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Value-Based Decision-Making and Its Relation to Cognition and Processing Noise in Young and Older Adults

Anja Richtmann[1] · Johannes Petzold[1] · Franka Glöckner[2] · Michael N. Smolka[1]

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Abstract

In all phases of life, people face decisions with important consequences. Weighing options involves using cognitive resources to assess valence, delay, and risk to achieve a desired outcome. Value-based decision-making changes over the lifespan, but studies disagree on the extent, domains, and mechanisms of this change. We assessed delay discounting, risk aversion for probabilistic gains, risk seeking for probabilistic losses, loss aversion as well as cognitive abilities, and processing noise in 86 young (25–38 years) and 93 older (63–76 years) adults. We tested whether decision-making differed between age groups and whether differences were mediated by cognitive abilities or processing noise as measured by reaction time variability and decision inconsistency. Older adults showed steeper delay discounting ($p = .003$) and trended towards more risk aversion for gains ($p = .071$). Age groups did not differ in risk seeking for losses or loss aversion. Lower decision consistency and better spatial working memory mediated older adults' steeper delay discounting. The relationship between delay discounting and age persisted when controlling for both mediators, suggesting robust age differences in delay discounting. This persistent age difference implies mechanisms beyond noise or cognitive parameters, such as changing life circumstances or limited future perspective.

Keywords Value-based decision-making · Delay discounting · Risk-taking · Processing noise · Cognitive performance · Adult life span

In all phases of life, people make decisions with important consequences for their future, such as taking out insurances or attending medical check-ups. Weighing options involves cognitive resources for assessing factors such as *valence* (i.e., the intrinsic positive or negative quality) of a decision, *delay* until making a decision and receiving the outcome, and *risk* to achieve the desired outcome depending on the subjective evaluation of the probability or uncertainty of an outcome.

Delay discounting—i.e., the tendency of individuals to devalue or discount future rewards and to prefer smaller immediate over larger delayed rewards (Green et al., 1999)—has frequently been studied. Individual studies on the association of aging with delay discounting revealed mixed results, with some showing no difference between young and older adults (Mata, et al., 2011; Samanez-Larkin et al., 2011; Whelan & McHugh, 2009) and others finding a stronger preference for delayed over immediate rewards in older adults (Bixter & Rogers, 2019; Eppinger et al., 2012; Green et al., 1994, 1999; Löckenhoff et al., 2011) or, conversely, in young adults (Read & Read, 2004). A recent meta-analysis of 50 publications totaling 115,496 participants (125 effect sizes extracted) has revealed a significant, but very small, negative correlation ($r = -0.04$) between age and delay discounting (Bagaïni et al., 2023). The authors conclude that the estimated effect size is so low that it is trivially small.

Michael N. Smolka
Michael.smolka@tu-dresden.de

Anja Richtmann
anja.stock@mailbox.tu-dresden.de

Johannes Petzold
Johannes.petzold@tu-dresden.de

Franka Glöckner
franka.gloeckner@tu-dresden.de

1 Section of Systems Neuroscience, Department of Psychiatry and Psychotherapy, Faculty of Medicine, Technische Universität Dresden, Würzburger Str. 35, 01187 Dresden, Germany

2 Chair of Behavioral Psychotherapy, Faculty of Psychology, Technische Universität Dresden, Dresden, Germany

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Regarding risk-taking tasks, research indicates greater risk aversion towards probabilistic gains among older adults (Mather et al., 2012; Rutledge et al., 2016; Tymula et al., 2013). Yet, conflicting results arise when tasks require choosing between two risky options (Mather et al., 2012; Pachur et al., 2017). The first meta-analysis (Best & Charness, 2015) reported a weak ($g = -0.25$) but significant association of age and risk taking in the gain domain, and is in line with the recent meta-analysis (Bagaïni et al., 2023) that also reported a slight but significant decline in risk seeking for gains with age ($r = -0.05$). While young and older adults show comparable choice behavior in decision-making tasks that fully disclose the information about outcome probabilities, age differences might be more apparent in tasks requiring the outcome probabilities to be learned (Mata et al., 2011), highlighting potential effects of task design.

Some studies investigating discounting of probabilistic losses suggest that older adults take more risks to avoid losses (Best & Freund, 2018; Fernandes et al., 2018; Mather et al., 2012), yet the (online) study with the largest sample size (> 25,000 participants) found no respective age-related differences (Rutledge et al., 2016). In line with the latter, both meta-analyses cited above (Bagaïni et al., 2023; Best & Charness, 2015) did not find significant associations between age and risk taking in the loss domain ($r = 0.02$ and $g = -0.02$, respectively).

Regarding tasks with mixed probabilistic outcomes, the large (online) study identified a small ($r = 0.02$), non-monotonic, but significant increase in risk taking across the adult lifespan when looking at decision-making behavior in tasks involving both potential gains and losses (Rutledge et al., 2016). The literature is unclear about how decision-making in these mixed tasks may change with increasing adult age, with studies reporting a reduced willingness to gamble (Arora & Kumari, 2015; O'Brien & Hess, 2020), referred to as loss aversion. However, again, other studies found no differences in loss aversion (Li et al., 2013; Seaman et al., 2018). The aforementioned meta-analysis by Bagaïni and colleagues (2023) found also no significant effect of age on the mixed domain ($r = 0.012$).

Discrepancies in findings regarding delay discounting could partly be related to high inter-individual differences (Kanai & Rees, 2011) or variations in the duration of delays (Leverett et al., 2022). Factors contributing to inconsistencies in the literature on risk attitudes might be due to different task characteristics regarding probability discounting (Mata et al., 2011) and loss aversion (Rutledge et al., 2016; Seaman et al., 2018). A nonlinear relationship between age and decision parameters (Guttman et al., 2021), demographic factors such as income status (Green et al., 1996), or the cultural context in which the studies were conducted (Rieger & Mata, 2015) may also explain some variance in the observed decision behaviors. Also whether studies are performed in the laboratory or online, possibly due to variations in sample characteristics, seem to moderate associations that seem to be of small effect size (Bagaïni et al., 2023).

Several theories elucidate potential age-related disparities in decision-making between young and older adults. These theories on aging-related changes in decision-making behavior can be categorized into biological or neurodegeneration-related mechanisms versus social psychological phenomena. A prominent hypothesis and representative of biological theories is the frontal aging hypothesis, which postulates that the frontal lobes are especially vulnerable to aging-related deteriorations with potentially adverse effects on higher cognitive functions like problem-solving, memory retention, and attention control (West, 1996). Neuromodulation theories further relate aging-related changes in neurotransmitter systems such as the dopamine system to age differences in decision-making, including changes in reward evaluation and risk tolerance (e.g., Eppinger et al., 2011). In addition, aging-related changes in relevant brain structures or in the efficiency of communication within the neural networks involved in decision-making processes are also assumed to impact reward processing (Best & Charness, 2015; Raz et al., 1998) as well as decision speed and accuracy (Bennett & Madden, 2014). These changes may be associated with increased cognitive noise (Li & Sikström, 2002; Li et al., 2001a, 2001b; MacDonald et al., 2009; Pachur et al., 2017), which in turn could affect decision-making processes in older age. Previous work (MacDonald et al., 2009, 2012; Papenberg et al., 2013) suggests that intra-individual response variability, i.e., trial-by-trial fluctuations in response behavior such as response time, can serve as behavioral indicators of neuronal noise. The aging-related increase in intra-individual response variability (hereafter referred to as processing noise) is often associated with reduced cognitive performance or a bias towards less demanding cognitive strategies in older age (Glöckner et al., 2021; cf. MacDonald et al., 2009 for review). In the context of decision-making, for example, individuals with higher levels of processing noise seem to prefer certain or immediate outcomes over delayed ones (Burks et al., 2009; Mather et al., 2012). Moreover, increasing the salience of information during value-based decision-making can improve choice behavior in older adults, presumably by increasing the distinctiveness of value representations (i.e., reducing noise in representations) and thereby reducing the cognitive demands during value computation (Chen et al., 2021). Regarding social psychological theories, the socioemotional selectivity theory (Carstensen, 2006) is of specific relevance and postulates that individuals prioritize emotional fulfillment as they age, recognizing the finite nature of their lifetime, which might impact the way older adults evaluate rewards and risk.

In summary, the literature reviewed above highlights the complexity of decision-making processes across the adult lifespan. While various studies have contributed valuable insights, a considerable uncertainty remains in understanding how these processes evolve with age. This study, which was conducted between June 2017 and October 2020, investigated whether older adults (63–76 years) and young adults (25–38 years) differ in four dimensions of value-based decision-making: delay discounting, risk attitudes towards probabilistic gains and probabilistic losses, and loss aversion. In addition, we investigated differences in cognitive abilities and processing noise between young and older adults and explored potential mediating effects of these variables on choice behavior. Our study used four computerized tasks providing full information on delays or odds and visual representations of probabilities to minimize cognitive load. We examined whether measures of crystallized abilities (verbal knowledge) and fluid abilities (specifically working memory and speed of processing), or processing noise (i.e., reaction time variability and decision consistency) might mediate or mask potential decision-making differences related to age. We hypothesized that reduced working memory capacity and increased processing noise in older adults might be associated with a preference for safer or earlier options. Thus, we expected older adults to demonstrate steeper temporal discounting, higher probability discounting for gains (indicating higher risk aversion), lower probability discounting for losses (indicating less risk seeking), and higher loss aversion compared to young adults. If age-related differences were observed, we anticipated that basic cognitive abilities such as working memory and speed of processing or processing noise parameters might mediate the observed age group differences.

Materials and Methods

This study is part of the "Aging and dopamine modulation of complementary control processes" project within the Collaborative Research Center 940 "Volition and Cognitive Control" (www.sfb940.de).

Participants

We recruited young (25–38 years) and older adults (63–76 years) by sending 5927 study information letters to addresses provided by the resident registration office of Dresden, Germany. We screened 672 interested adults via telephone interview and excluded 485. Exclusion criteria were severely impaired vision or hearing without correction, a lifetime history of major neurological or mental disorders, intake of drugs with potential impact on the dopaminergic system, and contraindications to L-DOPA or magnetic resonance imaging. We excluded all participants who tested positive for commonly used drugs (i.e., methamphetamine, amphetamine, morphine, benzodiazepines, and cocaine; urine test; SureStep, Innovacon, San Diego, CA, USA) or alcohol (breath alcohol analysis; Alcotest 6581 med, Dräger, Lübeck, Germany). Older adults completed the Montreal Cognitive Assessment (MoCA) for global dementia screening and were excluded if they scored fewer than 19 points to ensure a minimal level of cognitive function, while still including a range of cognitive abilities typical of older adults. This cutoff was selected based on research suggesting that lower MoCA scores can be indicative of significant cognitive impairment (Nasreddine et al., 2005), yet using a cutoff of 18 allows for the inclusion of individuals with mild cognitive deficits who can still meaningfully participate in decision-making tasks. In this study, 4 older participants were in the <23 range, indicating mild cognitive impairment (Carson et al., 2018). The final sample included 86 young adults ($M=31.08$, $SD=2.98$ years of age; 35 women) and 93 older adults ($M=69.06$, $SD=3.14$ years of age; 37 women). Participants received €34 for compensation and an additional performance-based payment ($M=$€17.86). During data collection (2017–2020), the Euro to US Dollar exchange rate fluctuated between approximately 1.12 and 1.22.

Value-Based Decision-Making Battery

We used a value-based decision-making battery consisting of four tasks (Pooseh et al., 2018) to measure delay discounting and risk taking. An example depiction of the four tasks as they were presented to the participants on the computer screen is provided in Fig. 1. In the delay discounting task, participants decided between an immediate smaller and a larger reward (€3–50) available at varying delays (3, 7, 14, 31, 61, 180, 365 days).

In the probability discounting for gains and losses tasks, participants chose between an uncertain higher and a certain smaller reward or loss ranging from €3 to 50. To limit demands for abstraction and numeracy skills, the different probabilities (2/3, 1/2, 1/3, 1/4, 1/5) were visually represented by ratios of blanks and wins or losses in two jars (Fernandes et al., 2018).

In the mixed gambles task, participants accepted or rejected a gamble with a 50% chance of winning (€1–40) and losing (€5–20) after receiving a one-time deposit of €10 to encourage gambling (Ert & Erev, 1930). Each task consisted of 50 trials with two offers presented simultaneously. The responses, which were limited to five seconds, were registered on standard keyboards, and the selected option was highlighted with a green frame. Participants saw the outcome of each decision in risk taking tasks. They were informed at the beginning that for each of the four tasks one of their decisions would be randomly selected and monetary compensation for study participation would be increased by the corresponding bonus

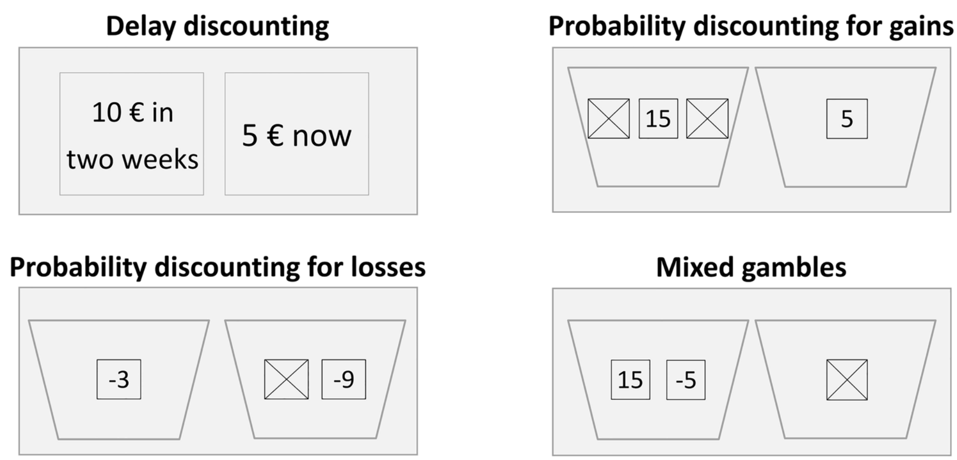

Fig. 1 Illustration of Exemplary Tasks from the Value-Based Decision-Making Battery. Throughout the battery, the amounts, probabilities, and delays were systematically varied. In delay discounting tasks, participants were presented with a choice between receiving an immediate payout or opting for a larger amount to be paid out after a delay, for example, in two weeks. During the probability discounting for gains task, participants had the option to select between a guaranteed gain and a larger, but uncertain gain. In the probability discounting for losses task, individuals were faced with the decision between a certain, smaller loss and a larger, uncertain loss. In the mixed gambles task, participants could choose either not to play, or to engage with a 50% chance of either incurring a loss or achieving a win

amount (minimum bonus = 0). Participants were instructed that the bonus payout could be delayed depending on the decisions they made in the delay discounting task, but basic monetary compensation was ultimately done without delay for administrative reasons. The average time taken to complete the entire test battery was 21.6 min ($SD = 3.4$; $range = 15.1–34.4$).

The battery employs an adaptive Bayesian algorithm based on trial-by-trial observations that updates offers following a hyperbolic function according to the individual indifference point (no preference for either offer). The likelihood of choosing between offers is described by a softmax probability function. Further information regarding the mathematical framework of the battery is provided by Pooseh et al. (2018).

Individuals exhibit higher delay discounting when they prefer smaller immediate gains (high k) and lower delay discounting when they choose larger delayed options (low k). Risk seeking individuals are more likely to accept the possibility of winning nothing to maximize outcomes (low k), whereas risk averse individuals favor smaller certain gains (high k). In the probability discounting for losses task, risk seeking individuals take the chance of losing a higher amount to avoid any loss (high k), and risk averse adults tend to choose a certain loss to prevent higher losses (low k). Loss-averse individuals (high λ) prefer maintaining the amount of money they possess at the start over taking the risk of losing or winning money (Tom et al., 2007). We applied a natural logarithmic transformation of k and λ values to approximate the data to a normal distribution. Five participants had missing data for at least one task.

Cognitive Covariates

To account for fluid cognitive abilities, we evaluated working memory for spatial locations and serial order, and perceptual processing speed (Identical Pictures Task). A verbal comprehension task (Spot-a-Word test) was implemented as a correlate of crystallized cognitive abilities (specifically verbal knowledge). All tests relating to the cognitive variables took 30 min, including a 5-min briefing. The cognitive tasks and covariate measures are described in greater detail below.

Verbal Knowledge

In a modified version of the Spot-a-Word test (Lindenberger et al., 1993), participants were asked to identify the one true word among five words, of which four were pronounceable non-words, as quickly and as correctly as possible. The test ended after 35 trials or three consecutive incorrect answers. We used accuracy (ratio of correct to all responses) as an indicator of verbal knowledge. Data were missing from the same two participants whose data were missing for the Identical Picture Task.

Working Memory for Spatial Location and Serial Order

We used a computerized version of a working memory task for spatial location and serial order (Nagel et al., 2008), wherein participants were shown a 4-by-4 grid of white circles on a blue background. For each of the 96 trials, four (low working memory load level) or seven (high working memory load level) circles were highlighted sequentially and participants indicated whether a probed circle was among those highlighted (working memory for spatial location). If so, a digit (1–7) appeared in the center of this circle and participants decided whether this digit matched the circle's position in the sequence (working memory for serial order). Participants indicated their responses by pressing one of two buttons (yes or no). Ratios of correct answers served as accuracy measures for both subtasks. Due to data loss, one older adult was excluded from the analysis of both subtasks, and 13 older participants were excluded from the analysis of the serial order memory subtask. A detailed description of the missing data can be found in the Supplementary Materials. We performed Mann–Whitney U tests to compare decision-making in older participants with complete versus incomplete data on working memory for serial order, finding no significant differences between the groups (all $p > 0.16$), as detailed in our missing data statement in the Supplementary Information.

Perceptual Processing Speed

In the Identical Pictures Task, participants saw a black-and-white line drawing in the upper part of the computer screen and selected the matching drawing from five options below by pressing a corresponding key (1–5) as quickly as possible. The test lasted 80 s. The mean response time served as a parameter for perceptual speed. One young and one older adult who did not comply with the task instructions were excluded from the analyses. Data from one young and one older participant were missing.

Correlates of Processing Noise

Processing noise can lead to less distinctive reward representation, affecting evaluation of risks and delayed rewards (Li et al., 2007). We computed two measures of processing noise reflecting response variability: The first was derived from the Identical Pictures Task, where intra-individual reaction time variability (standard deviation of reaction times) indicated cognitive fluctuations and neural noise. Three participants were excluded for this measure due to incomplete data.

The second measure, choice consistency parameter β, was estimated using a softmax probability function from the decision-making battery, with higher values reflecting higher consistency in selecting options, and thus a higher probability of taking more valuable offers (Pooseh et al., 2018). The correlations between the averaged parameter and the beta scores for each task range between 0.51 and 0.67 (Table S1), indicating that choice consistencies in the different tasks are highly associated. We were therefore able to compute one parameter by averaging the mean-centered β values from all four tasks, with lower consistency indicating higher decision noise.

Statistical Analysis

Analyses were performed in IBM SPSS Statistics (Version 25), applying a significance level of $p < 0.05$ for all tests. Two-tailed t tests assessed differences between age groups. We calculated Pearson's bivariate and partial correlation coefficients r and r_p (correcting for age group) for associations among decision-making, cognitive, and noise variables. We used bootstrapping (5000 samples) to compute bias-corrected accelerated 95% confidence intervals.

For significant correlations, we performed bootstrapping mediation analyses (Preacher & Hayes, 2008) using the PROCESS macro for SPSS (http://afhayes.com/spss-sas-and-mplus-macros-and-code.html) with age group as the independent variable (X), value-based decision-making scores as dependent variables (Y), and noise or cognition parameters as mediators (M). An illustration of the hypothetical mediation model is provided in Fig. 2. Coefficients were calculated for each association, including the total effect (c), the indirect effect (ab), and the direct effect (c') of age group on value-based decision-making. Path a indicates the relationship between X and M, while b represents the relationship between M and Y. Effect sizes were quantified by applying Cohen´s d.

Results

Differences Between Age Groups

In decision-making (Fig. 3a, Table 1), older adults showed higher delay discounting ($t_{175} = -3.01$, $p = 0.003$) than young adults, with a medium-sized effect ($d = 0.45$). Age group comparison regarding risk aversion for probabilistic

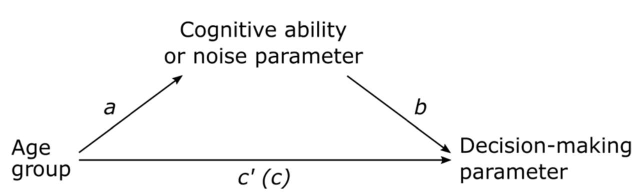

Fig. 2 Path Diagrams of Theoretical Mediation Models. The age group is used as independent variable. The decision-making parameter corresponds to the dependent variable. Either noise or cognitive abilities represent the mediator in this model. Age group can either have a direct effect (c') on the dependent variable after accounting for the mediator, or the influence of age group on the dependent variable is indirect and mediated by the respective mediator variable (indirect effect ab). The total effect c reflects the sum of the direct and the indirect effect ($c = a \times b + c$')

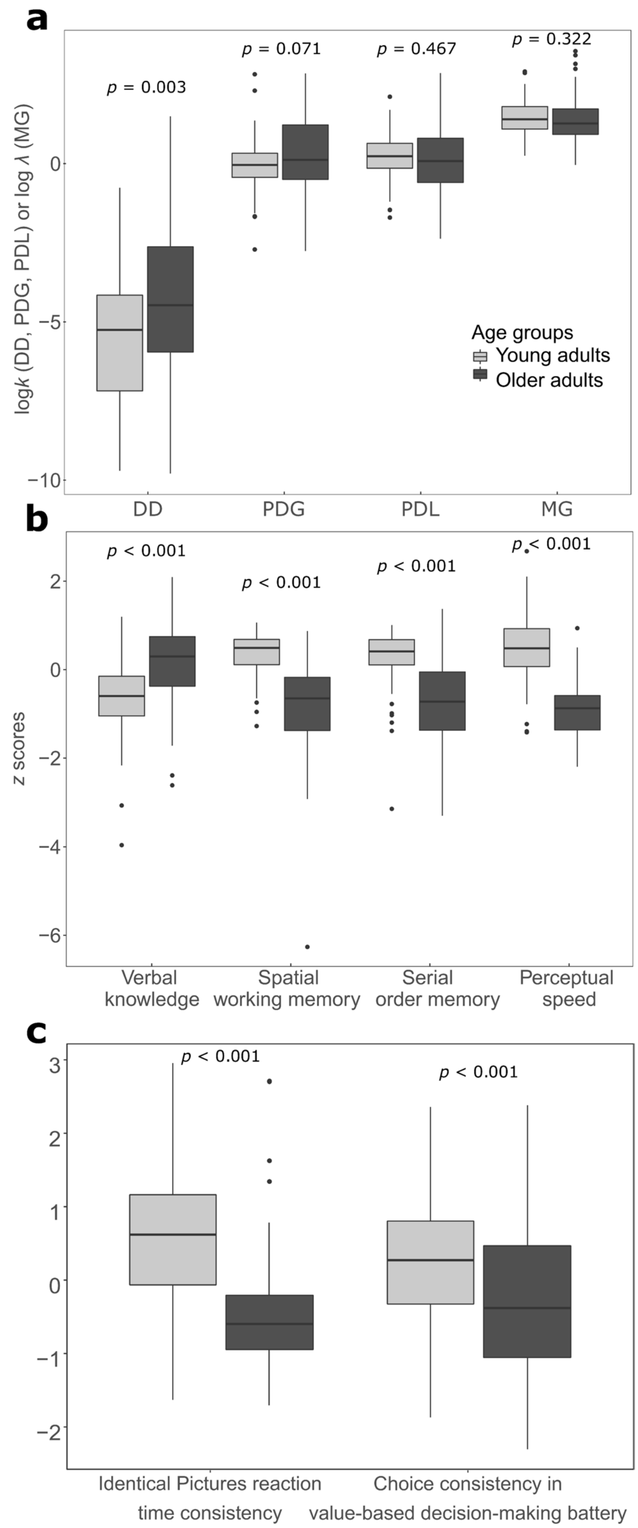

Fig. 3 Decision-Making, Cognitive and Noise Parameters. **a** Comparison of performance on value-based decision-making tasks between younger and older participants. *DD* delay discounting, *PDG* probability discounting for gains, *PDL* probability discounting for losses, *MG* mixed gambles. **b** Comparison of cognitive skills between young and older adults with high *z*-scores indicating superior and low *z*-scores indicating inferior performance. Perceptual speed is displayed as the reciprocal of reaction time in the Identical Picture tasks. **c** Comparison of noise parameters between young and older adults. Reaction time consistency is the reciprocal of intra-individual reaction time variability. High *z*-scores indicate superior and low *z*-scores indicate inferior performance

gains did not reach significance but trended higher among older adults ($t_{176} = -1.82$, $p = 0.071$, $d = 0.27$) than young adults. Risk seeking for probabilistic losses ($t_{176} = 0.73$, $p = 0.467$, $d = 0.11$) and loss aversion ($t_{178} = 0.99$, $p = 0.322$, $d = 0.15$) did not significantly differ between groups.

Young adults outperformed older adults ($p < 0.001$) in all tasks capturing fluid abilities (Fig. 3b, Table 1), including working memory for spatial location (92% vs. 80% accuracy, $d = 1.43$) and serial order (80% vs. 60%, $d = 1.33$), and processing speed (2.5 vs. 3.6 s, $d = 1.90$). As expected, the older group exhibited greater accuracy in the Spot-a-Word task (63% vs. 72%, $p < 0.001$, $d = 0.76$), which tests verbal knowledge as a correlate of crystallized abilities.

Furthermore, older adults exhibited more noisy responses than younger adults (Fig. 3c, Table 1), with increased reaction time variability in the Identical Pictures Task (740 ms vs. 1106 ms, $p < 0.0001$, $d = 1.06$) and reduced decision consistency across the decision-making battery (0.24 vs. − 0.22, $p < 0.0001$, $d = 0.59$).

Association Between Decision-Making and Cognitive/Noise Scores

To explore the relations between value-based decision-making, basic crystallized cognitive abilities (verbal knowledge), fluid abilities (working memory, processing speed), and processing noise, we computed bivariate and partial (controlling for age group) correlation coefficients (Table 2). The results indicated no significant associations between measures of decision-making and verbal knowledge or speed of processing.

We determined the age-corrected correlations between decision-making performance and cognitive abilities or noise parameters, which are presented in Figure S1 of the supplementary materials. Partial correlations with working memory were significant between delay discounting and working memory for spatial locations ($r_p = 0.171$, $n = 173$) as well as for risk seeking for losses and working memory for serial order ($r_p = 0.183$, $n = 161$). Regarding the correlates of processing noise, there were no significant associations between measures of decision-making and trial-by-trial variability in the speed of processing (Identical Pictures) task. However, higher processing noise (as operationalized as lower choice consistency) across the decision-making battery was associated with better performance in delay discounting ($r_p = -0.311$, $n = 175$) and mixed gambles (loss aversion) trials ($r_p = -0.180$, $n = 178$).

Table 1 Decision-making behavior, cognitive skills, and noise parameters by age groups

VBDM	Young adults			Older adults			*t* test		
	n	*M*	*SD*	*n*	*M*	SD	*t*	*p*	Cohen's *d*
$\log k_{DD}$	84	− 5.60	2.133	91	− 4.45	2.877	− 3.01	.003	− .45
$\log k_{PDG}$	84	.05	.804	92	.33	1.214	− 1.82	.071	− .27
$\log k_{PDL}$	84	.29	.753	92	.18	1.260	.73	.467	.11
$\log \lambda_{MG}$	86	1.54	.576	92	1.44	.736	.99	.322	.15
Cognitive abilities								CI	
Spatial working memory	86	92.15	5.03	91	79.79	11.04	9.67	[9.93, 15.02]	1.43
Serial order memory	86	79.98	11.57	79	60.22	17.76	8.39	[15.28, 24.16]	1.33
Perceptual speed	84	2465.41	468.08	91	3568.59	669.73	12.71	[− 1272.63, − 930.88]	− 1.90
Verbal knowledge	85	62.89	11.28	92	71.74	11.84	− 5.08	[− 12.21, − 5.48]	− .76
Noise parameters									
Reaction time SD in IDP task [ms]	84	739.55	309.39	91	1105.84	376.71	− 7.00	[− 464.48, − 267.73]	− 1.06
Decision consistency	86	.24	.68	93	− .22	.84	3.97	[.24, .68]	.59

VBDM value-based decision-making battery, *DD* delay discounting, *PDG* probability discounting for gains, *PDL* probability discounting for losses, *MG* mixed gambles, *IDP* identical pictures

We found significant bivariate correlations between delay discounting and decision consistency ($r = -0.352$, $n = 175$), between loss aversion and decision consistency ($r = -0.151$, $n = 178$), between risk aversion for gains and working memory for serial order ($r = -0.210$, $n = 162$), and risk seeking for losses and working memory for serial order ($r = 0.180$, $n = 162$).

Mediation Analyses

To clarify whether choice consistency during decision-making or working memory for spatial location and serial order influenced decision-making, we conducted mediation analyses with the variables that were significantly zero-order or partially (controlling for age group) correlated with value-based decision-making parameters (Fig. 4). Older adults' poorer performance in working memory for spatial location (CI $-1.42 \le a \le -0.93$) was related to less delay discounting (CI $0.03 \le b \le 0.38$). The mediation model revealed an indirect relationship between age group and delay discounting that is mediated by baseline working memory performance (CI $-0.58 \le ab \le -0.01$). The differences between age groups in delay discounting (CI $0.12 \le c \le 0.70$) increased when considering age differences in working memory for spatial location (CI $0.30 \le c' \le 1.00$; model Fig. 4a), indicating a competitive mediation (Zhao et al., 2010). Decision consistency fully mediated the age effect on delay discounting (CI $0.15 \le ab \le 0.73$) by weakening the correlation (CI $0.15 \le c \le 0.73$) between the age group and delay discounting (CI: $-0.02 \le c' \le 0.56$; model Fig. 4b). When controlling for both spatial working memory and decision consistency in one partial correlation model, we found steeper delay discounting in older adults ($r = 0.231$, $p = 0.002$, $d = 0.47$).

Working memory for serial order did not mediate the association between age and probability discounting for gains as indicated by the nonsignificant indirect path (CI: $-0.00 \le ab \le 0.60$; model Fig. 4c).

When probability discounting for losses and its potential mediators were examined, serial order memory (CI $-0.48 \le ab \le -0.02$) showed significant indirect effects. The numerical effect of age group on probability discounting for losses (CI $-0.40 \le c \le 0.21$) reversed when serial order memory was included (CI $-0.22 \le c' \le 0.50$; model Fig. 4d), indicating a competitive mediation.

The mediation analysis of loss aversion via decision consistency also revealed a significant indirect effect (CI $0.02 \le ab \le 0.22$). The association between age group and loss aversion (CI $-0.44 \le c \le 0.15$) increased when decision consistency was included as a mediator (CI $-0.56 \le c' \le 0.05$; model Fig. 4e), but this increase was not significant.

To further interpret the observed effects, we conducted separate correlation analyses for each age group in models, where competitive mediation effects were identified: In the younger age group, better spatial working memory was associated with higher delay discounting ($r = 0.323$, $p = 0.003$, CI 0.092; 0.507), a relationship that was not observed in older adults ($r = 0.128$, $p = 0.231$, CI − 0.069; 0.377). In contrast, in the older age group, higher decision consistency was linked to lower loss aversion ($r = -0.235$, $p = 0.024$, CI − 0.420; − 0.039), while this association did not appear in the younger age group ($r = -0.086$, $p = 0.434$, CI − 0.284;

Table 2 Zero-Order and Partial Correlations (Corrected for Age Group) Between Decision-Making Performance and Cognitive Abilities or Noise Parameters

Cognitive abilities	$\log k_{DD}$			$\log k_{PDG}$			$\log k_{PDL}$			$\log \lambda_{MG}$		
	Bivariate correlation	Lower bound	Upper bound	Bivariate correlation	Lower bound	Upper bound	Bivariate correlation	Lower bound	Upper bound	Bivariate correlation	Lower bound	Upper bound
Spatial working memory	.014	− .138	.188	− .042	− .238	.136	.103	− .054	.256	.071	− .110	.239
Serial order memory	− .049	− .225	.134	− .210*	− .366	− .035	.180*	.007	.340	.050	− .165	.259
Perceptual speed	.097	− .074	.266	.091	− .052	.238	− .040	− .202	.125	− .114	− .283	.049
Verbal knowledge	.138	− .009	.280	.026	− .158	.207	− .003	− .157	.149	.072	− .114	.246
Noise parameters												
Reaction time SD Identical Picture Task [ms]	.079	− .079	.220	.003	− .133	.145	− .070	− .247	.101	− .050	− .211	.112
Decision consistency	− .352*	− .479	− .209	− .082	− .238	.073	− .004	− .152	.139	− .151*	− .295	− .010
Cognitive abilities	Partial correlation	Lower bound	Upper bound	Partial correlation	Lower bound	Upper bound	Partial correlation	Lower bound	Upper bound	Partial correlation	Lower bound	Upper bound
Spatial working memory	.171*	.003	.379	.039	− .176	.226	.094	− .049	.238	.026	− .145	.182
Serial order memory	.067	− .115	.255	− .152	− .306	.006	.183*	.024	.334	.022	− .172	.212
Perceptual speed	− .072	− .234	.103	.015	− .122	.164	− .012	− .168	.143	− .065	− .219	.087
Verbal knowledge	.062	− .089	.210	− .021	− .217	.186	.019	− .147	.185	.107	− .100	.306
Noise parameters												
Reaction time SD Identical Picture Task [ms]	− .025	− .180	.120	− .059	− .193	.082	− .055	− .220	.105	− .005	− .164	.158

Table 2 (continued)

Noise parameters												
Decision consistency	− .311*	− .450	-.151	− .048	− .211	.115	− .020	− .162	.118	− .180*	− .322	− .037

DD delay discounting, *PDG* probability discounting for gains, *PDL* probability discounting for losses, *MG* mixed gambles

* $p < .05$

0.123). Better serial order memory was associated with higher probability discounting for losses only in older adults ($r = 0.254$, $p = 0.025$, CI 0.029; 0.445), whereas this association was not present in the younger age group ($r = 0.015$, $p = 0.890$, CI − 0.160; 0.177).

Discussion

This study explored potential differences between healthy young and older adults in decision-making, specifically in delay discounting, risk aversion for gains, risk seeking for losses, and loss aversion, thereby taking aging-related differences in cognition, especially in fluid cognitive abilities, and in behavioral indices of processing noise into account. Among 179 participants, older adults exhibited steeper delay discounting than young adults. Regarding the covariates for fluid cognitive abilities and processing noise, we replicated the expected age effect of lower spatial working memory, higher trial-by-trial response variability, and lower decision consistency in older adults compared to young adults. Exploratory mediation analyses indicated that lower decision consistency and better spatial working memory promoted steeper discounting, but these analyses also indicated robust age differences even when controlling for both mediators. We further observed a slight trend towards higher risk aversion for gains in older adults but no differences in risk seeking for losses and loss aversion, even when adjusting for cognitive abilities and processing noise. The lack of a clear age difference in those three tasks is in line with the recent meta-analysis by Bagaïni and colleagues (Bagaïni et al., 2023), which also reported nonsignificant effects of age on these decision-making parameters. In the following, we will therefore focus on the mediating effects of processing noise as indicated by choice consistency during decision-making and working memory capacity on the observed adult age differences in delay discounting.

Choice consistency fully mediated age differences in delay discounting such that age differences decreased when taking choice consistency into account. Lower choice consistency might be explained by increased processing noise in older adults (Li & Sikström, 2002; Li et al., 2001a, 2001b; MacDonald et al., 2009; Pachur et al., 2017), which impedes the evaluation of complex options' overall utility, leading older individuals to focus on simpler or more immediate options (Burks et al., 2009). Increased processing noise in older adults might reduce the specificity of value representations and thereby bias choice behavior towards computationally less demanding (i.e., immediate) choice options. This bias in choice behavior in older individuals may have important real-life implications for various decision-making domains, affecting economics, finances, health, social, and political topics.

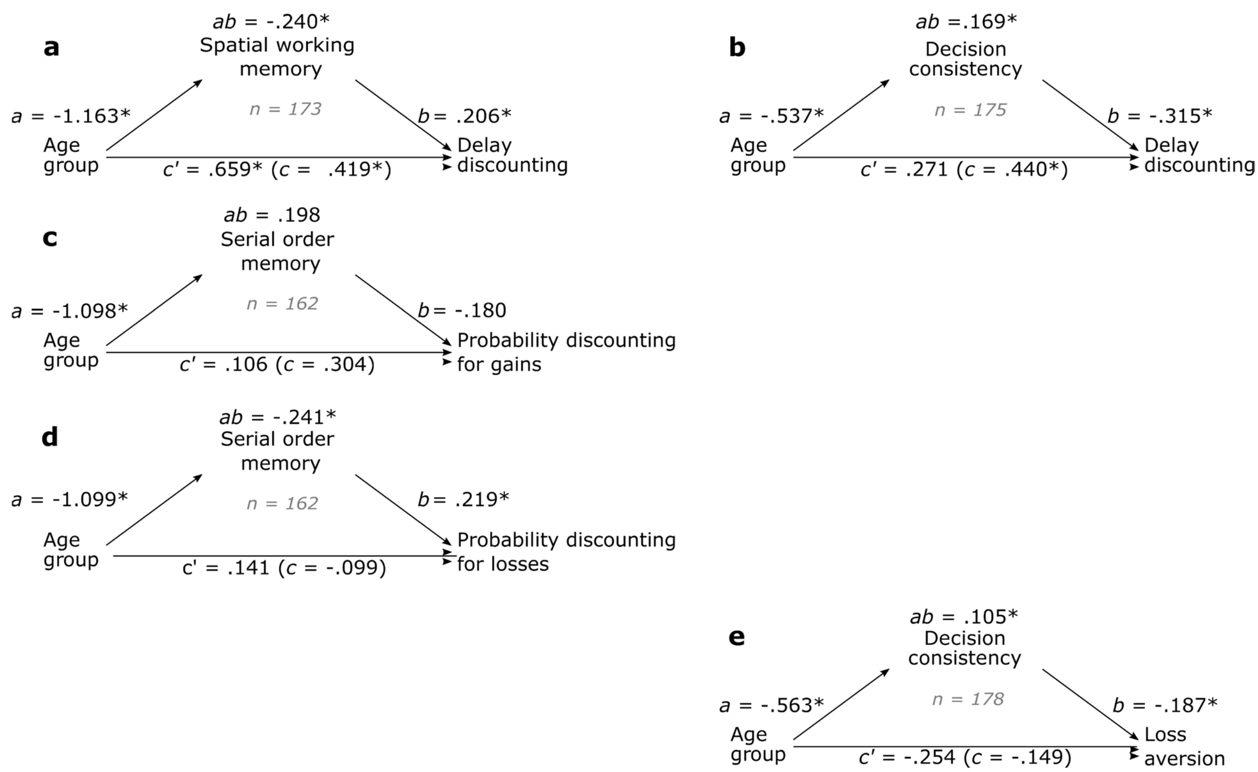

Fig. 4 Path Diagrams of Mediation Models. Standardized coefficients are shown for each association, including the total effect (*c*), the direct effect (*c'*), and the indirect effect (*ab*) of age group on value-based decision-making

We further observed a competitive mediation of age group via spatial working memory on delay discounting, suggesting that if both groups had had equal spatial working memory performance, the age difference would have been even larger. We found that in younger adults, better spatial working memory was significantly associated with higher delay discounting, implying that in younger individuals a more effective spatial working memory shifts their decision-making behavior towards more prioritization of immediate rewards over future ones. Conversely, the absence of a similar relationship in older adults suggests that the influence of spatial working memory on discounting diminishes with age. One possible explanation is that even older adults with above-average working memory capacity may be unable to allocate sufficient cognitive resources to enhance their decision-making performance. This limitation could stem from an overall decline in working memory capacity, which hinders their ability to compensate for the increased noise observed in their decision-making processes. Our finding of the association between higher spatial working memory and steeper delay discounting contradicts previous findings showing an inverse relation between working memory and delay discounting (Aranovich et al., 2016; Finn et al., 2015; Shamosh et al., 2008; Szuhany et al., 2018). This discrepancy might in part be related to the use of different tasks. We applied a visuospatial working memory task, whereas previous studies tested verbal working memory in retaining information while doing arithmetic (Finn et al., 2015) or n-back tasks (Aranovich et al., 2016; Szuhany et al., 2018). However, this shows that spatial working memory plays a role in this process by supporting the maintenance and manipulation of the information necessary for evaluating the delayed reward, which is a cognitive process that is involved in various decision-making tasks. Importantly, age differences persisted even when both mediators, working memory and processing noise, were considered. This result could indicate that other psychological mechanisms could play an important role in addition to neurodegeneration-related mechanisms. Possible causes contributing to age differences might also be related to motivational factors or recognition of the finite nature of life in old age. Understanding that age differences in delay discounting may even persist when accounting for mediators highlights the complexity of the underlying processes as well as the influence of individual differences in covariate measures on decision-making across the lifespan. However, the effect size found in our study ($d = 0.47$) is substantially greater and of opposite direction compared to the very recent meta-analysis by Bagaïni and colleagues (2023). One reason may be that our sample of older participants is not representative of the general older population given our strict screening process, but rather applies to high-functioning older adults.

Of note, both higher processing noise (i.e., lower choice consistency) and lower spatial working memory in older adults may reflect lower dopamine receptor density (MacDonald et al., 2012) and dopamine tone (Störmer et al., 2012), which decrease with age (Karrer et al., 2017; Samanez-Larkin et al., 2010). Dopamine appears to increase the signal-to-noise ratio, and thus reduce processing noise (Bäckman et al., 2010; MacDonald et al., 2012). Together, these studies support the claim that deterioration within the dopamine system may cause changes in behavior during aging (Bäckman et al., 2006).

Limitations

The cross-sectional design of this study precludes causal claims about the effects of age on decision-making and renders the results susceptible to cohort effects. For example, we did not control for factors such as income, which might be relevant in the context of our decision-making battery, so we can only speculate about possible differences between groups that are unrelated to age. Additionally, our task did not systematically manipulate the variation in delays (3–365 days) and in rewards (€3–50) between participants, and did not compare potential domain-specific adult age differences in delay discounting (e.g., Jimura et al., 2011). Furthermore, the ecological validity of our task may be rather limited, rendering our results to some extent measure-specific. We focused on basic cognitive abilities and processing noise as potential mediators of age effects on decision-making, and did not consider individual differences with regard to personality traits, socioemotional or other factors that might also be of relevance.

Due to non-response and sampling biases (as evident, for example, from the to be expected low response rate during recruitment and the necessity of rather strict exclusion criteria), our sample is non-representative, with our older adults likely being higher functioning than the general older population. In addition, a sensitivity analysis (G*Power, Version 3.1.9.6) indicated that our sample size is only sufficient to detect an effect size of $d = 0.42$ with 80% power. Studies in larger samples with less rigorous exclusion criteria and therefore fewer limitations with regard to representativeness are needed to extend our conclusions towards a broader population.

Conclusion

Our study contributes to the recent body of literature suggesting that age effects on decision-making, when comparing healthy young and older adults, are small (see also the recent meta-analysis by Bagaïni et al., 2023). Our study further highlights that adult age differences might in part depend on the decision-making domain and task, and are presumably also affected by individual differences in baseline cognitive function and processing noise (as reflected in the consistency of choice behavior). Of specific interest, our results indicate that older adults' less consistent choice behavior and poorer working memory performance might bias their decision behavior towards higher discounting rates in some tasks, resulting in a robust age effect on delay discounting in our sample. Although our study lacks sufficient representativeness, it might stimulate future studies that further elucidate individual differences in decision-making across the adult lifespan.

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Data Availability The data that support the findings of this study, along with syntax are openly available in the Open Science Framework at https://osf.io/t7v2j/. The data will be shared in preprocessed form that ensures full anonymity of participants, in line with funding and data security regulations.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Aranovich, G. J., McClure, S. M., Fryer, S., & Mathalon, D. H. (2016). The effect of cognitive challenge on delay discounting.

NeuroImage, 124(Pt A), 733–739. https://doi.org/10.1016/j.neuroimage.2015.09.027

Arora, M., & Kumari, S. (2015). Risk taking in financial decisions as a function of age, gender: Mediating role of loss aversion and regret. *International Journal of Applied Psychology, 5*(4), 83–89. https://doi.org/10.5923/j.ijap.20150504.01

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

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

Bagaïni, A., Liu, Y., Bajrami, A., Son, G., Tisdall, L., & Mata, R. (2023). Aging and economic preferences: Cumulative meta-analyses of age differences in risk, time, social, and effort preferences. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences, 78*(7), 1122–1135. https://doi.org/10.1093/geronb/gbad034

Bennett, I. J., & Madden, D. J. (2014). Disconnected aging: Cerebral white matter integrity and age-related differences in cognition. *Neuroscience, 276*, 187–205. https://doi.org/10.1016/j.neuroscience.2013.11.026

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

Best, R., & Freund, A. M. (2018). Age, loss minimization, and the role of probability for decision-making. *Gerontology, 64*(5), 475–484. https://doi.org/10.1159/000487636

Bixter, M. T., & Rogers, W. A. (2019). Age-related differences in delay discounting: Immediate reward, reward magnitude, and social influence. *Journal of Behavioral Decision Making, 32*(4), 471–484. https://doi.org/10.1002/bdm.2124

Burks, S. V., Carpenter, J. P., Goette, L., & Rustichini, A. (2009). Cognitive skills affect economic preferences, strategic behavior, and job attachment. *Proceedings of the National Academy of Sciences of the United States of America, 106*(19), 7745–7750. https://doi.org/10.1073/pnas.0812360106

Carson, N., Leach, L., & Murphy, K. J. (2018). A re-examination of Montreal Cognitive Assessment (MoCA) cutoff scores. *International Journal of Geriatric Psychiatry, 33*(2), 379–388. https://doi.org/10.1002/gps.4756

Carstensen, L. L. (2006). The influence of a sense of time on human development. *Science, 312*(5782), 1913–1915. https://doi.org/10.1126/science.1127488

Chen, H. Y., Dix, A., Goh, J. O. S., Smolka, M. N., Thurm, F., & Li, S. C. (2021). Effects and mechanisms of information saliency in enhancing value-based decision-making in younger and older adults. *Neurobiology of Aging, 99*, 86–98. https://doi.org/10.1016/j.neurobiolaging.2020.11.018

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

Eppinger, B., Nystrom, L. E., & Cohen, J. D. (2012). Reduced sensitivity to immediate reward during decision-making in older than younger adults. *PLoS ONE, 7*(5), e36953. https://doi.org/10.1371/journal.pone.0036953

Ert, E., & Erev, I. (1930). On the descriptive value of loss aversion in decisions under risk: Six clarifications. *Judgment and Decision Making, 8*(3), 214–235. https://doi.org/10.1017/S1930297500005945

Fernandes, C., Pasion, R., Gonçalves, A. R., Ferreira-Santos, F., Barbosa, F., Martins, I. P., & Marques-Teixeira, J. (2018). Age differences in neural correlates of feedback processing after economic decisions under risk. *Neurobiology of Aging, 65*, 51–59. https://doi.org/10.1016/j.neurobiolaging.2018.01.003

Finn, P. R., Gunn, R. L., & Gerst, K. R. (2015). The effects of a working memory load on delay discounting in those with externalizing psychopathology. *Clinical Psychological Science, 3*(2), 202–214. https://doi.org/10.1177/2167702614542279

Glöckner, F., Schuck, N. W., & Li, S. C. (2021). Differential prioritization of intramaze cue and boundary information during spatial navigation across the human lifespan. *Scientific Reports, 11*(1), 15257. https://doi.org/10.1038/s41598-021-94530-9

Green, L., Fry, A. F., & Myerson, J. (1994). Discounting of delayed rewards: A life-span comparison. *Psychological Science, 5*(1), 33–36. https://doi.org/10.1111/j.1467-9280.1994.tb00610.x

Green, L., Myerson, J., Lichtman, D., Rosen, S., & Fry, A. (1996). Temporal discounting in choice between delayed rewards: The role of age and income. *Psychology and Aging, 11*(1), 79–84. https://doi.org/10.1037/0882-7974.11.1.79

Green, L., Myerson, J., & Ostaszewski, P. (1999). Discounting of delayed rewards across the life span: Age differences in individual discounting functions. *Behavioural Processes, 46*(1), 89–96. https://doi.org/10.1016/S0376-6357(99)00021-2

Guttman, Z. R., Ghahremani, D. G., Pochon, J. B., Dean, A. C., & London, E. D. (2021). Age influences loss aversion through effects on posterior cingulate cortical thickness. *Frontiers in Neuroscience, 15*, 673106. https://doi.org/10.3389/fnins.2021.673106

Jimura, K., Myerson, J., Hilgard, J., Keighley, J., Braver, T. S., & Green, L. (2011). Domain independence and stability in young and older adults' discounting of delayed rewards. *Behavioural Processes, 87*(3), 253–259. https://doi.org/10.1016/j.beproc.2011.04.006

Kanai, R., & Rees, G. (2011). The structural basis of inter-individual differences in human behaviour and cognition. *Nature Reviews Neuroscience, 12*(4), 231–242. https://doi.org/10.1038/nrn3000

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

Leverett, S., Garza, C., & Seaman, K. (2022). The effect of delay duration on delay discounting across adulthood. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences, 77*(3), 467–471. https://doi.org/10.1093/geronb/gbab198

Li, S. C., Aggen, S. H., Nesselroade, J. R., & Baltes, P. B. (2001a). Short-term fluctuations in elderly people's sensorimotor functioning predict text and spatial memory performance: The MacArthur successful aging studies. *Gerontology, 47*(2), 100–116. https://doi.org/10.1159/000052782

Li, S.-C., Biele, G., Mohr, P. N. C., & Heekeren, H. R. (2007). Aging and neuroeconomics: Insights from research on neuromodulation of reward-based decision making. *Analyse & Kritik, 29*(1), 97–111. https://doi.org/10.1515/auk-2007-0107

Li, S. C., Lindenberger, U., & Sikström, S. (2001b). Aging cognition: From neuromodulation to representation. *Trends in Cognitive Sciences, 5*(11), 479–486. https://doi.org/10.1016/S1364-6613(00)01769-1

Li, S. C., & Sikström, S. (2002). Integrative neurocomputational perspectives on cognitive aging, neuromodulation, and representation. *Neuroscience and Biobehavioral Reviews, 26*(7), 795–808. https://doi.org/10.1016/S0149-7634(02)00066-0

Li, Y., Baldassi, M., Johnson, E. J., & Weber, E. U. (2013). Complementary cognitive capabilities, economic decision making, and aging. *Psychology and Aging, 28*(3), 595–613. https://doi.org/10.1037/a0034172

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8*(2), 207–220. https://doi.org/10.1037/0882-7974.8.2.207

Löckenhoff, C. E., O'Donoghue, T., & Dunning, D. (2011). Age differences in temporal discounting: The role of dispositional affect and anticipated emotions. *Psychology and Aging, 26*(2), 274–284. https://doi.org/10.1037/a0023280

MacDonald, S. W. S., Karlsson, S., Rieckmann, A., Nyberg, L., & Bäckman, L. (2012). Aging-related increases in behavioral variability: Relations to losses of dopamine D 1 receptors. *Journal of Neuroscience, 32*(24), 8186–8191. https://doi.org/10.1523/JNEUROSCI.5474-11.2012

MacDonald, S. W. S., Li, S. C., & Bäckman, L. (2009). Neural underpinnings of within-person variability in cognitive functioning. *Psychology and Aging, 24*(4), 792–808. https://doi.org/10.1037/a0017798

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

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

Nagel, I. E., Chicherio, C., Li, S. C., von Oertzen, T., Sander, T., Villringer, A., Heekeren, H. R., Bäckman, L., & Lindenberger, U. (2008). Human aging magnifies genetic effects on executive functioning and working memory. *Frontiers in Human Neuroscience, 2*, 1. https://doi.org/10.3389/neuro.09.001.2008

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The montreal cognitive assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

O'Brien, E. L., & Hess, T. M. (2020). Differential focus on probability and losses between young and older adults in risky decision-making. *Aging, Neuropsychology, and Cognition, 27*(4), 532–552. https://doi.org/10.1080/13825585.2019.1642442

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

Papenberg, G., Hämmerer, D., Müller, V., Lindenberger, U., & Li, S. C. (2013). Lower theta inter-trial phase coherence during performance monitoring is related to higher reaction time variability: A lifespan study. *NeuroImage, 83*, 912–920. https://doi.org/10.1016/j.neuroimage.2013.07.032

Pooseh, S., Bernhardt, N., Guevara, A., Huys, Q. J. M., & Smolka, M. N. (2018). Value-based decision-making battery: A Bayesian adaptive approach to assess impulsive and risky behavior. *Behavior Research Methods, 50*(1), 236–249. https://doi.org/10.3758/s13428-017-0866-x

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods, 40*(3), 879–891. https://doi.org/10.3758/BRM.40.3.879

Raz, N., Gunning-Dixon, F. M., Head, D., Dupuis, J. H., & Acker, J. D. (1998). Neuroanatomical correlates of cognitive aging: Evidence from structural magnetic resonance imaging. *Neuropsychology, 12*(1), 95–114. https://doi.org/10.1037/0894-4105.12.1.95

Read, D., & Read, N. L. (2004). Time discounting over the lifespan. *Organizational Behavior and Human Decision Processes, 94*(1), 22–32. https://doi.org/10.1016/j.obhdp.2004.01.002

Rieger, M., & Mata, R. (2015). On the generality of age differences in social and nonsocial decision making. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences, 70*(2), 200–212. https://doi.org/10.1093/geronb/gbt088

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

Samanez-Larkin, G. R., Kuhnen, C. M., Yoo, D. J., & Knutson, B. (2010). Variability in nucleus accumbens activity mediates age-related suboptimal financial risk taking. *Journal of Neuroscience, 30*(4), 1426–1434. https://doi.org/10.1523/JNEUROSCI.4902-09.2010

Samanez-Larkin, G. R., Mata, R., Radu, P. T., Ballard, I. C., Carstensen, L. L., & McClure, S. M. (2011). Age differences in striatal delay sensitivity during intertemporal choice in healthy adults. *Frontiers in Neuroscience, 5*, 126. https://doi.org/10.3389/fnins.2011.00126

Seaman, K. L., Green, M. A., Shu, S., & Samanez-Larkin, G. R. (2018). Individual differences in loss aversion and preferences for skewed risks across adulthood. *Psychology and Aging, 33*(4), 654–659. https://doi.org/10.1037/pag0000261

Shamosh, N. A., DeYoung, C. G., Green, A. E., Reis, D. L., Johnson, M. R., Conway, A. R. A., Engle, R. W., Braver, T. S., & Gray, J. R. (2008). Individual differences in delay discounting: Relation to intelligence, working memory, and anterior prefrontal cortex. *Psychological Science, 19*(9), 904–911. https://doi.org/10.1111/j.1467-9280.2008.02175.x

Störmer, V. S., Passow, S., Biesenack, J., & Li, S. C. (2012). Dopaminergic and cholinergic modulations of visual-spatial attention and working memory: Insights from molecular genetic research and implications for adult cognitive development. *Developmental Psychology, 48*(3), 875–889. https://doi.org/10.1037/a0026198

Szuhany, K. L., MacKenzie, D., & Otto, M. W. (2018). The impact of depressed mood, working memory capacity, and priming on delay discounting. *Journal of Behavior Therapy and Experimental Psychiatry, 60*, 37–41. https://doi.org/10.1016/j.jbtep.2018.03.001

Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. A. (2007). The neural basis of loss aversion in decision-making under risk. *Science, 315*(5811), 515–518. https://doi.org/10.1126/science.1134239

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

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*(2), 272–292. https://doi.org/10.1037/0033-2909.120.2.272

Whelan, R., & McHugh, L. A. (2009). Temporal discounting of hypothetical monetary rewards by adolescents adults and older adults. *Psychological Record, 59*(2), 247–258. https://doi.org/10.1007/BF03395661

Zhao, X., Lynch, J. G., & Chen, Q. (2010). Reconsidering Baron and Kenny: Myths and truths about mediation analysis. *Journal of Consumer Research, 37*(2), 197–206. https://doi.org/10.1086/651257

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