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Reward processing and risky decision making in the aging brain

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Abstract

Despite the graying of the world population and increasing relevance of decision competence across the life span, scant research has focused on whether or how reward processing and risky decision making may change across adulthood. Here, we review studies that have examined how age influences psychological and neural responses to financial incentives and risk. The findings suggest that while processing of basic rewards may be maintained across the adult life span, learning about new rewards may decline as a function of age. Further, these behavioral changes can be linked to relative preservation of striatal function in the face of age-related declines in the connectivity of the prefrontal cortex to the striatum. This frontostriatal disconnection may impair risky decision making, both in the laboratory and the real world. In addition to informing theory about how affect and cognition combine to guide choice, these novel findings imply that a deeper understanding of how the aging brain processes incentives may eventually inform the design of more targeted and effective decision aids for individuals of all ages.

Keywords: aging, reward, risk, affect, cognition, decision making, striatum, insula, prefrontal cortex

As global demographics shift towards an increase in the proportion of older adults in the population, older adults will control correspondingly more global resources. Will they allocate those resources in the same way they might have earlier in life, or will the very process of aging influence the manner in which financial decisions are approached and negotiated? While stereotypes about the effects of aging on financial risk taking abound (such as the notion that risk aversion globally increases with age), relatively little evidence has been collected to either verify or refute these commonly held beliefs. Even less is known about what psychological and neural mechanisms might underlie age differences in risky decision making. In this chapter, we aim to review the emerging literature on the influence of aging on incentive processing and financial risk taking, correlated neural substrates, and generalizations to real world behavior, with a goal of identifying fruitful directions for future research.

Multiple psychological factors, both cognitive and affective, contribute to decision making. An extensive body of research suggests that fluid cognitive capacities such as attention, working memory, and executive control decline with age (Salthouse, 2004), while leaving crystallized cognitive capacities relatively spared (Park et al., 2002). Neuroscience research has linked declines in fluid cognitive capacity to changes in medial temporal and lateral prefrontal cortical function (Hedden & Gabrieli, 2004). In contrast to these fluid cognitive declines, affective processing remains intact in old age and emerging neuroscience research has begun to link these affective variables to changes in striatal, insular, and prefrontal function (Samanez-Larkin & Carstensen, 2011). Yet, few studies have investigated how age-related changes in cognition, affect, or associated neural circuits influence incentive processing and risky decision making (Samanez-Larkin, 2010).

Over the past several years, we have conducted a series of studies in an initial attempt to examine individual differences in reward processing across the adult life span using an interdisciplinary and translational approach. This approach combines psychological theory, imaging methods from neuroscience, and experimental tasks from behavioral economics and finance to examine decision making in the laboratory and in the real world. Overall, the results reveal a pattern of age differences in the function of neural systems supporting aspects of incentive processing and risky decision making. These findings and related work from other laboratories have explored individual differences across a range of reward-related tasks ranging from basic anticipatory and consummatory responses to incentive cues, to probabilistic reward learning, to risky decision making about investments.

Processing of Monetary Gains and Losses

The development of event-related functional magnetic resonance imaging (FMRI) in the early 1990's allowed investigators to visualize second-to-second changes in cortical and subcortical brain function, illuminating neural responses not only in response to events, but also during anticipation of those events. Coupled with calibrated tasks involving monetary incentives, researchers could for the first time visualize subcortical responses during anticipation of uncertain gains and losses (Knutson & Cooper, 2005). These experiments were recently extended to studies of human aging. These studies suggested that older adults showed similar subcortical ventral striatal responses to younger adults when anticipating monetary gains (e.g., in the context of cued reaction time tasks such as the Monetary Incentive Delay (MID) task; (Knutson & Greer, 2008; Knutson, Adams, Fong, & Hommer, 2001) (Samanez-Larkin et al., 2007) (Figure 1). Younger and older adults also showed similar neural responses to reward outcomes in the medial prefrontal cortex and ventral striatum (K. M. Cox, Aizenstein, & Fiez, 2008; Samanez-Larkin et al., 2007; Samanez-Larkin, Kuhnen, Yoo, & Knutson, 2010) (Figure

1). Together, these findings provided initial evidence that basic neural responses to the anticipation and receipt of monetary gains are relatively preserved from young adulthood to old age.

A strikingly different pattern, however, emerged during anticipation of monetary losses. Specifically, older adults showed reduced reactivity in the dorsal striatum and anterior insula than younger adults while anticipating monetary loss (Samanez-Larkin et al., 2007). This age difference was also reflected in self-reported affect, such that older adults reported lower levels of anticipatory negative arousal when anticipating losses than did younger adults. This diminished negative arousal during loss anticipation for older adults replicated in an independent sample (Nielsen, Knutson, & Carstensen, 2008). Interestingly, these age differences did not extend to loss outcomes — when older adults actually lost money, they showed similar neural and affective reactions to loss outcomes as did younger adults (Figure 2).

This age-related asymmetry in gain and loss anticipation coheres with a large body of behavioral research suggesting an age-related "positivity" effect (Carstensen & Mikels, 2005; Mather & Carstensen, 2005). Socioemotional selectivity theory (Carstensen, 2006; Carstensen & Mikels, 2005) posits that as time horizons shrink across adulthood, humans are increasingly motivated to optimize well being. In fact, cross-sectional and longitudinal experience sampling research has repeatedly demonstrated that emotional experience in everyday life becomes less negative across adulthood (Carstensen, Pasupathi, Mayr, & Nesselroade, 2000; Carstensen et al., 2011). A similar age by valence interaction also emerges in studies of attention and memory

(Carstensen & Mikels, 2005; Mather & Carstensen, 2005) and appears to extend to incentive anticipation. By extension, diminished negativity during anticipation of losses (but not in response to loss outcomes) may result from older adults avoiding anxiety associated with potential losses unless they actually occur (however, see (Wood, Busemeyer, Koling, Cox, &

Davis, 2005) for evidence that positivity effects may sometimes extend to outcomes). Whether this suppression of anticipatory anxiety is strategic or more automatic remains an open question. Alternatively, regulation may grow more automatic and require less effort with age (Samanez-Larkin & Carstensen, 2011).

Reduced loss anticipation may enhance the well being of older adults, and may also contribute to age differences in some, but not all, decisions. In fact, a recent study found similarly reduced insula activation in older compared to younger adults when they were offered unfair divisions of money in an Ultimatum Game (Harlé & Sanfey, 2012). Older adults showed reduced insular activity (previously associated with heightened negative affect) but still rejected more unfair offers than younger adults. Thus, it remains unclear whether reduced insular responsiveness influences affective experience only or whether it also directly alters learning and decision making. In the monetary incentive delay paradigms mentioned above, performance is typically controlled via adaptive target durations, so that all subjects succeed (or “hit”) on approximately two-thirds of trials. Thus changes in loss anticipation have no consequence for task performance. It is possible that reduced neural anticipation of loss in old age only emerges when loss anticipation is not required for performance – a possibility we will return to later.

In contrast to research suggesting that neural responses to monetary gains are relatively preserved over adulthood, another early study of adult age differences in reward processing drew the opposite conclusion – that older adults show reduced neural anticipation of monetary gains and so are less motivated than younger adults (Schott et al., 2007). A number of important differences between these studies may account for their differential findings. First, the Schott et al (2007) study used very small magnitude rewards (€0.50) on each trial. They reported an age difference such that ventral striatal signals in older adults did not distinguish between €0.50 and €0.00 during anticipation. In fact, a similar effect is observed in Samanez-Larkin et al. 2007 (see the $0.50 and $0.00 lines in Figure 1). However, in the Samanez-Larkin et al 2007 study, the $5.00 cues elicited high levels of neural activity in both age groups. Thus, it is possible that low magnitude rewards were not large enough to elicit strong neural responses. In other studies, low magnitude rewards produce striatal signals with much lower levels of test-retest reliability than elicited by higher magnitude rewards (Wu, Samanez-Larkin, & Knutson, 2012). Second, the Schott et al 2007 study used symbolic cues that did not explicitly communicate reward magnitude on each trial during anticipation. Associations between the cue shapes and reward value were verbally communicated to subjects during the task instructions, but, at some level, the association between these symbolic cues and their value had to be learned. It is possible that older adults may not have encoded these cue-reward associations as strongly as younger adults. Such an alternative account predicts that the older adults should have had lower levels of striatal signal during the cue phase (anticipation), but higher levels of striatal signal during the outcome phase (due to a larger reward prediction error) – which exactly matches the observed pattern of findings. Thus, the study may reveal more about the influence of aging on reward learning than basic incentive processing and motivation. Accordingly, we now turn to studies that explicitly focused on adult age differences in reward learning.

Gain and Loss Learning

In contrast to the studies suggesting relative preservation of basic reward processing across adulthood, the literature on reward learning reveals more consistent age differences in performance and associated neural activity. For instance, older adults show reduced ventral striatal activation during probabilistic reward learning in FMRI studies (Mell et al., 2009). Electrophysiological studies have similarly shown reduced activity in frontal cortical regions during probabilistic reward learning in older adults (Eppinger, Hämmerer, & Li, 2011; Eppinger, Kray, Mock, & Mecklinger, 2008; Hämmerer, Li, Müller, & Lindenberger, 2011). Some have suggested that these age differences may be due to older adults' difficulty in dynamically computing prediction errors in novel environments (Eppinger et al., 2011), and some evidence exists to support this account. Specifically, in FMRI studies, striatal activity appears functionally intact in older adults during simple reward-based tasks that do not require novel learning, but more variable (Samanez-Larkin et al., 2010) and less associated with reward prediction error signals (Samanez-Larkin, 2010) during tasks that require learning in the same individuals and brain regions. These variable responses appear to generalize to some risk-taking tasks, as discussed in the next section on risky decisions.

Recently, theorists have begun to debate whether learning about gains versus losses differentially changes with age. Some evidence suggests that older adults are more sensitive to positive than to negative feedback during probabilistic learning, relative to younger adults (Denburg, Recknor, Bechara, & Tranel, 2006; Wood et al., 2005). Others have suggested the opposite — that older adults are more sensitive to negative than positive feedback (Hämmerer et al., 2011). However, one study often cited as providing evidence for increases in learning from negative feedback with age (Frank & Kong, 2008) did not include a younger adult group. Therefore, those findings cannot provide evidence for an age by valence interaction across adulthood. Instead, they suggest that a subset of older adults show a stronger bias toward learning from losses, whereas late middle-aged and young-older adults did not show the same bias. In contrast, healthy young adults and healthy older adults show no valence bias, consistent with an absence of an age by valence interaction in reward learning over much of the adult life span (Frank, Seeberger, & O'Reilly, 2004; Lighthall, Gorlick, Schoeke, Frank, & Mather, 2012). If a shift toward negativity occurs, it appears to occur much later in old age (e.g., after age 80) (Frank & Kong, 2008; J. R. Simon, Howard, & Howard, 2010a), when investigators must be careful to control for potential confounds related to declining health. A slight non-linear increase in negativity near the end of life is in fact consistent with the larger literature on emotional experience in everyday life (Carstensen et al., 2011).

Overall, across probabilistic reward learning tasks, investigators have most consistently reported main effects of age without qualification by valence (Eppinger et al., 2011). By implication, the majority of age differences in reward learning tasks may relate to more general difficulties with probabilistic learning. In probabilistic learning tasks, the uncertainty of the outcome on any individual trial may introduce risk. Might these age-related learning impairments also contribute to adult age differences in risky decision making? The tasks described thus far did not systematically vary the level of risk among options or include certain alternatives, but recent studies have begun to explore age differences in choice among risky and safe options.

Risky Decision Making

Risky decisions involve choices between options in which at least one alternative has an uncertain outcome. To test societal stereotypes of older adults as being more risk averse than younger adults, a long history of behavioral research has focused on aging and risk aversion, beginning with studies of cautiousness in responding (Botwinick, 1969; Calhoun & Hutchison, 1981; Okun, 1976). A critical review of this work suggests that stereotypes of age-related risk aversion are not supported by findings from well-controlled experimental tasks (Mather, 2006). The past several decades of this research were recently reviewed in a meta-analysis. The meta-analysis, which focused on gambling tasks and risky investment choices, found no evidence for systematic adult age differences in risk preferences (Mata, Josef, Samanez-Larkin, & Hertwig, 2011). Rather, the findings identified a subset of tasks in which older adults choose to avoid risk, but other tasks in which older adults choose to seek risk more often than younger adults (Mata et al., 2011). Notably, in many of these tasks, the expression of this “risk preference” is opposite of the reward maximizing strategy. Thus, in these tasks, apparent age differences in risk preferences may instead result from cognitive limitations (Henninger, Madden, & Huettel, 2010). Consistent with this account, tasks that require subjects to learn from recent experience show larger age differences in performance than do tasks in which performance does not depend on learning (Mata et al., 2011).

Few neuroimaging studies involving choices between high versus low risk options have compared younger and older adults. In an early study, which included a risky decision making task that does not require learning, older adults behaviorally chose more low risk options and showed greater insula activation during choice (Lee, Leung, Fox, Gao, & Chan, 2008). However, one important limitation of this study was that the older adult group included only nine subjects. This small sample size makes it difficult to evaluate the generalizability of either the behavior or brain activity observed in the older sample, especially in light of the results of the meta-analysis described above. Also, insula activation showed high variability between subjects — particularly in older adults. The unequal variance between groups implies strong individual differences in the older group, which may violate assumptions of conventional statistical comparisons. Thus, wide generalizations based on these findings may be premature.

Another study of adult age differences in risky decision making used a different task that elicits a mix of both low risk and high risk choices within each individual across the task (Kuhnen & Knutson, 2005). This investment task (the “BIAS Task”) was designed to emulate everyday financial decisions by requiring subjects to make a series of choices between “safe” bonds and “risky” stocks. Reward maximization requires rapid learning from probabilistic feedback throughout the task. Given the task structure, a “rational actor” (i.e., Bayesian updating, risk-neutral agent) should begin each task round by choosing the safe asset (bond) and then should shift over time to a risky asset (stock) when the expected value of choosing that risky asset exceeds the fixed expected value of the safe asset. Individual choices that deviate from those of the rational actor can be classified as risk averse (i.e., the choice of a bond over a better stock) or risk seeking (i.e., the choice of an uncertain stock over a bond or alternative stock). In a large community sample of young, middle-aged, and older adults, we found no age differences in risk aversion, but did find age differences in risk seeking (Figure 3A) (Samanez-Larkin et al., 2010). Age differences specifically surfaced during trials in which older adults chose risky assets – a pattern which replicated in two other groups who participated in the task outside the MRI scanner (Samanez-Larkin et al., 2010; Samanez-Larkin, Wagner, & Knutson, 2011b). Consistent with a neurocomputational account (Li, 2005; Li, et al., 2001), age differences in risky choice were mediated by a neural measure of functional variability in ventral striatal activity (Figure 3B) (Samanez-Larkin et al., 2010). This neural variability[1] increased with age in the midbrain and striatum, and the age-related variability effects replicated in an entirely independent study which used a different task that did not involve reward (Garrett, Kovacevic, McIntosh, & Grady, 2010).

The study suggests that variability in neural signals that compute and represent expected value in a dynamic environment may increase with age. Consistent with this account, related behavioral evidence suggests that older adults have more difficulty estimating the specific value of ambiguous stimuli during reward learning tasks (e.g., whether a non-rewarded outcome should be weighted positively or negatively following a gain or loss cue) (Eppinger & Kray, 2011). Together, these findings suggest that apparent age differences in risk preference may instead relate to differences in learning ability. In support of this conclusion, neuroimaging studies of decisions that do not require rapid learning from recent experience show similar

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[1] Note that the vast majority of fMRI studies compare mean signal between different task conditions. Signal variability may be an important, overlooked individual difference measure relevant to understanding age differences in brain function.

patterns of neural activity in striatal (Samanez-Larkin, Mata, Radu, Ballard, et al., 2011a) and prefrontal (Hosseini et al., 2010) regions of both younger and older adults.

Resolving an Apparent Paradox

The combined findings on basic reward processing, reward learning, and risky decision making raises a puzzling question. How can the same striatal regions that appear to be functionally intact in basic reward tasks show functional irregularities in learning and decision tasks? One solution to this apparent contradiction may be that a broader neural network lies at the source of the age differences in striatal activity during learning and decision making. For instance, while basic striatal function may remain preserved over the adult life span, prefrontal input may change. Functionally, such a disconnection might not impair basic motivation, but may instead misdirect that motivation away from appropriate but novel goals (Knutson, Fong, Bennett, Adams, & Hommer, 2003).

The highly interconnected anatomy of reward circuitry has been extensively characterized in both human and non-human primates (M. X. Cohen, Schoene-Bake, Elger, & Weber, 2009; Draganski et al., 2008; Haber, 2003; Haber & Knutson, 2010). If connections from the medial prefrontal cortex to the ventral striatum are compromised in aging, they might influence reward learning and risk taking. The recent development of diffusion tensor imaging tractography allows investigators to visualize the "integrity" (a combination of fiber density, axonal diameter, and myelination) of even subcorticcal tracts such as those implicated in reward processing. In a recent study we examined the structural integrity of reward circuitry using diffusion tensor imaging in a group of younger, middle-aged and older adults who also completed a probabilistic reward learning task (Samanez-Larkin, Levens, Perry, Dougherty, & Knutson, 2012). Analyses focused on a ventromedial circuit from the ventral tegmental area in the midbrain to the ventral striatum through the pallidum to the thalamus, from the thalamus to the medial prefrontal cortex, and from the frontal cortex back into the ventral striatum. Findings specifically indicated that the integrity of pathways connecting the thalamus to the prefrontal cortex and the prefrontal cortex to the ventral striatum was reduced in older age and was also associated with reward learning (Figure 4) (Samanez-Larkin et al., 2012). These findings suggest that one source of the age-related striatal functional variability observed in prior studies may arise from structural degradation of prefrontal input to the striatum, which might compromise reward learning. Interestingly, these frontostriatal pathways primarily utilize the neurotransmitter glutamate. While the vast majority of research and theory about age differences in neurochemical signaling has focused on dopamine (Braver & Barch, 2002; S.-C. Li, Lindenberger, & Bäckman, 2010), these findings emphasize the importance of also considering interactions with other neurochemical systems (Mora, Segovia, & Del Arco, 2007; Segovia, Porras, Del Arco, & Mora, 2001). Notably, age differences in reward learning are distinct from traditional impairments in explicit memory — both in terms of associated neural circuits (i.e., ventromedial frontostriatal networks versus lateral frontal and medial temporal networks) as well as psychological processes (e.g., feedback-driven learning versus working memory) (Samanez-Larkin, Wagner, & Knutson, 2011b).

In summary, apparently contradictory findings may reflect age differences in broader prefrontal networks associated with increased task demands, rather than more general deficits in striatal activity associated with motivation. Thus, what appear to be motivational deficits may instead result from cognitive deficits. Although some have claimed that basic motivational function declines with age (Eppinger, Nystrom, & Cohen, 2012), this claim is inconsistent with decades of behavioral research on the psychology of aging (Carstensen, 2006; Carstensen, Mikels, & Mather, 2005; Charles & Carstensen, 2010) as well as a growing number of neuroscience studies (Samanez-Larkin, 2011; Samanez-Larkin & Carstensen, 2011).

Individual Differences in Old Age

Studies of adult age differences in risky decision making often find that individual differences increase with age (Eppinger & Kray, 2011). Even in tasks in which decision making appears to decline on average with age, many older individuals show no deficits whatsoever compared to healthy young adults. For instance, using the Iowa Gambling Task (Denburg, Tranel, & Bechara, 2005), researchers found that while some older individuals took more risks and made fewer returns than younger adults, others performed equally as well as young adults. These findings raise at least two possibilities: (1) either a subset of older adults retains preserved function from young adulthood to old age, or (2) changes in motivation and cognition across adulthood alter the specific processes that guide decision making in some older individuals. While no longitudinal studies have definitively tested these alternative accounts, some suggestive cross-sectional evidence supports the latter account. For instance, in the Iowa Gambling Task, which involves risky choice, memory, and learning, the mechanisms that determine performance may change across the life span in the subset of individuals who continue to perform well. Interestingly, older adults who perform as well as younger adults seem to be guided by physiological responses (e.g., assessed with skin conductance) during anticipation of gains. In stark contrast, younger adults in the same circumstances appear to be guided instead by physiological responses during the anticipation of loss (Denburg et al., 2006). Thus, these findings are consistent with an age-related shift in the processing of positive relative to negative information (Carstensen & Mikels, 2005; Mather & Carstensen, 2005), and further imply that some older adults leverage this appetitive motivation in the service of making successful risky decisions.

Decision Making Does Not Globally Decline With Age

It is also important to note that there are a number of decision making scenarios where older adults perform just as well or ever better than younger adults (Castel, 2005; Hosseini et al., 2010; Kovalchik, Camerer, Grether, Plott, & Allman, 2005; Kühn et al., 2011; Y. Li, Baldassi, Johnson, & Weber, 2011; Löckenhoff, 2011; Mata & Nunes, 2010; Mata et al., 2012; Mather, 2006; Mienaltowski, 2011; Mikels et al., 2010; Nielsen et al., 2008; Reyna & Brainerd, 2011; Roalf, Mitchell, Harbaugh, & Janowsky, 2012; Roesch, Bryden, Cerri, Haney, & Schoenbaum, 2012; Samanez-Larkin, Mata, Radu, Ballard, et al., 2011a; Scheibe, Mata, & Carstensen, 2011; N. W. Simon et al., 2010b; Spaniol, Voss, Bowen, & Grady, 2011; Strough, Karns, & Schlosnagle, 2011; Worthy, Gorlick, Pacheco, Schnyer, & Maddox, 2011). Many of these scenarios involve decisions that do not require learning in a novel environment (however, see (Worthy et al., 2011)) but instead require accumulation of experience, crystallized intelligence, gist memory, or emotional and motivational processing.

Enhancing Choice Through Decision Aids

In decision scenarios where older adults do not perform as well as younger adults, research might ideally identify opportunities for effective intervention. The research reviewed above suggests that age differences in risky decision making may be related to difficulty computing dynamic representations of expected value in a novel environment. Thus, in subsequent work, we sought to determine whether targeted decision aids could improve the financial risk taking of older adults (Samanez-Larkin, Wagner, & Knutson, 2011b). We found that presentation of explicit expected value information (either in the form of a graphical representation of all trial outcomes or a summary measure of prior and projected earnings) improved decision making in both younger and older adults. Remarkably, providing expected value information improved the performance of older adults to match that of younger adults at baseline (Figure 3C). These findings imply that providing simplified information about expected value may improve financial decision making across the adult life span. Similar benefits of "informed" choice have also been reported in children (Van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012).

Although these results are encouraging, this research is many steps away from broad implementation outside of the laboratory. Some evidence suggests that these and related behavioral interventions may have limited effectiveness in older individuals. For example, describing an expected value computation strategy and exposure to repeated training with this strategy evokes less behavioral change in older than in younger adults (Westbrook, Martins, Yarkoni, & Braver, 2012), since older adults tend to shift away from the suggested strategy over time. Research has yet to clarify whether this shift away from a suggested strategy is related to memory decay or a subjective perception that the suggested strategy lacks efficacy.

New decision strategies may prove more difficult to train after a lifetime of experience with other strategies. In fact, in old age it may be more adaptive for individuals to stick with simpler strategies (Worthy & Maddox, 2012). Some evidence suggests that in many real world decision scenarios, more simple (or "satisficing") strategies do not diminish decision quality for older individuals (Mata & Nunes, 2010). Importantly, the extent to which age differences in decision quality emerge in the real world depends on the context or environment in which the decisions are made (Mata et al., 2012).

Although decision aids (Samanez-Larkin, Wagner, & Knutson, 2011b; Van Duijvenvoorde et al., 2012) may provide more reliable support than strategic training, they may be more limited in application. In many real-world circumstances, prior outcomes and expected values cannot be easily recorded, computed, or displayed. However, precise computations of value may not be required in most scenarios. In fact, some have argued that getting the gist rather than exact verbatim details is most critical in real-world scenarios (e.g., (Reyna & Farley, 2006; Reyna & Lloyd, 2006). Overall, initial findings seem promising enough to imply that experimentally-informed implementation of decision aids at a broader societal level represents a viable long-term research goal.

Extending Findings to the Real World

An important focus of our research on reward processing, reward learning, risky decision making, and aging involves extending performance measures from the laboratory to the real world. Interestingly, individuals who make fewer "mistakes" in our laboratory financial investment task (or more choices in line with those of a risk-neutral, Bayesian-updating actor) also accumulate more assets in the real world (Samanez-Larkin et al., 2010). In a related probabilistic learning task, we found that individual differences in learning to acquire gains were associated with accumulation of financial assets, whereas individual differences in learning to avoid losses were distinctly associated with avoidance of financial debt —which was reflected in individuals' credit scores (Knutson, Samanez-Larkin, & Kuhnen, 2011). Findings from this study also indicated that overall probabilistic learning ability was associated with a more general measure of financial well being — the debt-to-asset ratio (Knutson et al., 2011), and all of these effects remained significant after controlling for age and intelligence quotient. These studies not only provide evidence for the ecological validity of laboratory-based incentive tasks, but also may help to identify individuals with specific vulnerabilities that compromise financial decision making in the real world (Denburg et al., 2007). Unfortunately, older adults are disproportionately targeted by financial fraud (SaveAndInvest.org*Fighting Fraud 101*, 2011). In current work, we are studying older individuals who are at heightened risk for making financial mistakes based on prior fraud victimization. We are also examining how potential vulnerability to financial fraud may relate to affective or cognitive individual differences in neural activity and behavior across adulthood.

Conclusions

In summary, basic motivational processes and associated brain function appear to remain relatively intact across much of adulthood and into old age (Samanez-Larkin, 2010; Samanez-Larkin & Carstensen, 2011). In simple incentive processing tasks with low cognitive demands, younger and older adults show similar patterns of subcortical activity. In risky decision making tasks, contrary to societal stereotypes, risk tolerance appears relatively stable across adulthood (Mata et al., 2011) with some evidence that individual differences may increase later in life (Eppinger & Kray, 2011; Spaniol & Wegier, 2012). Rather than systematically increasing with age, suboptimal risky decisions in older adults seem more linked to cognitive demands of particular decision scenarios. Subcortical regions like the ventral striatum that reliably activate in reward tasks with low cognitive demands begin to show irregular activity in decision tasks with higher cognitive demands. Related studies of broader network structure suggest that these specific decision impairments may relate more closely to circuit dysfunction in general, and to frontostriatal connectivity in particular (Samanez-Larkin et al., 2012).

Taken together, these and other findings suggest that aging does not uniformly degrade decision making. Many studies find little evidence of declining decision quality in either some or all older adults compared to younger adults (Samanez-Larkin, 2011). Future research should explore both contexts in which older adults may show suboptimal choice as well as situations in which decision making remains stable or even improves with age (Y. Li et al., 2011; Löckenhoff, 2011; Strough et al., 2011). Future research should also strive to establish the ecological validity of laboratory findings. Currently, few studies have directly examined adult age differences in risky economic decision making in the real world (Agarwal, Driscoll, Gabaix, & Laibson, 2009; Korniotis & Kumar, 2011; Mata & Nunes, 2010). Researchers can and should integrate laboratory measures (including brain imaging) with real-world measures of decision making to more fully characterize how decision making changes across the life span.

Although the research reviewed here encompasses a broad range of processes, the field is still young, and will surely continue to grow in coming years. An integrative decision neuroscience approach has tremendous potential to have both scientific and societal impact. Given the current and unique moment in human history in which demographic changes are drastically increasing the age of decision makers around the globe, scientists have the potential to make major contributions to improving the well being of humans of all ages.

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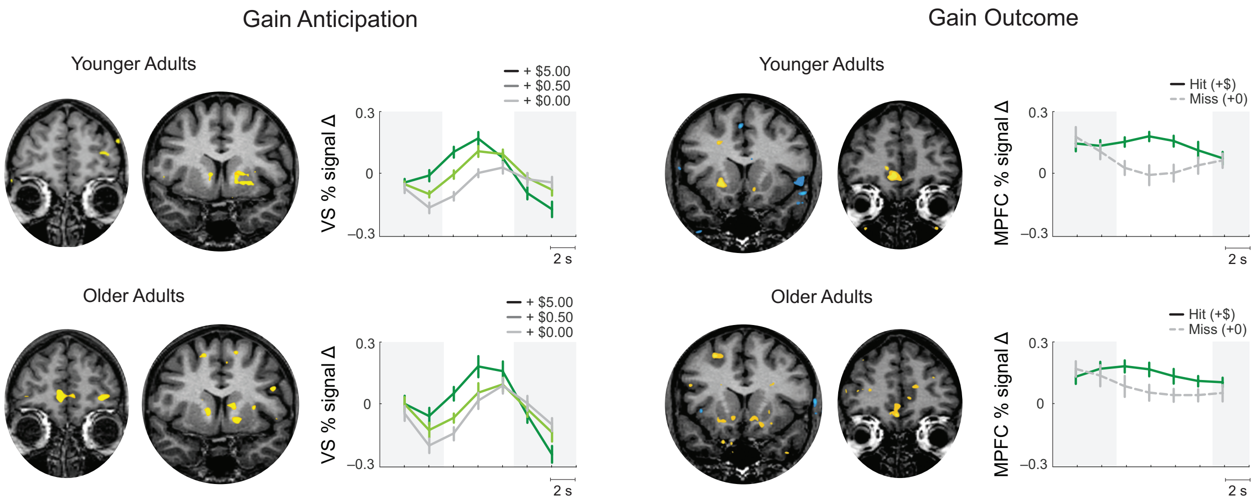
Figure Captions

Figure 1. Ventral striatal functional activity is modulated by magnitude during anticipation of monetary gains in both younger and older adults (left panel). Medial prefrontal regions show similar differences in signal change between gain and nongain outcomes in both younger and older adults (right panel). All statistical brain maps displayed are thresholded at $p < .0001$ uncorrected. All error bars on timecourses are s.e.m.

Figure 2. Functional activity in the caudate and insula is modulated by magnitude during anticipation of monetary gains in younger but not older adults (left panel). In contrast, medial prefrontal and ventral striatal regions show similar differences in signal change between nonloss and loss outcomes in both younger and older adults (right panel). All statistical brain maps displayed are thresholded at $p < .0001$ uncorrected. All error bars on timecourses are s.e.m.

Figure 3. In a risky financial investment task (N=110), older adults make more mistakes when choosing assets that are probabilistically associated with rewards (selection of stocks) but do not differ from younger adults in risk aversion (selection of bonds). These behavioral age differences were associated with increased neural variability with age in the striatum (N=53). Statistical maps are thresholded at $p < .0001$, uncorrected. In a follow-up study we found that decision aids which provided a visual depiction of the running history of prior outcomes (discrete value: DV) or a summary of prior performance and prediction of future performance (integrated value: IV) increased performance in older adults to the performance level of younger adults at baseline (BL). Figure is adapted from Samanez-Larkin et al 2010; 2011.

Figure 4. White matter integrity from the thalamus to the medial prefrontal cortex (left, blue) and the medial prefrontal cortex to the ventral striatum (right, green) is associated with both age and reward learning performance. Figure is adapted from Samanez-Larkin et al 2012.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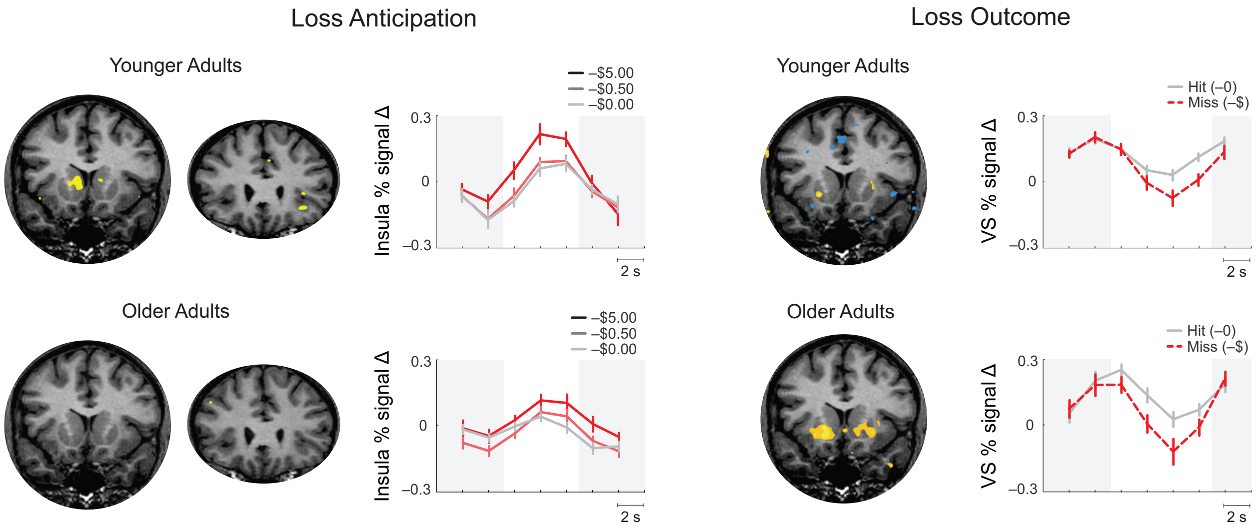
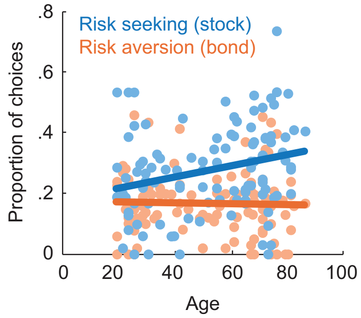


Loss Anticipation

Loss Outcome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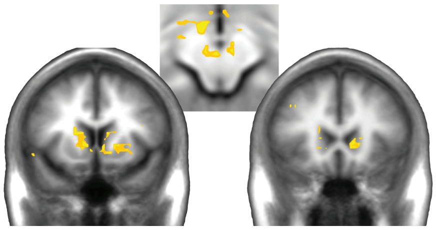

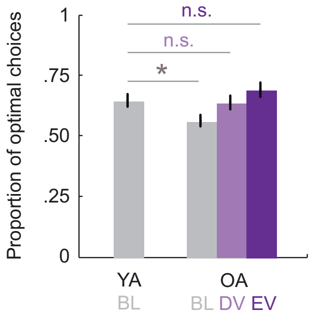
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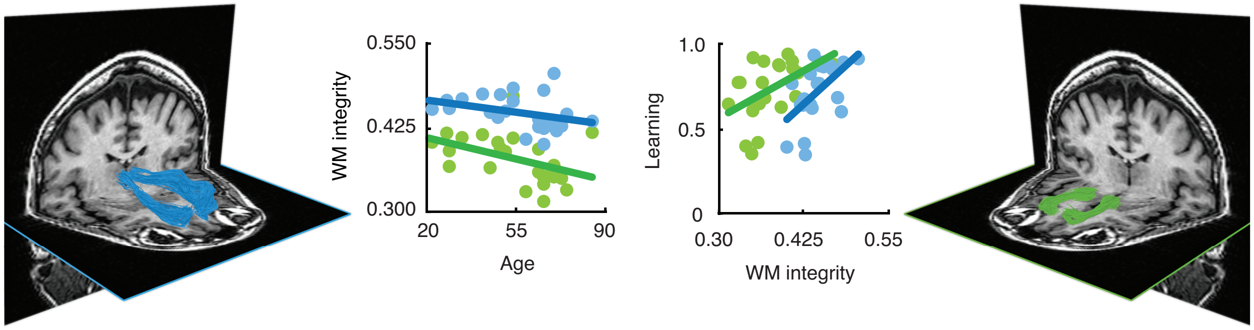
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