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# Observer

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## Financial Decision Making and the Aging Brain

By [Gregory R. Samanez-Larkin](#)

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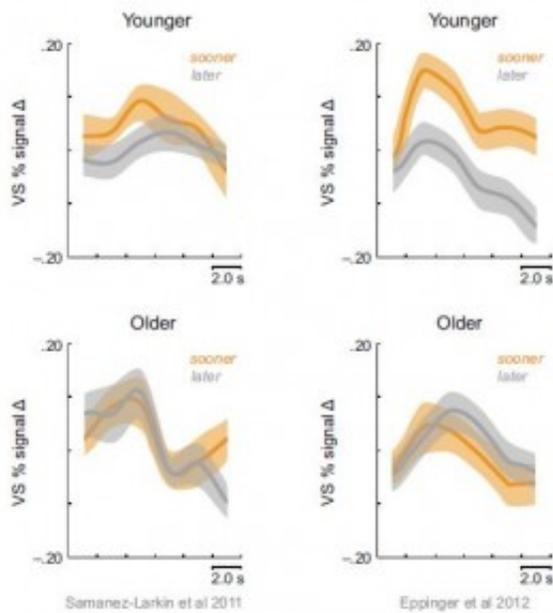


Many of the most influential financial decision makers in our society from business to politics happen to be middle-aged. The average age of Fortune 500 chief executive officers and chief financial officers is around the mid-fifties. Historically, the average appointment age of Federal Reserve Chairs and National Economic Council Directors is also in the fifties. The number is not an artifact of averaging; all current members of the Council of Economic Advisers and half of the National Economic Council members are fifty-something. Is there some sort of peak of financial reason in the fifties? Recent research in economics, psychology, and neuroscience suggests that there may be.

In an analysis of financial mistakes across a range of credit behaviors (e.g., suboptimal balance transfers, fee payments, etc.), a recent paper identified the age around where mistakes are minimized as 53 (Agarwal, Driscoll, Gabaix, & Laibson, 2009). Heavily influenced by classic work in the psychology of aging on fluid and crystallized intelligence (Horn & Cattell, 1967), the authors presented a model of how financial decision-making performance may be influenced by divergent changes in cognitive abilities over adulthood. The idea is that the youngest and oldest decision makers make mistakes for different reasons. The young are cognitively robust but inexperienced; the elders can draw on a lifetime of experience but are limited in some fluid cognitive abilities. The peak in middle age is at a sweet spot where individuals have not suffered much fluid decline but also have decades of life experience.

Importantly, the evidence is not limited to credit behavior. In general, increases in risky financial mistakes at older ages have been linked to limitations in fluid cognitive ability and age differences in frontostriatal network structure and function. A meta-analysis of behavioral studies on risky decision making and aging reveals the largest age differences for decisions that depend on learning in a novel environment (Mata, Josef, Samanez-Larkin, & Hertwig, 2011). A series of recent neuroimaging studies has focused on age differences in risky financial decision making (Samanez-Larkin & Knutson, 2014). These studies have shown that subcortical regions like the ventral striatum, which reliably activate in older adults in simple reward tasks (Samanez-Larkin et al., 2007), show irregular functional activity in old age in decision tasks that depend on recent learning (Chowdhury et al., 2013; Samanez-Larkin, Kuhnen, Yoo, & Knutson, 2010). Evidence from structural imaging suggests that the learning-related decision impairments and neural signal irregularities are associated with reduced white matter integrity in frontostriatal circuits (Chowdhury et al., 2013; Samanez-Larkin, Levens, Perry, Dougherty, & Knutson, 2012). Together, the findings suggest that basic striatal function may remain preserved over adulthood, but that broader network disruption may underlie the fluid cognitive limitations on making wise decisions in an uncertain and novel environment. Based on these findings, studies are beginning to test various “decision aids” that may provide

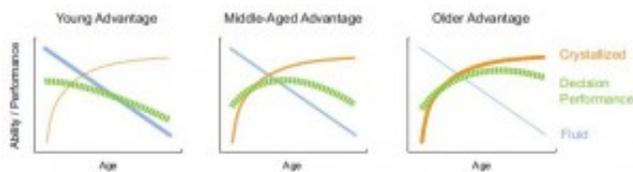
external environmental support to compensate for limitations in fluid cognition (Samanez-Larkin, Wagner, & Knutson, 2011b).



**Figure 1. In two recent studies, young adults show reduced activation of the ventral striatum (VS) for delayed rewards (grey) compared to rewards available now (orange), whereas this oversensitivity to immediacy was not present in older adults. Older adults showed equivalent activation of the VS for rewards available at short and long delays. Figures adapted from Samanez-Larkin et al. (2011) and Eppinger et al. (2012).**

However, in many situations, crystallized intelligence compensates for reduced fluid cognitive abilities without the need for external environmental support. There is growing evidence of preservation or even improvement in old age for decisions that depend on accumulated life experience (Li, Baldassi, Johnson, & Weber, 2012). One example is intertemporal choice. A review of the behavioral literature reveals that older adults are often more willing to wait over short-time delays for a larger amount of money compared to a smaller amount of money available immediately (Löckenhoff, 2011). Recent neuroscience research suggests that the accumulation of experience with delayed rewards over the life span may serve to tune activity in regions like the ventral striatum. In two recent datasets, the strong sensitivity to immediately available rewards in the striatum in young adulthood is reduced in older age (Figure 1); older adults show similar activity for rewards available now or later (Eppinger, Nystrom, & Cohen, 2012; Samanez-Larkin et al., 2011a). One interpretation is that it is as if the older folks know that \$20 is going to be just as good in two weeks as it is today. The twenty-somethings just haven't had the opportunity to realize interest rates over decades and appreciate the long-term rewards of waiting. This may be a situation where we should be trying to get those impatient young people to make decisions more like the older folks. A fascinating series of recent studies is doing just that; increasing the connectedness of younger people to their older selves (e.g., using virtual reality) reduces temporal discounting and increases savings in early

life (Hershey, 2011).



**Figure 2. Fluid cognitive abilities decline across adulthood (blue line) while crystallized cognitive abilities improve (orange line). The dependence of decision performance (green line) on these two sets of abilities varies across contexts. For decisions that require flexible learning in a new situation (fluid), older adults may be at a disadvantage (left). When decisions can be made largely based on knowledge and experience (crystallized) older adults may make better decisions than young adults (right). Figure concept adapted from Agarwal et al. (2009).**

The evidence for declines in learning-based risky decisions and improvement in intertemporal decisions in old age is consistent with the model Agarwal and colleagues adapted from Horn and Cattell. It also suggests that the model can be flexibly adapted to explain decision behavior across a range of contexts. Decision-performance differences across adulthood are heavily dependent on the specific cognitive demands or opportunities for drawing on prior knowledge in different contexts (Mata et al., 2012). An extension of the model from Agarwal and colleagues suggests that in situations that are more dependent on fluid ability, performance will be worse in old age; in situations with greater opportunity to rely on crystallized skills, performance will be better in old age (Figure 2).

In addition to identifying potential psychological and neural mediators of age differences in financial decision making, an emerging focus of research in this area has been to examine how well behavior in the lab or the brain scanner is related to decision making in everyday life. Several studies have linked performance on laboratory tasks to measures of financial well-being in everyday life such as accumulated assets, avoidance of debt, debt-to-assets ratio, and credit scores (Knutson, Samanez-Larkin, & Kuhnen, 2011; Kuhnen, Samanez-Larkin, & Knutson, 2013; Samanez-Larkin et al., 2010). Assessing the ecological validity of these laboratory-based tasks should greatly enhance our ability as scientists to make predictions about everyday behavior and in doing so help to identify individuals who may be especially vulnerable to making poor financial decisions (Denburg et al., 2007).

Combining the traditional focus on decisions in everyday life from economics and finance (Agarwal et al., 2009; Korniotis & Kumar, 2011) with detailed analysis of brain and behavior from psychology and neuroscience (Samanez-Larkin & Knutson, 2014) has led to the emergence of a truly multidisciplinary subfield of research on decision making across the life span. Although the recent progress is promising, this area is still very much in its infancy. The integrative “decision neuroscience approach” has tremendous potential for scientific and societal impact. If we are successful as scientists, the knowledge that we gain from research can be used on a broad

scale to inform policy decisions and on an individual scale to help people of all ages make better decisions. One promising step in this direction will occur this month (May) when scientists and policymakers gather together for a meeting in Washington, DC, on *Psychological Science and Behavioral Economics in the Service of Public Policy*. The meeting is co-sponsored by the White House Council of Economic Advisers, the White House Office of Science and Technology Policy, the National Institute on Aging at the National Institutes of Health, and the Association for Psychological Science.

We are currently at a unique moment in human history where demographic changes are and will continue to drastically alter the profile of decision makers in the global population. These changes highlight the challenges of (e.g., rising entitlement costs) but also opportunities for a graying population. To the extent that this emerging subfield can respond to the immediate demand for integrative and translational research, we have the potential to make major contributions to improving the well-being of humans across the life span.

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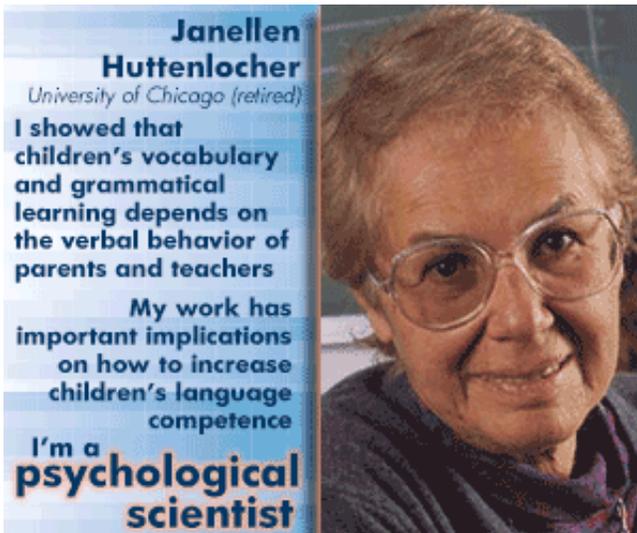
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# Variability in Nucleus Accumbens Activity Mediates Age-Related Suboptimal Financial Risk Taking

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As human life expectancy continues to rise, financial decisions of aging investors may have an increasing impact on the global economy. In this study, we examined age differences in financial decisions across the adult life span by combining functional neuroimaging with a dynamic financial investment task. During the task, older adults made more suboptimal choices than younger adults when choosing risky assets. This age-related effect was mediated by a neural measure of temporal variability in nucleus accumbens activity. These findings reveal a novel neural mechanism by which aging may disrupt rational financial choice.

## Introduction

The increases in life expectancy that occurred during the twentieth century will continue to expand the proportion of older adults in the global population (Hayutin, 2007), magnifying the relative economic impact of their financial decisions (Cairncross, 2007). Despite the growing importance of decision competence in old age (Finucane et al., 2002), little research has focused on how aging might influence financial risk taking. Although popular stereotypes suggest that older adults are more risk averse than younger adults, these stereotypes are not well supported by research (Mather, 2006). Instead, research suggests that, in some situations, older adults may simply make more errors when making risky decisions (Denburg et al., 2007; Peters et al., 2007; Mohr et al., 2009). For instance, in the domain of finance, healthy older investors have been shown to continue to invest in risky assets even after suffering losses in the stock market large enough to necessitate postponing retirement (American Association of Retired Persons, 2002).

Age differences in financial decision making could occur for a number of reasons. Extensive research, for instance, has linked age-related deficits in cognitive ability to diminished neural function in the lateral prefrontal and medial temporal cortex (Hedden and Gabrieli, 2004; Cabeza et al., 2005). Beyond cognitive deficits (e.g., related to executive function or memory), aging might also influence value estimation, which might recruit both cortical (e.g., medial prefrontal cortex) and subcortical (e.g., ventral striatum) regions (Knutson and Bossaerts, 2007). In addition to age-related declines in the structural integrity of the prefrontal cortex

and striatum (Hicks and Birren, 1970; Rubin, 1999; Buckner, 2004; Head et al., 2005; Raz et al., 2005), theoretical accounts propose that aging may compromise dopaminergic modulation of these regions (Li et al., 2001; Braver and Barch, 2002; Bäckman et al., 2006).

Only a few neuroimaging studies have focused on how aging might influence subcortical function in general (Samanez-Larkin and Carstensen, 2010) and striatal function in particular (Aizenstein et al., 2006; Samanez-Larkin et al., 2007; Schott et al., 2007; Dahlin et al., 2008; Dreher et al., 2008; Mell et al., 2009). These emerging findings suggest that, although age may not influence neural responses to explicitly signaled reward cues (Samanez-Larkin et al., 2007) and outcomes (Samanez-Larkin et al., 2007; Cox et al., 2008), age may compromise striatal activity during more cognitively demanding reward tasks (Schott et al., 2007; Mell et al., 2009). Currently, however, no studies have explored age differences in financial decisions related to investments with functional neuroimaging.

Combining computational theories implicating age-related compromises in dopamine function with neuroimaging evidence for altered reward learning, theorists have proposed that “noisy” value signals may bias risky decisions (Li et al., 2007). We tested this proposition by examining whether measures of variance in frontostriatal function might relate to age-related biases in financial risk taking. Specifically, in the context of a financial investment task, we examined whether age might compromise behavioral performance as well as variability in medial prefrontal cortex (MPFC) and nucleus accumbens (NAcc) activity.

## Materials and Methods

**Subjects.** All subjects were recruited by a survey research firm to be ethnically and socioeconomically representative of San Francisco Bay Area residents. Across the age range, subjects were matched on basic demographic variables (socioeconomic status, income, ethnicity). One hundred ten healthy volunteers (mean age, 51.4; range, 19–85 years; 52% female) completed the study. All subjects played an investment task, but 54 of these subjects (mean age, 51.3; range, 21–85 years; 54% female) played the task while undergoing functional magnetic resonance imaging (fMRI). A subset of 38 subjects was specifically not recruited for fMRI as a behavioral control group. Fifty-seven of the remaining 72 adults were

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eligible for fMRI and completed the scan session. Three of these individuals were excluded from fMRI analyses because of a structural abnormality (71-year-old male) or excessive motion (26-year-old male, 74-year-old male).

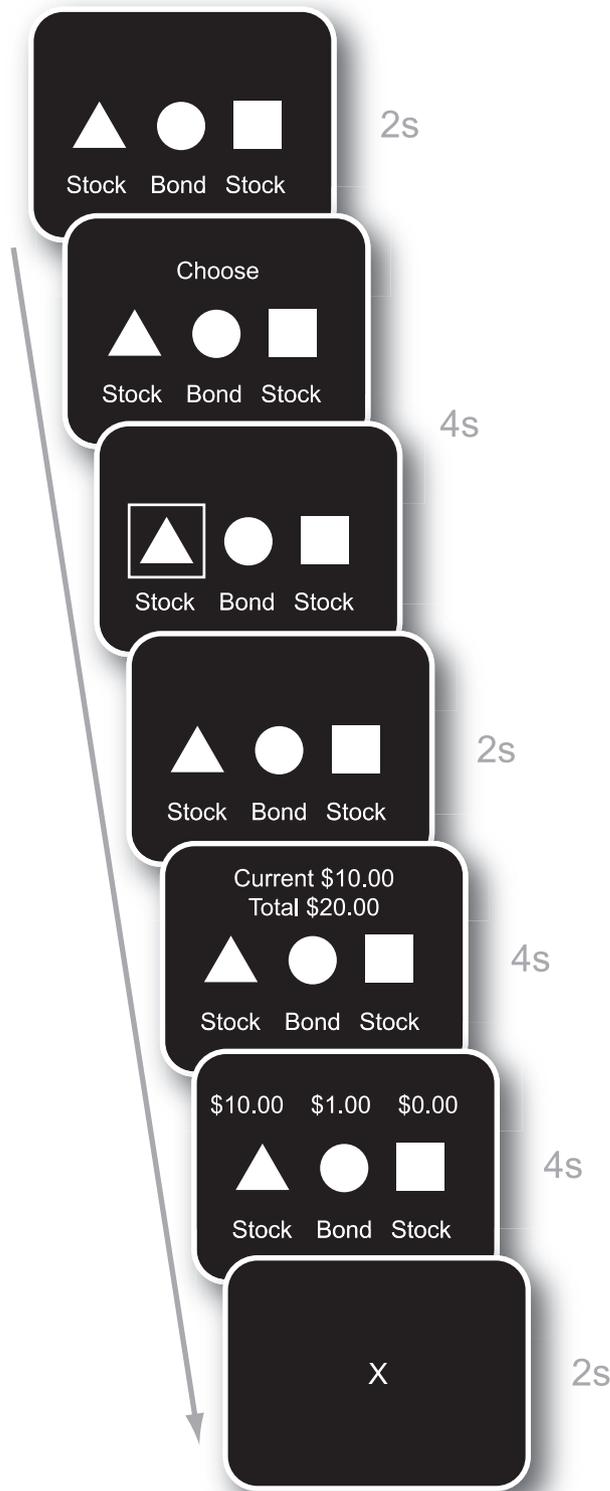
All subjects first played a practice version of the investment task. Subjects were then shown the cash they could earn by performing the task successfully. Subjects received a fixed compensation of \$20 per hour, as well as a tenth of their total earnings during the task. They were also informed that it was possible to lose money on the task and that any losses would be deducted from their total earnings.

**Experimental task.** A slightly modified version of the Behavioral Investment Allocation Strategy (BIAS) task (Kuhnen and Knutson, 2005) was used to elicit a range of investment behaviors from each subject, including both optimal and suboptimal financial choices. Each subject completed 10 blocks of 10 trials each for a total of 100 trials. During each trial, subjects first saw two stocks and a bond (anticipation, 2 s), selected one of these assets when prompted with the word “Choose,” and then viewed their highlighted choice on the screen (choice, 4 s). After a brief delay (wait, 2 s), their earnings for that trial and total earnings were displayed (outcome, 4 s) followed by a display of the outcomes of all assets on that trial (market, 4 s), and finally a fixation cross (fixation, 2 s) (Fig. 1).

At the beginning of each block, the computer randomly assigned one of the two stocks to be the “good” stock, and the other to be the “bad” stock. Subjects were informed that the computer would make these assignments before performing that task but were not informed which stock was assigned to be good and which was assigned to be bad at the beginning of each block. The good stock dominated the bad stock in the sense of first-order stochastic dominance (Huang and Litzenberger, 1988). Specifically, outcomes of the good stock (i.e., +\$10 with 50% probability, +\$0 with 25% probability, and −\$10 with 25% probability) were better than outcomes of the bad stock (i.e., +\$10 with 25% probability, +\$0 with 25% probability, and −\$10 with 50% probability) on average for each trial. The bond paid \$1 with 100% probability on each trial. Earnings were drawn independently from these distributions for each trial. After being shown the distributions, all participants were additionally explicitly told that stock choices were riskier than bonds. For instance, an excerpt from the instructions reads: “Once again, the three assets available to choose from are two stocks and a bond. The stocks are risky, because their earnings can be +\$10, −\$10, or \$0. The bond is riskless, because it always pays \$1.”

**Behavioral analysis.** In the BIAS task, the optimal strategy of a rational, risk-neutral agent is to pick a stock if he or she expects to receive a dividend that is at least as large as the bond earnings. Since the actual monetary amounts at stake in each trial were small (−\$1 to \$1), we used risk neutrality as the baseline model of the rational actor’s behavior. A rational actor should also update his or her beliefs about the probability of each stock being optimal according to Bayes’ rule. Based on these assumptions, we derived the optimal portfolio selection strategy (for model details, see supplemental material, available at [www.jneurosci.org](http://www.jneurosci.org)). This optimal model is identical with that applied in previous research using the BIAS task (Kuhnen and Knutson, 2005). To some extent, individual investors approximated the strategy of the rational actor, suggesting that this model provides a reasonable baseline for group comparisons. Like the rational actor, subjects on average showed an initial preference for bonds at the beginning of each block, and then shifted toward preferring the good stock (supplemental Fig. 1, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material).

For each trial, we compared subjects’ investment choices with those of the rational actor. Choices that deviated from the rational actor’s optimal choices were labeled as suboptimal or “mistakes” and included three types. Risk-seeking mistakes occurred if subjects chose a risky option (i.e., a stock) when the riskless option (i.e., a bond) was the optimal investment. These mistakes tend to occur early within blocks when it is not yet clear which stock is the good stock. Confusion mistakes occurred if subjects chose a risky option (i.e., a stock) when the other risky option (i.e., a stock) was the optimal investment. These mistakes can only be made later within each block when there is enough evidence for the rational actor to distinguish the good from the bad stock. Risk aversion mistakes occurred if subjects chose the riskless option (i.e., the bond)



**Figure 1.** Investment (BIAS) task design. During each trial, subjects first saw two stocks and a bond (anticipation, 2 s), selected an asset when prompted with the word “Choose,” and then viewed their highlighted choice on the screen (choice, 4 s). After a brief delay (wait, 2 s), their earnings for that trial and total earnings were displayed (outcome, 4 s), followed by a display of the outcomes of all assets on that trial (market, 4 s), and finally a fixation cross (fixation, 2 s).

when a risky option (i.e., a stock) was the optimal investment. These mistakes also tend to occur relatively later within blocks when the rational actor has enough evidence to distinguish the good from the bad stock. We explored the effect of age on rational choices as well as on each type of mistake.

**fMRI acquisition and analyses.** Brain images were acquired with a 1.5 T GE Healthcare MRI scanner using a standard birdcage quadrature head coil. Twenty-four 4-mm-thick slices (in-plane resolution,  $3.75 \times 3.75$  mm; no gap) extended axially from the midpons to the top of the skull, providing adequate spatial resolution of subcortical regions of interest (e.g., midbrain, ventral striatum). Functional scans of the whole brain were acquired every 2 s [repetition time (TR), 2 s] with a T2\*-sensitive in/out spiral pulse sequence [echo time (TE), 40 ms; flip,  $90^\circ$ ] designed to minimize signal dropout at the base of the brain (Glover and Law, 2001). High-resolution structural scans were subsequently acquired using a T1-weighted spoiled grass sequence (TR, 100 ms; TE, 7 ms; flip,  $90^\circ$ ), facilitating subsequent localization and coregistration of functional data.

Preprocessing and whole-brain analyses were conducted using Analysis of Functional Neural Images (AFNI) software (Cox, 1996). For preprocessing, voxel time series were sinc interpolated to correct for nonsimultaneous slice acquisition within each volume, concatenated across runs, corrected for three-dimensional motion, slightly spatially smoothed (full width at half-maximum, 4 mm), and high-pass filtered. Statistical maps for individual subjects were coregistered with structural maps, spatially normalized by warping to Talairach space (using manual placement of landmarks in single subjects), and transformed into  $Z$  scores. Whole-brain thresholds for statistical significance were set at  $Z > 3.888$ ,  $p < 0.0001$ , with a required cluster size of eight contiguous 2 mm resampled voxels.

**Outcome analyses.** Preprocessed time series were submitted to a regression model that included three regressors indexing residual motion and six regressors modeling baseline, linear, and quadratic trends for each of the two runs. Regressors of interest were convolved with a  $\gamma$ -variate function that modeled a canonical hemodynamic response before inclusion in the regression model (Cohen, 1997). For whole-brain outcome analyses, regressors of interest contrasted stock versus bond choice, as well as gain versus loss outcomes after stock choices. The model also included covariate regressors representing cumulative earnings (defined as current wealth earned during the task, updated at each outcome period) and current trial uncertainty (updated at each market period). For each trial, “uncertainty” referred to the minimum of the objective probabilities (computed using Bayes’ rule) of the two individual stocks being dominant.

**Temporal variability analyses.** In the present study, we used a statistic called the mean squared successive difference (MSSD) (von Neumann et al., 1941) to index the temporal variability (or lability) of fMRI activation. Although this statistic has been used to assess temporal variability of both self-report measures of affect (Woyshville et al., 1999; Jahng et al., 2008) and physiological measures of heart rate variability (Owen and Steptoe, 2003; Berntson et al., 2005), it has not been previously applied to neuroimaging data. MSSD approximates variance but, here, more precisely indexes a lack of temporal specificity of neural activation by computing the variability of the signal from one brain acquisition to the next. For each subject, we calculated the MSSD over the entire preprocessed, detrended, and normalized activation time course averaged and extracted from each of four volumes of interest (VOIs): (1) NAcc, (2) anterior caudate, (3) MPFC, (4) and anterior insula. Given the importance of testing for mediation in evaluating theories of aging (Salthouse, 2006), we then used individual MSSD estimates in a mediation analysis exploring the relationship between age and investment mistakes (Baron and Kenny, 1986). We examine mediation effects both across adult age and within narrow age ranges (Lindenberger and Pötter, 1998; Hofer et al., 2006). Before the mediation analysis, outliers were identified by averaging the MSSD from all four VOIs and excluding individuals  $>3$  SDs away from the mean. One subject (70-year-old male) was identified as an outlier and excluded from the temporal variability analyses. Analyses were conducted on the remaining 53 subjects.

**VOI definition.** VOIs were anatomically specified with 6-mm-diameter spheres in individual subjects based on clusters of activation identified in previous research and based on specific anatomy. The NAcc was defined anatomically (Knutson et al., 2008). The anterior caudate was defined based on the primary cluster of activation from a previous probabilistic learning study that characterized this region as the “actor” in the actor–critic reinforcement learning model (O’Doherty et al., 2004;

Balleine et al., 2007). The other two regions used in the analyses were anatomically defined based on functional effects observed in previous studies in the MPFC (Knutson et al., 2003; Samanez-Larkin et al., 2007) and anterior insula (Samanez-Larkin et al., 2007, 2008). VOI data were used for the temporal variance analyses (described above) and to generate seed time courses for the functional connectivity analyses (described below). For sample VOI placement in four individuals, see supplemental Figure 2 (available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material).

**Functional connectivity analyses.** Using the right NAcc VOI as a seed, functional connectivity analyses examined age and performance differences in frontostriatal connectivity (Draganski et al., 2008) during both anticipation and outcome phases of the task (Rissman et al., 2004). One regression model examined age differences in connectivity and a second regression model examined relationships between individual differences in risk-seeking mistakes and connectivity (controlling for age).

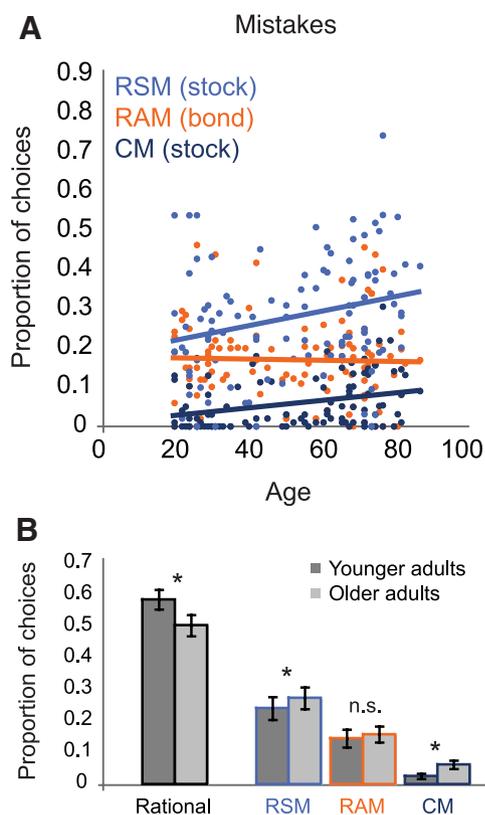
**Methodological issues related to age differences.** In all analyses, special care was taken to minimize potential confounds associated with age differences (Samanez-Larkin and D’Esposito, 2008). Each individual was screened for dementia and their structural and functional brain imaging data were inspected for abnormalities. Each individual’s brain was warped into Talairach space with reference to hand-placed anatomical landmarks. Additionally, all VOIs were anatomically defined on each individual’s anatomical images, ensuring that equal amounts of data would be extracted from gray matter in each region for each subject. In this particular study, we did not include a separate hemodynamic response function control (such as hypercapnia or a primary sensory task), but in previous studies examining age differences in striatal regions with similar samples we have included these controls [Samanez-Larkin et al. (2007), their supplemental data], and they did not reveal striking age differences. However, group differences in hemodynamics cannot account for the present effects because similar responses to outcomes were observed across age in the striatum and prefrontal cortex (see Results).

## Results

### Behavioral results

Providing evidence for the ecological validity of behavioral performance in the investment task, a regression analysis revealed a significant relationship between rational choices (i.e., choices that matched the rational actor model) in the BIAS task and the accrual of real-world financial assets, after controlling for debts and age (supplemental Table 2 and supplemental Fig. 3, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material). Subjects who made a higher proportion of rational choices in the investment task also reported accumulating more real-world wealth. Although working memory function [as measured by Letter–Number Sequencing (Wechsler, 1997)] was also correlated with assets ( $\beta = 0.246$ ;  $t = 2.08$ ;  $p < 0.05$ ), the relationship between rational choices and assets held ( $\beta = 0.203$ ;  $t = 2.20$ ;  $p < 0.05$ ) after controlling for this index of working memory as well as two other measures of individual differences in cognitive ability [i.e., Digit Span (Wechsler, 1997) and the Trail-Making Test (Delis et al., 2004)].

Rational choices in the task decreased with age. Conversely, investment mistakes in the BIAS task increased with age, as indicated by a significant main effect of age on suboptimal choices ( $\beta = 0.339$ ;  $t = 3.75$ ;  $p < 0.0001$ ). The effect of age on suboptimal choices remained significant ( $\beta = 0.265$ ;  $t = 2.36$ ;  $p < 0.05$ ) after controlling for education, numeracy (Lipkus et al., 2001), and performance on Letter–Number Sequencing, Digit Span, and Trail-Making Test. Of these mistakes, however, risk-seeking mistakes ( $\beta = 0.238$ ;  $t = 2.55$ ;  $p < 0.05$ ) and confusion mistakes ( $\beta = 0.293$ ;  $t = 3.18$ ;  $p < 0.05$ ) specifically increased with age, whereas risk aversion mistakes did not ( $\beta = -0.026$ ;  $t = -0.27$ ;  $p = 0.79$ ) (Fig. 2A). When including both linear and quadratic effects of age in the model, the linear effects remained the same but no qua-



**Figure 2.** Age-related increase in risky investment mistakes. **A**, Age was associated with increased risk-seeking mistakes (RSM) and confusion mistakes (CM), but not risk aversion mistakes (RAM). **B**, A subset of younger and older subjects who were not recruited for fMRI showed the same behavioral results. \*Significant difference between age groups ( $p < 0.05$ ). Error bars represent SEM.

dratic effects were significant (all  $p > 0.25$ ). Thus, we only report linear effects of age in subsequent analyses.

Although the present community sample was selected to be representative of the demographics of the San Francisco Bay Area, selection may have occurred for the subset of subjects that participated in scanning (e.g., for more risk-seeking individuals). Thus, we ran a follow-up behavioral analysis of age differences in financial risk taking in the subgroup of 19 younger adults (aged 19–30) and 19 older adults (aged 65–81) who did not undergo fMRI. These subjects were only recruited to participate in a behavioral version of the task and no mention of scanning was made to them at any time during recruitment or completion of the study (based on the small sample size and directional predictions, one-tailed tests are reported). In this subset of subjects, the same pattern appeared. Relative to younger adults, older adults made significantly fewer rational choices ( $t_{(36)} = -2.03; p < 0.05$ ), and more risk-seeking mistakes ( $t_{(36)} = 1.47; p < 0.05$ ) and confusion mistakes ( $t_{(36)} = 1.64; p < 0.05$ ), but did not differ in terms of risk aversion mistakes ( $t_{(36)} = 0.46; p = 0.33$ ) (Fig. 2B).

Although older adults made more mistakes when choosing stocks because of both excessive risk seeking and confusion, risk-seeking mistakes occurred much more frequently than confusion mistakes across the entire sample of 110 adults. Specifically, risk-seeking mistakes comprised 32% of choices in the oldest third of subjects aged 67–85 and 24% in the youngest third aged 19–35, whereas confusion mistakes comprised 8% in the oldest third and 3% in the youngest third. Because of the low incidence of confusion mistakes, the following results focus on explaining age differences in risk-seeking mistakes.

**Table 1.** Neural activation during monetary outcomes: gain versus loss outcomes across all subjects (controlling for age)

Region	R	A	S	Z	Voxels
L medial frontal gyrus/cingulate	−10	46	0	4.423	16
R middle frontal gyrus	28	38	−12	3.892	8
L putamen/nucleus accumbens	−14	10	−8	5.678	248
R putamen/nucleus accumbens	14	4	−4	4.976	192
R posterior cingulate gyrus	10	−36	34	4.405	24
R posterior cingulate gyrus	4	−40	26	4.942	140

L, Left; R, right; A, anterior; S, superior.

Z > 3.888;  $p < 0.0001$ ; eight voxel cluster threshold.

**Neuroimaging results**

Neuroimaging analyses sought to identify neural markers that could account for the age differences in investment decision making in the subset of individuals who underwent fMRI. One simple account might posit that age diminishes the strength of neural responses to feedback, which then compromises subsequent reward prediction and choice selection. To examine this possibility, we compared subjects’ neural responses to monetary outcomes. Across all subjects, activation in the MPFC, NAcc, anterior caudate, and posterior cingulate (Table 1) increased in response to monetary gain (+\$10) versus loss (−\$10) outcomes (Fig. 3). An age by outcome interaction revealed significantly greater neural sensitivity to outcomes in older adults in the inferior frontal and temporal gyri (Table 2), but responses to outcomes in the MPFC, NAcc, and anterior caudate did not differ as a function of age. Individual difference analyses evaluated whether sensitivity to outcomes could account for age-related investment mistakes, but none of the regions that showed age-related effects were significantly associated with risk-seeking mistakes (supplemental Fig. 4 and supplemental Table 3, available at www.jneurosci.org as supplemental material). Follow-up VOI analyses confirmed this absence of effects by demonstrating that measures of neural sensitivity to outcomes were not significantly correlated with risk-seeking mistakes after controlling for age in the MPFC, NAcc, or anterior caudate (all  $p > 0.33$ ). Thus, age-related neural responses to feedback could not account for the observed age-related increases in risk-seeking mistakes.

Although mean anticipatory activity in the NAcc predicted risky (i.e., stock) choices on individual trials (supplemental Table 4) replicating previous findings in younger adults only (Kuhnen and Knutson, 2005), mean activity in the NAcc did not predict risk-seeking mistakes ( $p = 0.36$ ) in this sample that spanned the adult life span.

By an alternative account, temporal variability in NAcc activation might generate mistakes in risky financial decision making (Li et al., 2007). Specifically, if NAcc activation primarily promotes financial risk seeking and becomes noisy (yet not necessarily diminished), this could promote risk-seeking mistakes. We tested this hypothesis by examining whether temporal variability in NAcc activity mediated the relationship between aging and risk-seeking mistakes. As described above, age was associated with risk-seeking mistakes in the subset of subjects who underwent fMRI ( $\beta = 0.310; t = 2.23; p < 0.05$ ) (Fig. 4A). Whole-brain analyses revealed that temporal variability (MSSD) increased with age primarily in the NAcc and anterior caudate but not the MPFC. Although the largest cluster had a peak voxel in the thalamus (Table 3), additional peaks within this cluster also appeared in the NAcc and anterior caudate (Fig. 4B). Variability also increased with age in several additional smaller clusters in the midbrain and lateral frontal and parietal cortices (Table 3).

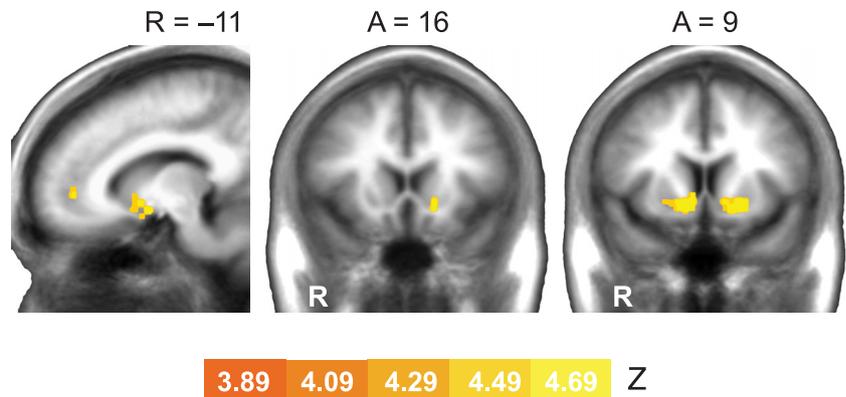
Follow-up mediation analyses were conducted with temporal variability estimates drawn from each VOI. Age was associated with increased temporal variability in the right NAcc ( $\beta = 0.490$ ;  $t = 3.13$ ;  $p < 0.005$ ). Controlling for age, increased temporal variability in the NAcc was associated with increased risk-seeking mistakes ( $\beta = 0.260$ ;  $t = 2.47$ ;  $p < 0.05$ ). After simultaneous entry of age and NAcc temporal variability into the regression, age no longer significantly predicted risk-seeking mistakes ( $\beta = 0.182$ ;  $t = 1.18$ ;  $p = 0.12$ ), consistent with full mediation of age-related financial risk-seeking mistakes by NAcc temporal variability (Fig. 4C). The relationship between NAcc variability and risk-seeking mistakes remained significant ( $\beta = 0.268$ ;  $t = 2.67$ ;  $p < 0.05$ ) after controlling for education, numeracy, and performance on Letter–Number Sequencing, Digit Span, and Trail-Making Test, in addition to age.

A similar, but weaker, effect was observed in the left anterior caudate. Age was also associated with increased temporal variability in the left anterior caudate ( $\beta = 0.566$ ;  $t = 4.48$ ;  $p < 0.0001$ ). After controlling for age, anterior caudate temporal variability was marginally associated with increased risk-seeking mistakes ( $\beta = 0.286$ ;  $t = 1.91$ ;  $p = 0.06$ ), and simultaneous entry of age and anterior caudate temporal variability into the regression revealed that age no longer significantly predicted risk-seeking mistakes ( $\beta = 0.148$ ;  $t = 0.96$ ;  $p = 0.34$ ). The relationship between anterior caudate variability and risk-seeking mistakes was similar ( $\beta = 0.270$ ;  $t = 1.77$ ;  $p = 0.09$ ) after controlling for education, numeracy, and performance on Letter–Number Sequencing, Digit Span, and the Trail-Making Test in addition to age.

When splitting the sample into thirds by age, the strength of the variability effect appeared to increase with age. Specifically, the relationship between NAcc variability and risk-seeking mistakes (controlling for age) was strongest in the oldest third ( $N = 18$ ) of the sample ( $\beta = 0.449$ ;  $t = 2.29$ ;  $p < 0.05$ ). There was a trend effect for the middle third of the sample ( $N = 17$ ) ( $\beta = 0.468$ ;  $t = 1.77$ ;  $p < 0.10$ ), and a nonsignificant effect for the youngest third of the sample ( $N = 18$ ) ( $\beta = 0.062$ ;  $t = 0.24$ ;  $p = 0.81$ ). This weaker effect in the younger adults is likely attributable to this group's relative lack of measurable neural decline and consequent limited temporal variability.

Importantly, these mediation effects could not be attributed to global increases in temporal variability, since substitution of temporal variability from other brain regions into the model (e.g., left or right MPFC or insula) did not reveal significant associations with risk-seeking mistakes, controlling for age (all  $p > 0.33$ ). Additionally, temporal variability (MSSD) over the task was a better predictor of risk-seeking mistakes than simple variance of the signal at distinct task phases, since substitution of NAcc signal variance did not predict risk-seeking mistakes (controlling for age) during either anticipation ( $p = 0.24$ ) or outcome ( $p = 0.11$ ).

Functional connectivity analyses explored the possibility that age-related declines in frontostriatal connectivity might also contribute to financial risk-seeking mistakes. Although functional connectivity between the rostral anterior cingulate cortex and NAcc decreased with age both during anticipation (supplemental



**Figure 3.** Mesolimbic regions discriminate gain versus loss outcomes. Across all subjects (controlling for age), regions of the medial prefrontal cortex, caudate, putamen, and nucleus accumbens showed greater activation in response to monetary gains than losses (Table 1). Sensitivity to outcomes in these regions did not vary with age (Table 2). Anatomical underlay is an average of all subjects' spatially normalized structural scans.

**Table 2.** Neural activation during monetary outcomes: effects of age on gain versus loss outcomes

Region	R	A	S	Z	Voxels
L inferior frontal gyrus	−32	16	−12	4.039	16
R superior temporal gyrus	58	−10	4	−4.585	16
L superior temporal gyrus	−62	−44	18	3.923	8
R middle temporal gyrus	46	−66	22	4.168	16

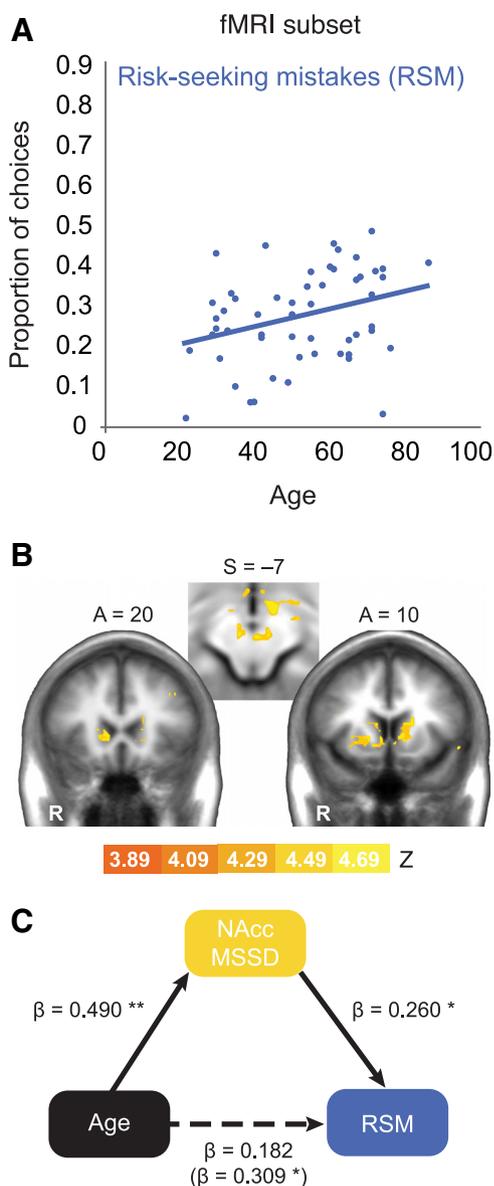
Positive Z scores indicate greater sensitivity to the difference between monetary gains and losses in older adults. L, Left; R, right; A, anterior; S, superior.

Z > 3.888;  $p < 0.0001$ ; eight voxel cluster threshold.

Fig. 5A and supplemental Table 5A, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material) and outcome periods (supplemental Fig. 5B and supplemental Table 5B, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material), functional connectivity between these regions was not significantly associated with risk-seeking mistakes (controlling for age). Functional connectivity with other regions also did not correlate with risk-seeking mistakes at the initial whole-brain threshold. At a less stringent statistical threshold ( $p < 0.005$ ), reduced functional connectivity between the insula/inferior frontal gyrus and NAcc was associated with increased risk-seeking mistakes (supplemental Fig. 5C and supplemental Table 5C, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material). Since functional connectivity between these regions did not vary with age, however, it could not account for specific age-related increases in financial risk-seeking mistakes.

## Discussion

The present study investigated age differences in behavior and neural activity in a large community sample of healthy adults as they participated in a dynamic investment task [i.e., the BIAS task (Kuhnen and Knutson, 2005)]. The BIAS task allows comparison of subjects' actual investment choices with those of a "rational" risk-neutral actor who maximizes expected value. Although this investment task is an abstract version of financial decision making, it appears to have some ecological validity. Individuals who make more rational choices in the laboratory also report having accrued more assets in the real world. Despite the growing popularity of laboratory-based financial decision-making tasks, to the best of our knowledge, this represents the first validation of an experimental investment task with real-world financial outcomes. Using this investment task, we found that older adults made more risk-seeking mistakes, and these mistakes were medi-



**Figure 4.** Nucleus accumbens variability mediates age-related risk-seeking mistakes. **A**, Age was associated with increased risk-seeking mistakes (RSM) in the fMRI subject subset. **B**, Temporal variability (MSSD) increased with age throughout the midbrain and striatum with peaks in the substantia nigra, ventral tegmental area ( $S = -7$ ), anterior caudate ( $A = 20$ ), putamen, medial caudate, and the nucleus accumbens ( $A = 10$ ). Anatomical underlay is an average of all subjects' spatially normalized structural scans. **C**, Variability in the right NAcc fully mediated the relationship between age and RSM; the relationship between age and RSM became insignificant after adding NAcc variability to the model (0.309–0.182; path coefficients are standardized  $\beta$  values).

ated by increased temporal variability in the NAcc. The findings thus indicate an age-related subcortical deficit that may promote risky decision-making mistakes.

Although behavioral research does not suggest that aging impairs decision making overall (Mather, 2006), some findings suggest that aging may bias financial decisions (Denburg et al., 2007; Peters et al., 2007; Mohr et al., 2009). In fact, consistent with the present findings, behavioral studies have found that some older adults will persistently choose a risky asset with a negative expected value over a less risky asset with a positive expected value (Denburg et al., 2005), providing additional evidence for age-related impairments in updating expected value estimates (Mell

**Table 3.** Age-related increase in temporal variability

Region	R	A	S	Z	Voxels
L middle frontal gyrus	-21	53	16	4.267	16
R middle frontal gyrus	31	47	20	4.261	13
R anterior cingulate	7	39	6	4.397	12
L middle frontal gyrus	-41	23	20	4.800	71
L middle frontal gyrus	-41	19	36	4.817	25
L inferior frontal gyrus	-47	15	22	4.360	8
L inferior frontal gyrus	-49	5	22	5.066	25
L insula	-45	1	10	4.787	23
R cingulate gyrus	9	1	46	4.436	8
L amygdala	-27	-5	-16	4.353	12
R precentral gyrus	53	-9	30	4.440	14
L precentral gyrus	-49	-17	32	4.900	71
Ventral tegmental area	-1	-17	-6	4.853	64
R thalamus	23	-23	-2	4.893	52
L postcentral gyrus	-41	-25	40	4.393	11
R inferior parietal lobule	41	-29	44	4.536	18
L paracentral lobule	-5	-29	52	4.315	8
R thalamus (extends to NAcc/caudate)	21	-31	10	5.901	4522
R inferior parietal lobule	43	-49	42	4.656	13

L, Left; R, right; A, anterior; S, superior.

$Z > 3.888$ ;  $p < 0.0001$ ; eight voxel cluster threshold.

et al., 2005). The present findings cannot be accounted for by differences in investment experience (see supplemental material, available at [www.jneurosci.org](http://www.jneurosci.org)) and run contrary to popular stereotypes of increasing risk aversion with age. Although adults who undergo brain scans might be more risk seeking than adults in general, additional subjects who completed a behavioral version of the investment task without scanning showed a similar increase in risk-seeking mistakes with age (Fig. 2B). The observed association between age and risk-seeking mistakes also replicated in a separate sample of subjects who were not recruited for brain imaging (Samanez-Larkin et al., 2010).

These findings imply a general decline in the dynamic representation of value (Knutson et al., 2005) with age. This decline may impair older adults' ability to use probabilistic feedback over time to build, alter, and implement optimal value predictions about uncertain future events (Fera et al., 2005). The neuroimaging findings extended those of previous research (Samanez-Larkin et al., 2007; Schott et al., 2007; Cox et al., 2008; Mell et al., 2009) by demonstrating that, although age did not disrupt the representation of specific outcomes (i.e.,  $-\$10$ ,  $+\$10$ ) in mesolimbic regions, older adults did not appear to use this feedback as effectively over time to make optimal decisions (Mell et al., 2009).

Novel analyses suggested that increased temporal variability in NAcc activation fully mediated the age-related increase in risk-seeking mistakes. This finding is generally consistent with recent evidence for age-related disruptions in the function of dopamine projections (Braskie et al., 2008; Dreher et al., 2008). The finding also more specifically supports the proposition of one computational theory that aging increases variability in neural function (Welford, 1965; Li et al., 2001), extending that proposition to a context that involves financial risk taking.

Variability in dopamine firing, however, may or may not translate into variability in fMRI activity. Alternatively, increased variability in dopamine firing may decrease fMRI activity, particularly when averaged over time. Future studies may more directly test for an association between dopamine firing and neuroimaging signal variability in dopamine target regions with multimodal neuroimaging methods [e.g., positron emission tomography combined with fMRI (Schott et al., 2008)] or by combining neu-

roimaging methods with pharmacological manipulations of dopamine (Pessiglione et al., 2006). Consistent with translation across levels of analysis, comparative studies suggest a link between phasic dopamine release and the phasic increases in NAcc activity indexed by fMRI (Choi et al., 2006; Knutson and Gibbs, 2007).

Additionally, an fMRI study found increased variability in the prefrontal activation (i.e., residual variance) of individuals who carried a genotype associated with reduced dopaminergic tone [i.e., COMT (catechol-*O*-methyltransferase) Val carriers] (Winterer et al., 2006). These findings suggest a potential link between age-related changes in dopamine function and variability of activity in specific frontostriatal dopamine targets such as the NAcc.

The novel measure of temporal variability in neural activity used in this study was averaged across the entire scanning session for each subject. The lack of sufficient measurement samples and dynamism of the present design precluded computation of stable mean differences for specific trial phases. Future studies with optimally timed experimental designs might better assess whether this variability is constant across time or related to specific trial phases. Despite these limitations and beyond observing increased temporal variability in the activity of some brain regions innervated by dopamine, we further found support for another key prediction of a computational account (Li et al., 2001). Along with increased temporal variability of neural activity, we also observed reduced discrimination between risky alternatives in older subjects (supplemental Fig. 1, available at [www.jneurosci.org](http://www.jneurosci.org) as supplemental material).

Age-related variability in NAcc activity may have compromised subjects' ability to accurately predict the value of risky assets, which might have promoted suboptimal choices. In support of this interpretation, more traditional analyses revealed that individuals who make more risk-seeking mistakes show less correlation between NAcc activity and the expected value of risky options (Samanez-Larkin et al., 2010). In a separate behavioral study, risk-seeking mistakes of older adults were reduced by providing visual decision aids indicating the expected value of each risky option (Samanez-Larkin et al., 2010). Together, this evidence suggests that older adults may have difficulty using dynamic probabilistic feedback to predict and select the next best financial option over time.

Although this study focused on ventral striatal activity that mediated age-related mistakes in financial decision making, connected frontal regions may also play important roles specifically in facilitating the integration of value signals over time (Kennerley et al., 2006) and more generally in promoting value-based choice (Hampton et al., 2006; Platt and Huettel, 2008). In the present study, functional connectivity analyses revealed that, independent of age, individuals with reduced connectivity between the NAcc and inferior frontal gyrus/insula made more risk-seeking mistakes. Because connectivity between these regions did not vary as a function of age in this sample, however, this relative disconnection could not account for the effects of age on financial risk taking. Although connectivity between the NAcc and anterior cingulate declined with age, connectivity between these regions was not associated with risk-seeking mistakes. This absence of significant effects should not, however, rule out a possible role for frontostriatal disconnections in age-related differences in decision making. Future studies combining structural and functional neuroimaging techniques may more comprehensively address the possible functional consequences of age-related structural disconnections.

Although we did observe a negative association between NAcc and insula connectivity and risk-seeking mistakes, insula activity could not account for age-related differences in choice. Previous studies have found associations between insula activation and representation of risk (Preuschoff et al., 2006) as well as risk prediction error (Preuschoff et al., 2008; d'Acremont et al., 2009). Additionally, a previous study using the BIAS task found that insula activation predicted risk avoidance (i.e., risk aversion mistakes) (Kuhnen and Knutson, 2005) but not excessive risk seeking (i.e., risk-seeking mistakes, the focus of the present study). Thus, one might not necessarily expect to find a relationship between insula activity and risk-seeking mistakes. However, it is also important to note that age differences in insular responses to incentives (Samanez-Larkin et al., 2007) may have limited our ability to detect insular effects.

From a psychological standpoint, one additional explanation for the increase in risk-seeking mistakes in the present sample is that older adults may disproportionately anticipate gains over losses when choosing risky assets. Previous evidence suggests that, although older adults show similar responses to gain and loss outcomes, as well as during anticipation of gains in the absence of learning, they show reduced anticipation of losses, reflected by both self-reported affect and neural activity (Samanez-Larkin et al., 2007). Because of the dynamic and changing nature of the investment task, task-related affect measures were not included, and so this hypothesis could not be directly tested in the present study.

If age-related changes in neural function systematically compromise financial decisions, this might hold significant implications for economic forecasting and policy. Researchers have only begun to empirically explore how individual differences in cognitive capacity might systematically influence financial decisions (Burks et al., 2009; Agarwal et al., 2010; Korniotis and Kumar, 2010). In the present study, older adults made investment errors more frequently than younger adults, possibly because of differences in the representation of expected value. According to this interpretation, variability in NAcc activity diminishes the accuracy of value predictions in older adults, which generates mistakes in financial risk taking. Older adults may find it more difficult to dynamically build value predictions to select the best risky financial option. If so, policy or incentive schemes might consider ways to ameliorate these age-related effects, for instance, by explicitly providing value-based decision aids. Alternatively, policy makers might facilitate more optimal choice among older investors by recommending expert consultation when value computational demands exceed neural capacities (Thaler and Sunstein, 2008).

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# Expected value information improves financial risk taking across the adult life span

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**When making decisions, individuals must often compensate for cognitive limitations, particularly in the face of advanced age. Recent findings suggest that age-related variability in striatal activity may increase financial risk-taking mistakes in older adults. In two studies, we sought to further characterize neural contributions to optimal financial risk taking and to determine whether decision aids could improve financial risk taking. In Study 1, neuroimaging analyses revealed that individuals whose mesolimbic activation correlated with the expected value estimates of a rational actor made more optimal financial decisions. In Study 2, presentation of expected value information improved decision making in both younger and older adults, but the addition of a distracting secondary task had little impact on decision quality. Remarkably, provision of expected value information improved the performance of older adults to match that of younger adults at baseline. These findings are consistent with the notion that mesolimbic circuits play a critical role in optimal choice, and imply that providing simplified information about expected value may improve financial risk taking across the adult life span.**

**Keywords:** aging; decision making; learning; memory; reward; fMRI

## INTRODUCTION

Unlike the rational actors posited by traditional financial models of optimal choice (Huang and Litzenberger, 1988), humans (and other organisms) must rely upon limited cognitive capacities when making decisions (Simon, 1982). Furthermore, some cognitive capacities related to attention, memory and cognitive control decline with age (Park *et al.*, 2002; Salthouse, 2004; Birren and Schaie, 2006). These limitations might bias human choice, with more extreme repercussions for older adults. Little research, however, has focused on whether aging exacerbates biases in financial decision making, which neuropsychological mechanisms underlie those biases, and how they might be minimized.

Although financial decision-making doubtlessly requires some explicit recall (which typically enlists attentional and declarative memory resources), it may also rely on implicit evaluative processes. Declarative memory, which supports explicit recall, has been primarily associated with activity in lateral prefrontal and medial temporal brain regions (Brewer *et al.*, 1998; Wagner *et al.*, 1998; Ranganath and D'Esposito, 2001; Paller and Wagner, 2002; Davachi, 2006; Blumenfeld and Ranganath, 2007), whereas valuation has been associated primarily with activity in mesolimbic dopamine projection regions, including the medial prefrontal

cortex (MPFC) and connected ventral striatum, including the nucleus accumbens (NAcc; O'Doherty, 2004; Knutson and Bossaerts, 2007; Knutson *et al.*, 2008).

Event-related functional magnetic resonance imaging (fMRI) studies have specifically implicated mesolimbic projection areas associated with valuation in both optimal and suboptimal financial risk taking (Kuhnen and Knutson, 2005). For example, while increased NAcc activity precedes optimal financial risk-seeking choices, excessive NAcc activity can foreshadow suboptimal risk-seeking 'mistakes' (which deviate from the choices of a risk-neutral Bayesian-updating actor).

Extensive research has linked age-related deficits in attention, memory and cognitive control to changes in lateral prefrontal and medial temporal cortical function (Cabeza *et al.*, 2005; Hedden and Gabrieli, 2004), but remarkably little research has investigated the influence of aging on valuation and associated mesolimbic function (Samanez-Larkin and Carstensen, *in press*). Emerging findings suggest age-related declines in the structure of frontal and striatal circuits (Hicks and Birren, 1970; Rubin, 1999; Buckner, 2004; Head *et al.*, 2005); however, it is not yet clear whether these structural declines contribute to functional deficits in decision making. Early evidence has implied preservation of mesolimbic function in older adults in simple value assessment tasks (Samanez-Larkin *et al.*, 2007), while other studies have documented age-related declines in mesolimbic function during probabilistic learning tasks (Fera *et al.*, 2005; Aizenstein *et al.*, 2006; Mell *et al.*, 2009; Samanez-Larkin *et al.*, 2010).

Although prevalent stereotypes suggest that older adults avoid risk, in some situations older adults may seek risk, or

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simply make more errors than younger adults (Denburg *et al.*, 2005; Henninger *et al.*, in press; Mather, 2006; Mohr *et al.*, 2009). For instance, in a recent study, we found that older adults made more risk-seeking financial mistakes in an investment task than younger adults (Samanez-Larkin *et al.*, 2010). This bias did not extend to risk-aversion mistakes. Furthermore, increased variability in NAcc function could account for the observed age differences in investment mistakes. While these findings implicate ‘noisier’ striatal activity in suboptimal financial risk taking, they do not specify which associated psychological processes impair choice, or how the impairment could be minimized. If NAcc activation supports the representation of expected value (Knutson *et al.*, 2005; Yacubian *et al.*, 2006), and disruptions in NAcc function compromise financial risk taking (Kuhnen and Knutson, 2005; Samanez-Larkin *et al.*, 2010), then interventions that provide expected value information might *improve* decision making.

Alternatively, deficits in cognitive control associated with lateral prefrontal activity (D’Esposito *et al.*, 1995; Miller and Cohen, 2001; Koechlin *et al.*, 2003; Badre and Wagner, 2004; Badre, 2008) may compromise financial risk taking. Specifically, age-related changes in prefrontal function have been associated with impairments in attention and memory (Gazzaley and D’Esposito, 2007). These age-related deficits in cognitive control may underlie age-related impairments in decision making (Brand and Markowitsch, 2010; however, see McCarrey *et al.*, 2010). If disrupted lateral prefrontal function compromises financial risk taking, then interventions that interfere with attention and declarative memory might *impair* decision making.

In two studies, we sought to determine whether disruptions in mesolimbic function might account for financial mistakes, and to improve the financial risk taking of both younger and older investors. In Study 1, we tested whether individuals whose mesolimbic activity most closely tracked expected value also made more optimal risky financial choices by reanalyzing data from a recently published study (Samanez-Larkin *et al.*, 2010). In Study 2, we examined whether increasing cognitive load or providing expected value information would alter the financial risk taking of healthy younger and older adults. Based on previous neuroimaging research, we speculated that individuals whose mesolimbic activation most closely tracked expected value would make more optimal choices in Study 1, and that provision of

expected value information would improve the choices of both younger and older investors in Study 2.

## METHODS

### Study 1

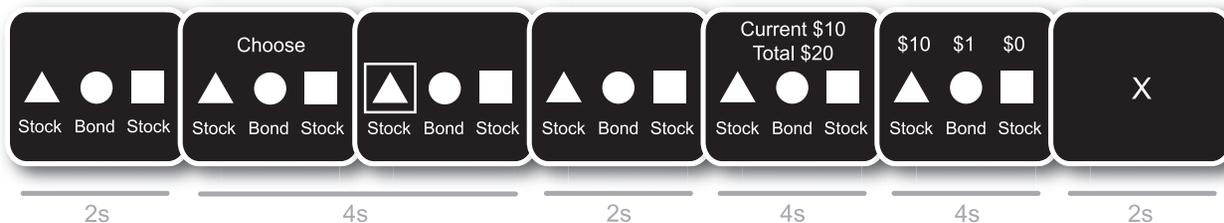
Study 1 presents a new analysis of a recently published dataset (Samanez-Larkin *et al.*, 2010). More detailed information on the subjects and procedures is presented in the prior publication. While previous analyses focused on age differences in NAcc activity, the goal of the present analysis was to further determine whether individual differences in rational choices correlated with the degree to which neural activation in the NAcc and MPFC tracked expected value.

Fifty-four subjects (mean age = 51.3 years, range = 21–85, 54% female) played an investment task while undergoing functional magnetic resonance imaging (fMRI). All subjects were recruited by a local survey research firm to socio-economically represent the population of the San Francisco Bay Area peninsula. Across the age range, subjects were matched on basic demographic variables (SES, income and ethnicity) by the recruitment agency. Subjects received a fixed compensation of \$20 per hour, as well as a tenth of their total task earnings (or a deduction of a tenth of their total task losses), contingent on their performance.

### BIAS task

A modified version of the Behavioral Investment Allocation Strategy (BIAS) task (Kuhnen and Knutson, 2005) elicited both optimal and suboptimal financial choices from each subject. During the task, subjects completed 10 blocks of 10 trials for a total of 100 trials. During each trial (Figure 1), subjects first saw two stocks and a bond (2 s), selected an asset when prompted with the word ‘choose’, and then viewed their highlighted choice on the screen (4 s). After a brief delay (2 s) their earnings for that trial and total earnings were displayed (4 s), followed by a display of the outcomes of all assets on that trial (4 s), and finally, a fixation cross (fixation, 2 s).

At the beginning of each block, the computer randomly assigned one of the two stocks to be the ‘good’ stock and the other to be the ‘bad’ stock, without the subject’s knowledge. On average, outcomes of the good stock (i.e. +\$10 with 50% probability, +\$0 with 25% probability and –\$10 with 25% probability) were better than outcomes of the bad stock



**Fig. 1** Study 1 BIAS task design. The investment task used in Study 1 for functional neuroimaging. For brain imaging analyses, the rational actor’s expected value estimate was modeled during the anticipatory period prior to choice at the beginning of the trial. A response deadline for choice was set at 4 s.

(i.e. +\$10 with 25% probability, +\$0 with 25% probability and -\$10 with 50% probability) for each trial. The bond paid \$1 with 100% probability on each trial. Earnings were independently drawn from each distribution for each trial, and subjects were informed about the distributions before performing the task.

In the context of the BIAS task, the optimal strategy of a rational, risk-neutral agent is to pick a stock if he or she expects to receive a return that is at least as large as the bond return. Since the actual monetary amounts at stake in each trial were small (from -\$1 to \$1), we adopted risk neutrality as the baseline model of investor behavior—a model which assumes that individuals maximize expected return. Performance was assessed by comparing the choices of individual subjects to those made by a risk-neutral Bayesian-updating rational actor on each trial (for complete model details, see Kuhnen and Knutson, 2005). The model makes a discrete choice (i.e. chooses one asset) on each trial. Any deviation from the model by the subject (i.e. choosing either of the other two assets) on each trial was classified as a ‘mistake’.

### **fMRI acquisition and analyses**

Images were acquired with a 1.5T General Electric MRI scanner using a standard birdcage quadrature head coil. Twenty-four 4-mm-thick slices (in-plane resolution  $3.75 \times 3.75$  mm, no gap) extended axially from the mid-pons to the top of the skull, providing adequate spatial resolution of subcortical regions of interest (e.g. midbrain, ventral striatum). Functional scans of the whole brain were acquired every 2 s (TR = 2 s) with a  $T_2^*$ -sensitive in-/out-spiral pulse sequence (TE = 40 ms, flip =  $90^\circ$ ) designed to minimize signal dropout at the base of the brain (Glover and Law, 2001). High-resolution structural scans were subsequently acquired using a  $T_1$ -weighted spoiled grass sequence (TR = 100 ms; TE = 7 ms, flip =  $90^\circ$ ), facilitating subsequent localization and coregistration of functional data. Preprocessing and whole brain analyses were conducted using Analysis of Functional Neural Images (AFNI) software (Cox, 1996). For preprocessing, voxel time series were sinc interpolated to correct for non-simultaneous slice acquisition within each volume, corrected for three-dimensional motion, slightly spatially smoothed (FWHM = 4 mm), converted to percentage signal change and high-pass filtered.

Analyses of brain imaging data involved two steps. In the first analytic step (a within-subject analysis), preprocessed time series were submitted to a regression model that included a primary regressor of interest that indexed the rational actor's current trial estimate of the expected value of a stock (i.e. the integrated value estimate later used in Study 2) during anticipation. Specifically, the raw expected value estimates for the individual stock that the subject subsequently chose on each trial were modeled during anticipation of choice in one single regressor. Trials where subjects chose bonds were not included in this regressor. The

regression model also included covariate regressors of potential interest representing anticipation of stock vs bond choices, individual trial earnings at outcome (-\$10, \$0, \$1, \$10), and two separate regressors representing task phases (anticipation, outcome). The regression model also included covariate regressors of non-interest, which indexed cumulative earnings (current wealth earned during the task, updated at each outcome period), current trial uncertainty (updated at each market period), residual motion and trends across the scan session (i.e. baseline, linear and quadratic). Regressors of interest were convolved with a  $\gamma$ -variate function that modeled a canonical hemodynamic response prior to inclusion in regression models (Cohen, 1997). These statistical maps were coregistered with structural images for each individual and spatially normalized by warping to Talairach space.

The second analytic step (a between subject analysis) investigated whether individuals whose NAcc and MPFC activation closely tracked expected value also made fewer mistakes (or more choices that conformed to those of the rational actor). Across subjects, expected value coefficients derived from the first analysis were regressed against the proportion of rational stock choices and age across the whole brain. Thus, the second analysis specifically regressed coefficients representing the dynamic association of brain activity with the rational actor's estimate of expected value for each subject against a summary measure of task performance for each subject (i.e. number of rational stock choices), controlling for age.

Voxelwise thresholds for statistical significance at the whole brain level were set at  $P < 0.005$ , uncorrected. AFNI's AlphaSim (Cox, 1996) was used to estimate the minimum cluster size of 36  $2.0\text{-mm}^3$  voxels for a  $P < 0.05$  whole-brain corrected threshold. Small volume correction was applied to the NAcc at the same threshold ( $P < 0.005$ ) but without the cluster criterion (which was too large to allow detection of activation in regions as small as the NAcc). In summary, this analysis examined whether individuals whose mesolimbic regions more closely tracked expected value also made fewer financial mistakes.

### **Methodological issues related to age differences**

In all fMRI analyses, care was taken to minimize potential confounds associated with age differences in subject characteristics, brain morphology and hemodynamics (Samanez-Larkin and D'Esposito, 2008). Each individual was screened for dementia using the Mini-Mental State Exam and their structural and functional brain imaging data were inspected for abnormalities. Three individuals (not included in the 54 subjects described above) were excluded due to a structural abnormality (71-year-old male) or motion  $>4$  mm in any dimension from one volume acquisition to the next (26- and 74-year-old male). Each individual's brain was warped into Talairach space with reference to hand-placed anatomical landmarks.

## Study 2

### Subjects

A separate sample of 108 healthy subjects completed Study 2. Forty-nine younger adults between the ages of 20–35 years (mean age = 27.3, 35% female) and 59 older adults between the ages of 64–82 years (mean age = 70.6, 37% female) were recruited by a local survey research firm to socio-economically represent the population of the San Francisco Bay Area peninsula. Across age groups, subjects were matched on basic demographic variables (SES, income and ethnicity) by the recruitment agency prior to being scheduled for a laboratory visit. Across the sample, 62% percent of subjects were Caucasian, 13% Asian American, 11% Hispanic, 10% African American and 4% more than one race. Fifty-five percent of subjects were married, 40% single and 5% divorced. As displayed in Supplementary Table 1, for both trait affect and cognitive abilities, these age groups were similar to other between-group studies in the literature. Subjects received fixed compensation of \$20 per hour, as well as a 10th of their total task earnings or a deduction of a 10th of their total task losses contingent on performance. Subjects in this study did not undergo fMRI.

### Baseline BIAS task

The same version of the BIAS task used in Study 1 was used in Study 2 as a baseline condition with two modifications. First, subjects completed five blocks of 10 trials each for a total of 50 trials (i.e. half of the trials included in Study 1). Second, the response deadline was removed for choices, such that all subject responses were self-paced. During each trial, subjects first saw two stocks and a bond (2 s), selected an asset when prompted with the word ‘choose’ (self-paced), and then viewed their highlighted choice on the screen (2 s). After a brief delay (2 s), the subjects’ earnings for that trial and total earnings were displayed (4 s), followed by the outcomes of all assets on that trial (4 s), and finally, a fixation cross (2 s; Figure 2, top row). After being led through extensive instructions by an experimenter, subjects played three blocks of practice baseline trials (totaling 30 trials) before playing the baseline task for actual cash. Although subjects viewed all probability distributions, the experimenter also explicitly stated that the stocks were risky and the bonds were riskless. For instance, an excerpt from the instructions reads: ‘once again, the three assets available to choose from are two stocks and a bond. The stocks are risky, because their earnings can be +\$10, –\$10 or \$0. The bond is riskless, because it always pays \$1’.

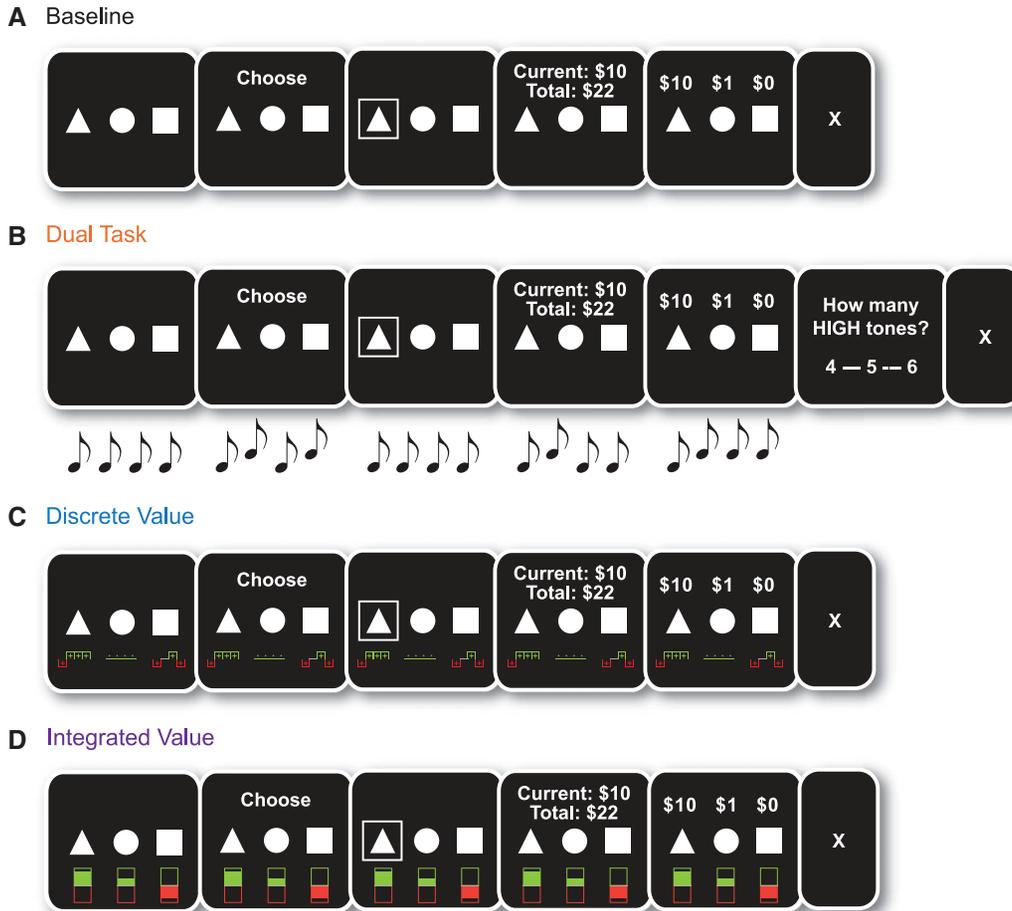
In all conditions, performance was assessed by comparing each subject’s choices to the choices of a risk-neutral rational actor on each trial. Choices that matched the model were characterized as ‘rational’ choices. Choices that deviated from the model were characterized as ‘irrational’ mistakes and classified into one of three different categories: risk-aversion (bond choice), risk-seeking (stock choice) or confusion (stock choice) mistakes. Risk-seeking mistakes

occurred if subjects chose a risky option (i.e. a stock) when the riskless option (i.e. a bond) was the optimal investment. Risk-seeking mistakes tended to occur early within blocks when the rational actor lacked sufficient evidence to distinguish the good from the bad stock. Confusion mistakes occurred if subjects chose a risky option (i.e. a stock) when the other risky option (i.e. the other stock) was the optimal choice. Confusion mistakes tended to occur later within blocks when the rational actor had sufficient evidence to distinguish the good from the bad stock. Risk-aversion mistakes occurred if subjects chose the riskless option (i.e. the bond) when a risky option (i.e. a stock) was the optimal investment. Risk-aversion mistakes also tended to occur later within blocks when the rational actor had sufficient evidence to distinguish the good from the bad stock. The threshold for distinguishing between risk-seeking mistakes and confusion or risk-aversion mistakes occurred in the trial when the expected value of one stock exceeded the expected value of the bond. In Study 2, the rational actor chose the bond on 50% of trials. Thus, the maximum number of risk-seeking mistakes was 25 (out of 50 choices) in each condition and the maximum sum of confusion and risk-aversion mistakes was 25 (out of 50 choices). Analyses of individual mistake types appear in the Supplementary Results section.

Performance was examined using ANOVAs with rational choices (rational, irrational) and asset choices (stock, bond) as within-subject factors and age group (younger, older) as a between-subject factor. Follow-up *t*-tests are reported when main effects or interactions required further clarification. The analyses reported below focus on rational choices at baseline as well as on changes in rational choices in each manipulated condition with respect to the baseline condition. In addition to examining subjects’ investment choices, we also assessed their explicit knowledge of which assets had performed best at the end of each block (series of 10 trials). Means of rational choices on individual trials and asset knowledge at the end of blocks by age group are provided in Supplementary Tables 2 and 3, respectively.

### Dual-task condition

In the dual-task manipulation, we examined whether adding an auditory task (i.e. dividing attention) previously shown to engage lateral prefrontal cortex and reduce explicit (declarative) memory (Foerde *et al.*, 2006) would disrupt rational choices relative to baseline. Thus, a continuous series of high- and low-pitched tones were played during the display frame of each individual trial (Figure 2, second row). Subjects were asked to keep a running sum of the count of both high- and low-pitched tones during each trial. After viewing the assets, choosing, viewing the outcome and market results, subjects were asked either how many high- or how many low-pitched tones were played during that trial by choosing from one of three options. Tones were



**Fig. 2** Study 2 modified BIAS task design. All four conditions of the modified investment task used in Study 2. (A) Baseline task, (B) dual-task condition, (C) discrete value condition and (D) integrated value condition. Although not depicted here, the asset icons (triangle, circle and square) were labeled with the words ‘stock’ or ‘bond’.

not played during the end-block question in which subjects indicated which stock performed best overall.

**Discrete value condition**

In the discrete value manipulation, we examined whether adding a decision aid that provided episodic value information would enhance rational choices relative to baseline. Thus, the outcomes of each individual previous trial within a block were presented to subjects as they made investment decisions. During each trial, a visual representation of the individual outcomes of all prior trials within that block appeared below each asset (Figure 2, third row). Specifically, a large green plus symbol indicated that a stock had won \$10 in the past, whereas a large red minus symbol indicated that a stock had lost \$10 in the past. An unsigned grey line indicated that a stock had yielded \$0 in the past. A small green plus symbol (one-tenth the size of the green plus symbol corresponding to \$10 under stocks) indicated that the bond had earned \$1 on each previous trial. This discrete value display was updated on the first screen of the following trial. Discrete value displays were reset after each block of ten trials and did not appear during the

end-block question in which subjects identified which stock seemed best overall.

**Integrated value condition**

In the integrated value manipulation, we examined whether adding a decision aid that provided integrated value information would enhance rational choices relative to baseline. In this integrated value condition, subjects saw a summary of the current expected value of each asset based on prior outcomes within a block as they made individual investment decisions. During each trial, a visual representation of the rational actor’s current value estimate appeared below each asset (Figure 2, bottom row). For each stock, the expected value was equal to the current probability of that stock being the ‘good’ stock multiplied by the expected value of the good stock (+\$2.50) plus the current probability of that stock being the ‘bad’ stock multiplied by the expected value of the bad stock (−\$2.50).

$$\begin{aligned}
 E[V_t^i | I_{t-1}] &= x_t^i [0.5 \times 10 + 0.25 \times (-10) + 0.25 \times 0] \\
 &\quad + (1 - x_t^i) [0.5 \times (-10) + 0.25 \times 10 + 0.25 \times 0] \\
 &= 2.5 \times (2x_t^i - 1).
 \end{aligned}$$

These estimates were updated on each trial according to Bayes' rule. For bonds, the expected value on each trial was equal to \$1 and never changed. Estimates were displayed on a bivariate 'meter' with an increasingly positive green bar indicating increasingly positive expected values and an increasingly negative red bar indicating increasingly negative expected values. This display of the integrated value of each asset was updated on the first screen of the following trial. The displays reset after each block of 10 trials and were not displayed during the end-block question in which subjects identified which of the stocks performed best overall.

An experimenter led subjects through a brief summary of the instructions, the probability distributions, and one sample trial of each condition before playing each of the three manipulated versions of the task. In the dual-task condition, subjects listened to sample high, low, and mixed high/low-tone series before viewing the sample trial, and were additionally asked to 'try hard to focus on both counting tones and making wise investment decisions on every single trial'. In the decision aid conditions, subjects were informed that the additional information provided was only an aid and that they should always use their best judgment to make the final decision. Beyond explaining the information that the decision aids represented, subjects were not instructed to use the aids in any specific way. Complete task instructions can be obtained by contacting the authors.

While all subjects played the baseline condition first, the order of the subsequent manipulated blocks was counter-balanced between subjects. Outcomes were pseudorandomly generated for each condition. Specifically, multiple sets of 50 trials of outcomes were randomly drawn from the probability distributions, and four of these randomly generated series were selected for the four task conditions for all subjects. The four series of outcomes were selected such that the rational actor model earned \$75 in each to control for difficulty across conditions. Outcomes earned by individual subjects, however, were determined by their individual choices and were not in any way manipulated or controlled. Subjects earned significantly less than the rational actor in all versions of the task (baseline:  $t_{107} = -11.98$ ,  $P < 0.0001$ ; dual-task:  $t_{107} = -10.89$ ,  $P < 0.0001$ ; discrete value:  $t_{107} = -10.16$ ,  $P < 0.0001$ ; integrated value:  $t_{107} = -11.89$ ,  $P < 0.0001$ ). Younger and older adults did not significantly differ in their actual earnings in the baseline,  $t_{106} = 0.30$ ,  $P = 0.77$ , dual-task,  $t_{106} = -1.66$ ,  $P = 0.10$ , discrete value,  $t_{106} = 1.32$ ,  $P = 0.19$ , or integrated value,  $t_{106} = 0.02$ ,  $P = 0.98$ , conditions.

## RESULTS

### Study 1

The key neuroimaging analysis examined whether individuals whose mesolimbic regions most closely tracked expected value also made more rational choices overall while investing. As predicted, whole brain regression revealed that individuals whose activation most closely tracked expected value (i.e. the rational actor's integrated value computation) in

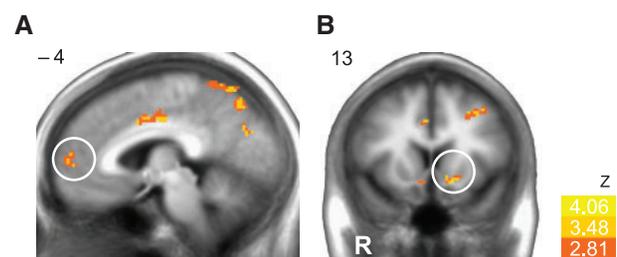
mesolimbic regions (i.e. NAcc and MPFC) during anticipation made more rational choices overall. More specifically, this analysis revealed a correlation between coefficients representing the dynamic association of activity in mesolimbic regions with the rational actor's estimate of expected value for each subject and a summary measure of task performance for each subject (i.e. number of rational stock choices) (Table 1 and Figure 3). This association implicates mesolimbic circuitry not only in the computation of expected value, but also in rational financial risk taking.

Beyond these regions of interest, activity in other areas associated with declarative memory (i.e. parahippocampal gyrus) and attention (i.e. superior parietal lobule) also showed a positive association between rational choices and

**Table 1** Whole brain individual difference analysis

Region	BA	Z	Voxels	R	A	S
L Medial frontal gyrus	9	3.633	86	-13	49	20
R Superior frontal gyrus	9	-3.841	44	35	45	30
L Superior frontal gyrus	8	3.794	125	-23	29	44
L Nucleus accumbens		4.055	22 [SVC]	-15	14	-8
L Insula	13	3.896	93	-39	1	18
L Middle frontal gyrus	6	3.622	51	-31	1	40
R Middle frontal gyrus	9	3.805	47	51	-1	34
R Cingulate gyrus	24	4.007	144	7	-5	52
R Precentral gyrus	4	4.371	428	51	-11	38
L Cingulate gyrus	24	3.852	135	-5	-11	38
L Precentral gyrus	6	4.177	264	-59	-15	42
R Parahippocampal gyrus	22	4.082	63	39	-19	-8
R Inferior parietal lobule	40	3.979	55	47	-31	34
L Superior temporal gyrus	13	4.081	37	-49	-49	20
R Superior parietal lobule	7	3.541	41	25	-51	50
R Superior parietal lobule	7	3.263	53	27	-53	60
L Middle temporal gyrus	39	4.35	52	-43	-53	10
L Precuneus	7	4.308	112	-9	-61	58
L Precuneus	7	3.971	60	-7	-65	48
L Cuneus	18	4.123	45	-3	-75	28

BA: Brodmann area. Regions where coefficients representing the association between brain activation and the actor's changing estimate of expected value over time were correlated (controlling for age) with individual differences in the number of rational stock choices.



**Fig. 3** Expected value signals in mesolimbic regions correlate with task performance. An individual difference analysis revealed that more accurate representation of the actor's estimate of expected value in mesolimbic regions, the MPFC (A) and NAcc (B), at anticipation was positively correlated with rational choices in the investment task.

the representation of expected value. The only brain region that showed a negative association between expected value and rational choices was a small region of the right dorso-lateral prefrontal cortex (Table 1).

## Study 2

Beyond comparison of age groups in a baseline condition, the key behavioral analyses focused on how manipulations of attention and value information might influence individuals' rational choices. Based on the neuroimaging findings, we sought to determine whether manipulations of attention or value might influence both rational choices and the acquisition of explicit knowledge about which assets were best (Foerde *et al.*, 2006). We predicted that the presentation of value information would increase rational choices in both younger and older adults.

### Baseline condition

Analysis of choices in the baseline condition yielded a significant rational choice  $\times$  group interaction,  $F_{1,106} = 5.824$ ,  $P < 0.05$ , suggesting that performance differed between the two age groups. Follow-up tests confirmed that the older adults made fewer rational choices than the younger adults overall,  $t_{106} = -2.41$ ,  $P < 0.05$  (Figure 3A). Despite these differences in choice, older adults did not differ from younger adults in their explicit knowledge of which assets were best, since older adults did not make significantly more errors when explicitly identifying the correct stock at the end of a block,  $t_{106} = 0.64$ ,  $P = 0.53$ .

### Dual-task condition

In the dual-task (divided-attention) condition, secondary task performance (tone counting accuracy) was significantly above chance (33%) for both younger,  $t_{48} = 6.18$ ,  $P < 0.001$ ; and older,  $t_{58} = 6.24$ ,  $P < 0.001$ , subjects. Although mean tone counting accuracy was numerically higher for younger (45.1%) than older adults (41.4%), the two groups did not significantly differ,  $t_{106} = -1.59$ ,  $P = 0.12$ , suggesting a similar effect of the manipulation on attention. The dual-task condition effectively disrupted declarative memory contributions, as revealed by a significant decrease in explicit asset knowledge at the end of blocks in the dual-task condition relative to baseline in younger adults,  $t_{48} = -2.10$ ,  $P < 0.05$ , as well as a trend toward decreased explicit asset knowledge in older adults,  $t_{58} = -1.82$ ,  $P = 0.07$ . The two age groups did not differ, however, in this decrease in asset knowledge,  $t_{106} = -0.40$ ,  $P = 0.69$ .

Relative to the baseline condition, a non-significant condition (baseline, dual-task)  $\times$  rational choice interaction,  $F_{1,106} = 0.707$ ,  $P = 0.40$ , revealed that the number of rational choices was similar in baseline and dual-task conditions, implying that the presence of the secondary task did not significantly influence rational choices. A non-significant interaction of condition, rational choices and age group,  $F_{1,106} = 0.03$ ,  $P = 0.86$ , suggested that this lack of an effect

of the secondary task on rational choices did not differ between younger and older adults. Follow-up tests confirmed that in the dual-task condition, the number of rational choices did not differ from baseline in younger adults,  $t_{48} = -0.42$ ,  $P = 0.67$ ; or older adults,  $t_{58} = -0.80$ ,  $P = 0.43$  (Figure 3B). These findings, together with the negative impact of dual-task inference on the acquisition of explicit knowledge, suggest that at least partially distinct forms of learning and memory may support investment choices and explicit asset knowledge.

### Discrete value condition

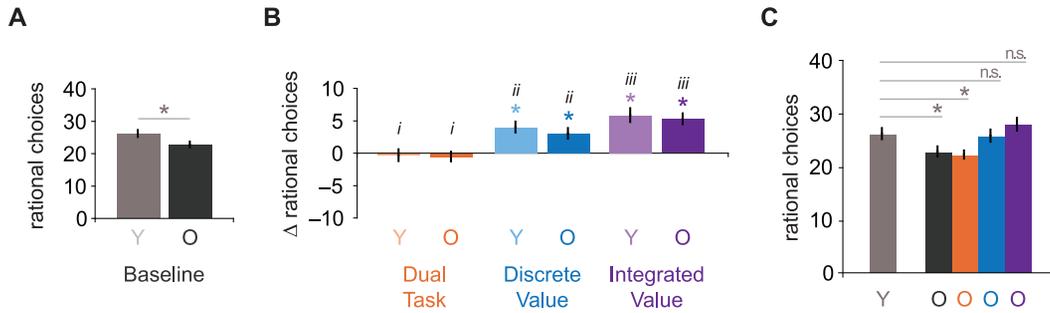
A significant condition (baseline, discrete value)  $\times$  rational choice interaction,  $F_{1,106} = 34.58$ ,  $P < 0.001$ , revealed that relative to the baseline condition, the number of rational choices increased in the discrete value condition. A non-significant interaction of condition, rational choice, and age group,  $F_{1,106} = 0.68$ ,  $P = 0.41$ , suggested that these improvements did not differ between younger and older adults. Follow-up tests confirmed that overall rational choices increased in both younger adults,  $t_{48} = 4.80$ ,  $P < 0.0001$ ; and older adults,  $t_{58} = 3.60$ ,  $P < 0.001$ , with provision of discrete value information (Figure 3B).

The addition of discrete value information on individual trials also improved explicit asset knowledge at the end of blocks (even when decision aids were no longer visible). There was a significant increase in explicit asset knowledge in the discrete value condition in younger adults,  $t_{48} = 5.51$ ,  $P < 0.0001$ ; and older adults,  $t_{58} = 5.49$ ,  $P < 0.0001$ . The two age groups did not differ in increased asset knowledge,  $t_{106} = 0.15$ ,  $P = 0.88$ .

### Integrated value condition

A significant condition (baseline, integrated value)  $\times$  rational choice interaction,  $F_{1,106} = 67.27$ ,  $P < 0.0001$ , revealed that relative to the baseline condition, the number of rational choices also increased in the integrated value condition. A non-significant interaction of condition, rational choice, and age group,  $F_{1,106} = 0.18$ ,  $P = 0.67$ , suggested that these improvements did not differ between younger and older adults. Follow-up tests confirmed that overall rational choices increased in both younger adults,  $t_{48} = 5.42$ ,  $P < 0.0001$ ; and older adults,  $t_{58} = 6.19$ ,  $P < 0.0001$ , with the provision of integrated value information (Figure 3B).

Adding integrated value information on individual trials also improved explicit asset knowledge at the end of blocks (even when decision aids were no longer visible). There was a significant increase in asset knowledge in the integrated value condition in both younger adults,  $t_{48} = 4.90$ ,  $P < 0.0001$ , and in older adults,  $t_{58} = 5.91$ ,  $P < 0.0001$ . The two age groups did not differ in increased asset knowledge,  $t_{106} = -0.49$ ,  $P = 0.63$ .



**Fig. 4** Improving financial risk taking. **(A)** Older adults made fewer rational choices at baseline. **(B)** The addition of a secondary task did not disrupt performance relative to baseline (orange) for either younger (lighter bars) or older (darker bars) adults. However, the addition of discrete value information (blue) or integrated value information (purple) increased rational choices from baseline for both younger (lighter bars) and older adults (darker bars). For both age groups, the integrated value condition (*iii*) produced greater improvements than the discrete value condition (*ii*), which produced greater improvements than the dual-task condition (*i*). **(C)** Although older adults at baseline (dark grey O) and in the dual-task condition (orange O) made fewer rational choices than younger adults at baseline (light grey Y), older adults did not differ significantly in either the discrete value (blue O) or integrated value (purple O) conditions from young adults at baseline. Thus, presentation of information related to expected value matched the performance of older adults to that of younger adults at baseline. \* $P < 0.05$ ; n.s.: not statistically significant.

### Comparisons across conditions

All of the manipulations appeared to have similar effects on both age groups. Older adults, however, made fewer rational choices than younger adults at baseline and in every manipulated condition of the task (Supplementary Results section). One of the primary goals of this study was to improve the decision making of older adults. Relative to younger adults at baseline, older adults made significantly fewer rational choices at baseline and in the dual-task condition,  $t_{106} = -3.13$ ,  $P < 0.01$  (Figure 4C). Older adults, however, did not differ in rational choices from younger adults at baseline in either the discrete value,  $t_{106} = -0.27$ ,  $P = 0.79$ ; or integrated value,  $t_{106} = 1.08$ ,  $P = 0.28$ , conditions (Figure 4C). The increase from baseline in rational choices was higher in the discrete value condition than the dual-task condition for both younger adults,  $t_{48} = 4.89$ ,  $P < 0.0001$ ; and older adults,  $t_{58} = 3.90$ ,  $P < 0.0001$ . Furthermore, rational choices were even higher in the integrated value condition than in the discrete value condition for both younger adults,  $t_{48} = 2.39$ ,  $P < 0.05$ ; and older adults,  $t_{58} = 2.75$ ,  $P < 0.01$  (Figure 4B). Thus, providing value information (particularly in an integrated and simplified format) increased older adults' rational choices to a level comparable to those of younger adults in the baseline condition.

### DISCUSSION

In two studies of community members spanning a broad age range, we examined neural and behavioral evidence for individual differences in financial risk taking, and sought to identify interventions that could minimize those differences. Study 1 combined neuroimaging with an investment task to reveal that individuals whose mesolimbic activation (i.e. in the NAcc and MPFC) most closely tracked a rational actor's expected value estimates also made the most rational risky choices. Study 2 demonstrated not only that older adults made more mistakes (or irrational choices) than younger adults (Samanez-Larkin *et al.*, 2010), but also that task

modifications related to expected value improved rational choice in both younger and older adults. Specifically, while attentional interference of declarative memory had little influence on rational choices in either group, provision of decision aids that provided value information increased rational choices in both groups, matching older adults' rational choices to the level of younger adults at baseline. Together, these findings suggest that accurate neural representation of expected value supports rational financial risk taking, and suggest that providing expected value information can improve financial risk taking in both younger and older adults.

From a neural standpoint, these findings are consistent with the notion that optimal financial risk taking requires input from mesolimbic circuits. Remarkably, disrupting the acquisition of declarative memory by dividing attention in the dual-task condition did not compromise the rational choices of younger or older adults (although it did make younger adults more conservative in their choices; Supplementary Results section). Dividing attention did, however, reduce the accuracy of subjects' explicit retrospective estimates of which stock was best. This dissociation between explicit report and implicit performance has previously been observed in studies in which attentional interference with explicit declarative learning occurs without influencing implicit probabilistic learning performance (Fuerde *et al.*, 2006). Neuroimaging research suggests that when lateral prefrontal resources are occupied, striatal systems may play a more prominent role in learning (Poldrack and Fuerde, 2008). Although Study 2 did not assess neural activity, its behavioral findings conceptually extend the distinction between explicit and implicit processing to a group of older adults. Since a 'functional lesion' of declarative memory in the dual-task condition did not impair performance, these findings clearly contradict the notion that declarative memory is the primary or critical process required for rational choice in this investment task.

These findings also indicated that providing both discrete and integrated value information increased rational choices relative to baseline in both younger and older adults. Investment choices of both age groups, however, still only matched those of the rational actor less than 60% of the time, demonstrating room for further improvement (for comparison, 75% of choices of Stanford PhD students matched those of the rational actor in a previous study; Kuhnen and Knutson, 2005). In the discrete value condition, although each trial presented complete information about the prior history of outcomes, this temporally varying episodic representation of value may have misled subjects on individual trials. Previous researchers have reported choice anomalies in the context of discrete and sequentially updated value information, including illusory correlations, the gambler's fallacy, and others (de Laplace, 1951; Tversky and Kahneman, 1971; Gilovich *et al.*, 2002; Ayton and Fischer, 2004). Accordingly, providing integrated rather than discrete estimates of expected value further increased rational choices in both groups, suggesting that this simplified and integrated value information was more effective in improving decision making.

If integrated value information is dynamically computed by or acts through mesolimbic circuits to promote rational risk taking, then individuals whose mesolimbic activity best represents the expected value estimates of a rational actor should make the most rational choices, as seen in Study 1. Although subjects in Study 2 did not undergo neuroimaging, it is plausible that the value information they received either directly or indirectly provided a more accurate estimate of expected value to upstream neural systems that guide behavioral choice (e.g. the dorsal striatum and connected supplementary motor cortex) (O'Doherty, 2004; Knutson and Cooper, 2005).

While converging evidence across the two studies suggests that expected value information may commonly act through mesolimbic circuits to improve financial risk taking, it is also important to acknowledge that the findings of Study 2 do not provide direct verification of this underlying neural mechanism. Although NAcc and MPFC activation have been implicated in representing expected value, integrating value across different stimulus dimensions, and assigning value to appropriate actions (O'Doherty, 2004; Knutson and Cooper, 2005), external presentation of expected value information in Study 2 may have bypassed the need for mesolimbic recruitment. It is also possible that the presence of expected value information provided a concurrent complementary source of evidence via the declarative memory system. The improvements in both individual investment decisions and explicit asset knowledge in the value conditions provides some evidence for this possibility, suggesting that task performance can be based on either implicit or explicit knowledge. This is consistent with evidence from related experimental tasks which rely on experience-based learning from probabilistic feedback (Poldrack and

Packard, 2003; Poldrack and Foerde, 2008; Shohamy *et al.*, 2008; Filoteo *et al.*, in press). The lack of a choice impairment in the dual-task condition indicates that explicit knowledge isn't typically necessary, but the choice improvements in the presence of expected value information might suggest that explicit representations of value may supplement implicit representations under some conditions. Future neuroimaging research will be required to determine whether expected value information improves financial risk taking by modulating activity in mesolimbic or dorsolateral prefrontal circuits.

One important alternative explanation for performance differences between age groups or across conditions is that these manipulations invoked the use of different or even divergent strategies. Performance measures over time, however, suggest that subjects (either knowingly or unknowingly) approximated the strategies of the rational actor in all conditions. Specifically, subjects chose the bond early, followed by an increasing preference for the good stock over time (Supplementary Figure 1). Furthermore, in the presence of additional value information both younger and older subjects' choices more closely matched those of the rational actor over time (Supplementary Figure 1).

Although the present analyses focused on 'rational' choices (or choices that converged with those of the rational actor), additional analyses of 'mistakes' (or choices that diverged from those of the rational actor; Supplementary Results section) revealed that age differences in performance across conditions were driven by age-related increases in mistakes when subjects chose stocks relatively early in blocks (i.e. made risk-seeking mistakes) (Supplementary Figure 2). Additionally, analyses of mistakes revealed that expected value information selectively reduced stock mistakes both early and later in blocks (Supplementary Results section). No age differences in mistakes were observed when subjects chose bonds (i.e. made risk-aversion mistakes), and presentation of expected value information did not influence risk-aversion mistakes.

While presentation of value information improved the decisions of older adults, age differences still persisted across conditions. This same pattern of findings has been documented in classic cognitive training studies (Baltes and Kliegl, 1992). Although age differences were not eliminated within any particular condition, the present findings suggest that appropriately tailored interventions can improve the decision making of older adults to the baseline performance of younger adults. In the case of financial risk taking, decision aids that provide simplified estimates of expected value may help because they mimic the output of neural mechanisms that represent expected value. Informational content alone is not sufficient, and style of presentation may also matter, since both younger and older adults improved more when presented with integrated value information rather than with discrete value information. Unfortunately, in the world of financial risk taking,

expected value information often cannot be reliably computed or is not available to investors. Nonetheless, the present findings suggest that understanding how the brain processes value information may eventually inform the design of more targeted and effective behavioral interventions for investors of all ages.

## SUPPLEMENTARY DATA

Supplementary data are available at SCAN online.

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