–225. https://doi.org/10.1037/0882-7974.20.2.220

Worthy, D. A., Byrne, K. A., & Fields, S. (2014). Effects of emotion on prospection during decision-making. *Frontiers in Psychology, 5*, 591. https://doi.org/10.3389/fpsyg.2014.00591

Yu, A. J., & Dayan, P. (2005). Uncertainty, Neuromodulation, and Attention. *Neuron, 46*(4), 681–692. https://doi.org/10.1016/j.neuron.2005.04.026

Zamarian, L., Sinz, H., Bonatti, E., Gamboz, N., & Margarete, D. (2008). Normal aging affects decisions under ambiguity, but not decisions under risk. *Neuropsychology, 22*, 645–657. https://doi.org/10.1037/0894-4105.22.5.645

Zilker, V., Hertwig, R., & Pachur, T. (2020). Age differences in risk attitude are shaped by option complexity. *Journal of Experimental Psychology: General, 149*(9), 1644–1683. https://doi.org/10.1037/xge0000741