Research report

Age-related characteristics of risky decision-making and progressive expectation formation

Zsófia Kardos[a, b, *]

kardos.zsofia.klara@ttk.mta.hu

Andrea Kóbor[c]

Ádám Takács[d]

Brigitta Tóth[a, e]

Roland Boha[a]

Bálint File[a, f]

Márk Molnár[a, d]

[a]Institute of Cognitive Neuroscience and Psychology, RCNS, HAS, Budapest, Hungary

[b]Department of Cognitive Science, Budapest University of Technology and Economics, Budapest, Hungary

[c]Brain Imaging Centre, RCNS, HAS, Budapest, Hungary

[d]Institute of Psychology, Eötvös Loránd University, Budapest, Hungary

[e]Center for Computational Neuroscience and Neural Technology, Boston University, Boston, MA, USA

[f]Faculty of Information Technology, Pázmány Péter Catholic University, Budapest, Hungary

*Corresponding author at: Institute of Cognitive Neuroscience and Psychology, Research Centre for Natural Sciences, Hungarian Academy of Sciences;, Magyar tudósok körútja 2,. H-1117 Budapest, Hungary.

Abstract

During daily encounters, it is inevitable that people take risks. Investigating the sequential processing of risk hazards involve expectation formation about outcome contingencies. The present study aimed to explore risk behavior and its neural correlates in sequences of decision making, particularly in old age, which represents a critical period regarding risk-taking propensity. The Balloon Analogue Risk Task was used in an electrophysiological setting with young and elderly age groups. During the task each additional pump on a virtual balloon increased the likelihood of a balloon burst but also increased the chance to collect more reward. Event-related potentials associated with rewarding feedback were analyzed based on the forthcoming decisions (whether to continue or to stop) in order to differentiate between states of expectation towards gain or loss. In the young, the reward positivity ERP component increased as a function of reward contingencies with the largest amplitude for rewarding feedback followed by the decision to stop. In the elderly, however, reward positivity did not reflect the effect of reward structure. Behavioral indices of risk-taking propensity suggest that the performance of the young and the elderly were dissociable only with respect to response times: The elderly was characterized by hesitation and more deliberative decision making throughout the experiment. These findings signify that sequential tracking of outcome contingencies has a key role in cost-efficient action planning and progressive expectation formation.

Keywords: Aging; Decision making; Feedback-related ERPs; Reward positivity; Risk-taking behavior

1 Introduction

Whether we are aware of the fact or not, risk-taking behavior occurs more frequently during our everyday actions than generally thought. Besides those simple and common examples like taking only one more drink before driving, a temporary excursion from one's self-regulatory goals, i.e., risking the long-term goals for short-term advantages such as making a cheat in a diet, can be considered as a more complex form of 'gambling' [1]. Risk-taking behavior can be defined as a decision making propensity motivated by gain reward beside the possible opportunity to lose [2–4]. Since natural circumstances usually include continuous fluctuations in risk, the ability of making decisions based on the acquisition of action-outcome contingencies is an essential part of adaptive risk behavior [5]. In particular, old age represents a critical period due to substantial neurocognitive changes having an effect on both frontal cortical and subcortical brain areas known to be involved in decision making [6,7]. The question remains, however, whether there is a specific inability of the acquisition of relevant information behind the possibly reduced decision quality of the elderly.

From the perspective of self-report questionnaires, elderly are characterized by higher risk-avoidance tendency [8]. However, regarding risk behavior, results show evidence for both normal and altered patterns of decision making [6,9]. Both extremely cautious and hazardous decisions can be found when only partial information is available about the outcome structure of the task [8]. In these situations, participants are unaware of the possible outcome after a safe choice, and the exploration of the options and boundaries are necessary. These age differences can be eliminated, however, with experience with the task, especially when the task complexity is relatively low [8,10]. Nevertheless, providing partial information could jeopardize the chance of error correction, in particular in the elderly, who are generally less certain in ambiguous decision making situations [6,8].

The Balloon Analogue Risk Task (BART) developed by Lejuez et al. [11] is an experimental paradigm that requires sequential decision making without providing explicit information about outcome probabilities. This paradigm is specifically suitable for the investigation of the flexibility of risk attitudes and risk-avoidant behavior, since in the BART it is adaptive to take risks. However, adaptive risk-taking behavior cannot be acquired without exploring and learning the structure of the task. During task performance, participants are required to collect points by pumping up virtual balloons. Participants may pump as long as they decide to 'cash-out' (i.e., to collect the reward points) or until the balloon bursts and the points collected so far on that balloon are lost. Each additional pump on the balloon increases the likelihood of balloon burst and losing the accumulated reward but deciding to go on pumping increases the chance to collect more reward. The experience gained through the repeated sequential decision making process ensure the step-by-step acquisition of the reward structure of the task and supports progressive expectation formation about the outcome distribution.

The basic properties of the BART implies a wide range of strategic processes that could possibly explain the behavior from the basic preconceptions of the decision maker to the extent the action-outcome representations can modulate the learning process [12]. Computational modeling works suggest that those models that take into account expectancy and outcome values (e.g., Bayesian Sequential Risk Taking Model) provide better fit with the behavior data instead of simple reinforcement learning models (e.g., the Target model) that do not rely on the sequential evaluation of gains and losses [12,13]. Hence, the context of pump-outcome pairs (i.e., action-outcome pairs) in the BART should be regarded in the light of extended action sequences and past experiences. Thus, probably there are some simple action-outcome contingencies that are more important in determining future behavior than others. The possible outcomes — gain (reinforcement) by cash-out or loss (punishment) by the balloon burst — represent the consequences of prior decisions, which are essential components of the outcome evaluation sub-process. Considering that these events have a subsequent effect on behavior, it would be plausible to propose that the evaluative processing of positive events (balloon increase) preceding cash-out or balloon burst would be more appropriate indices of the learning process.

Event-related potential (ERP) analysis is suitable to track feedback-evaluation processes related to these special events, which could give further insight to expectation formation during the task. These expectations are assumed to have an effect on behavior through neural processes constantly signaling not only whether the outcome of actions reached the task goals or not but also to what extent these could fit the participants' preconceptions/predictions [14]. According to the theories concerning the brain's reward prediction system, unexpected reward or punishment elicits brief bursts of phasic dopamine signaling originating from the midbrain dopamine system [15,16]. This reward prediction error (RPE) signal is thought to have an interplay with prefrontal cortical areas such as the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC) [14,17,18]. This frontostriatal circuit with dopaminergic activation plays an essential role in reward seeking behavior and decision making [19,20], and the ERPs related to feedback evaluation, like the FRN and the reward positivity, are assumed to be the correlates of the activity of this dopaminergic circuit [17,21,22].

The FRN occurring at approximately 250 ms after feedback onset corresponds mainly to the erroneous nature of the outcome [22,23]. Contrary to this, the reward positivity (occurring in a similar time window as the FRN) is elicited by positive feedback informing about reward [24–26]. The reward positivity occurs with larger amplitude for unexpected than expected rewarding events [26]; thus, it can be regarded as a decisive index of outcome evaluation which reliably reflects the predictive processing. In addition, both the FRN and the reward positivity ERP components typically constitute a 'complex' with the following P3 component peaking at approximately between 300 and 500 ms [27–29]. The P3 is thought to reflect a more thorough evaluative process of the outcome events [30–32], including the local and global probabilistic properties, motivational significance of the stimuli, and also the amount of expended/invested attention [33].

Data collected in various experimental conditions in which inferences of reinforcement learning were addressed via feedback-related evaluation processes show an age-dependent decrease regarding the amplitudes of feedback-related ERP components [34–36]. Accordingly, imaging approaches suggest that the elderly have difficulties in representing outcome values during predictive processing due to decreased frontostriatal connectivity with age [5,20]. Furthermore, the activity of the dopaminergic system also declines during aging, which results in higher signal-to-noise ratio in the frontostriatal communication pathway [37–39]. The decreased reliability of prediction error processing may provide an explanation for the alterations in learning-dependent decision making situations in the elderly.

In the present study, our aim was to investigate age-related characteristics of feedback-related ERP correlates of predictive processing in the BART. Although the BART is a naturalistic experimental setting, it also has a hidden probabilistic structure requiring flexible adaptation and exploration, which results in an uncertain decision making condition [40]. As the most prominent indices of risk behavior, the number of pumps, as well as the number of balloon bursts allow the characterization of the progress of adaptation to the task structure at the behavioral level [11]. These indices are important to define whether or not learning occurred during task solving, and whether the patterns of risk taking can be categorized as typical. The decision time is also an informative index of uncertainty and deliberative decision making, which could be particularly important regarding the age-related aspects of risk taking. It was hypothesized that although experience with the task would likely boost the performance of the elderly, strategic differences would be detected in their decision times compared to that seen in the young.

Regarding the ERP data, special emphasis was put on those events that precede decisions whether to continue or to stop the balloon trial. It was assumed that differentiating between states of risk taking (to continue pumping prior to balloon bursts) and those corresponding to risk avoidance (cash-out) would be informative about the mapping of reward contingencies by relating them to reward prediction error processes. It was hypothesized that larger reward positivity would be obtained in those cases when a rewarding event was better than expected (i.e., before cash-out), suggesting active predictive processes regarding the outcome structure of the task. Consequently, although the sustained experience with the task suggests reduced age-related differences in risk behavior in the long run, it was hypothesized that the potentially inefficient evaluative and predictive processes in the elderly would result in more deliberate decision making and in decreased reward positivity amplitudes in the feedback-related ERP components.

2 Methods

2.1 Participants

Data were collected in 22 young and 23 elderly participants. However, ultimately, data of 17 young adults (12 females, age range = 21–28 years) and 18 elderly (13 females, age range = 62–72 years) were analyzed in the present study as a result the artifact rejection procedure (see section 2.3 EEG data collection and analysis). All participants in the final sample were right-handed and had normal or corrected-to-normal vision. None of them reported a history of neurological or psychiatric diseases and they were not on medication which may influence the EEG. The study was accepted by the relevant institutional ethics committee. All participants gave written consent and received financial compensation for taking part in the investigation. The two groups were matched on gender and years of education, and the IQ of all participants was tested by the Hungarian standardized version of the Wechsler Adult Intelligence Scale-Revised [41] prior to the experimental session. Descriptive characteristics of participants and their WAIS-R scores are shown in Table 1.

Table 1 Descriptive characteristics of participants.

alt-text: Table 1

	Young n = 17		Elderlyn = 18		Difference
	Mean	SD	Mean	SD	t/χ^2
Age	22.69	±~~1.9965.78±~~1.99	65.78	±3.64	−42.06**
Male/Female	10/7		6/12		1.8
Years of education	12.75	±1.34	13.5	±3.97	−0.72
IQ	118.25	±8.76	120.61	±8.47	−0.8
Verbal IQ	112	±10	118.94	±7.57	−2.3*
Performance IQ	122.75	±13.09	121.44	±9.57	0.33

Note~~.~~: *$p < 0.05$; **$p < 0.01$.

2.2 Stimuli, ~~Task, and P~~task, and procedure

The Balloon Analogue Risk Task [11] used in the present study was based on the paradigm provided by Fein and Chang in 2008 [42], although this modified version of the task was designed to suit the requirements of simultaneous EEG recording [40]. During the experiment, participants were instructed to pump up virtual balloons to as large a size as possible but try to avoid their burst. As clarified in the instruction given to participants, each successful pump resulting in balloon inflation increased the amount of points (potential reward) but also the chance of balloon burst (loss of the potential reward).

The experiment consisted of 90 balloon trials distributed in 3 blocks with 30 balloon trials in each. All balloons had the maximum breaking point of 20 pumps, thus, the maximum amount of successful pumps for every balloon could not be higher than 19. After any successful pump, participants could either collect their points by choosing to quit from a given trial ('cash-out') or to go on and risk the loss of the potential reward. The goal was to maximize the reward by collecting as many points as possible. Unknown to participants, no burst could have occurred during the first two pumps in order to avoid the near-zero gain outcomes. The probability of a balloon burst was defined as 1/18 for the third, 1/17 for the fourth pump and so on for the further pumps with 1/1 for the 20th pump. The reward increased from pump-to-pump with 1 point, so participants could earn 1 point at the first, 2 more points at the second pump, and so forth, e.g., 10 additional points at the tenth pump. In order to be able to keep track the accumulated points from successful pumps, it was persistently shown in the middle of the balloon; furthermore, points collected from the last balloon as well as the sum of the already collected points from all of the prior balloons were shown in the bottom of the screen. The total gain at the end of the experiment was added to the participation fee as an extra bonus.

The timing of different events in the experiment was the following: At the beginning of a trial, the picture of a small-sized balloon appeared and remained on the screen until the participant made his/her move ('pumping' or 'cash-out'); then, after a randomly adjusted delay (1100–1300 ms) following pumping, the balloon size increased and the accumulated reward was presented in the middle of the balloon providing feedback about the outcome of the given pumping action. Following the third balloon pump, two possible outcomes could occur: either the size of the balloon (and the points inside) increased, or it burst. In case of the latter event, the feedback stimulus was a picture showing a balloon burst, which appeared on the screen for 3000 ms. In those cases when participants decided to collect the points from the temporary bank, a feedback screen appeared for 3000 ms informing about the points participants had won. After the termination or end of a given trial (by a negative feedback or by the feedback screen of the collected points), a new balloon trial started immediately with a new small-sized balloon appearing on the screen. The layout of the experimental trials is shown in Fig. 1. For the choice responses, two buttons of a gamepad (Logitech Precision) were available, one (right) to pump the balloon further and another (left) button to terminate the block and collect the accumulated earnings.

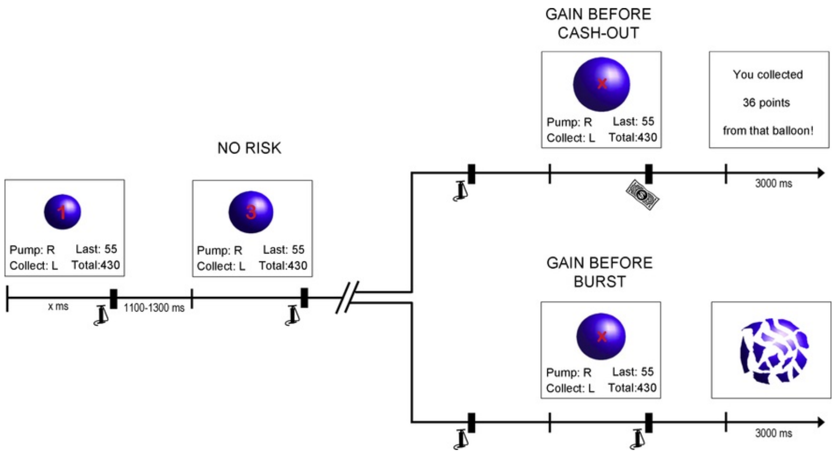

Fig. 1 Layout of the experimental trials in the BART—In each trial, participants started with a zero-value balloon. The examples represent the trials for the ERP analysis. The condition named 'no risk' represents the feedback screen after the second pump on a given balloon. Conditions 'gain before cash-out' and 'gain before burst' could have occurred at any point afterwards. 'Last' denotes points from the last balloon trial, 'Total' denotes the already accumulated points from the previous balloon trials. Icons of hand pump indicate the pumping response initiation, which was followed by the feedback screen after a randomly predetermined delay of 1100–1300 ms. The icon of cash denotes the initiation of a cash-out response in a given trial.

alt-text: Fig. 1

2.3 EEG ~~Data Collection and A~~data collection and analysis

Participants were seated in an electrically shielded and acoustically attenuated room in front of a 19" CRT screen at a distance of 125 cm. The EEG was recorded with 62 Ag/AgCl electrodes, placed according to the international 10-–20 system, using Synamps amplifiers and Neuroscan software 4.5. (Compumedics Neuroscan, Charlotte, NC, USA). Vertical and horizontal eye movements were recorded by electrodes attached above and below the left eye, and the left and right outer canthi. The tip of the nose was used as reference and an electrode placed between Cz and FCz was used for ground (AFz). The sampling rate was 1000 Hz and the signals were filtered on-line (DC–70 Hz, 24 dB/octave roll-off). The impedance of the electrodes was kept below 10 kΩ. After the recording, the continuous EEG signal was filtered to 0.5–45 Hz (digital FIR filter with 24 dB/octave roll-off). After visual screening for major deflections, Independent Component Analysis (ICA) was performed on the continuous dataset using the ICA function of the EEGLab 11.0.3.1b Matlab toolbox [43] including ADJUST Trial Version plugin [44] in order to identify and subtract components associated with artifacts like blinking or horizontal eye-movements. All further analyses of EEG data were performed using custom written scripts in Matlab 8.2 (The MathWorks Inc., USA).

The different experimental trials for segmenting the EEG were defined by the balloon increase or burst serving as feedback events. Epochs started from −200 ms before and lasted 1000 ms after the feedback stimulus. A negative feedback condition was defined as the one in which the expectation of the forthcoming balloon increase was violated ('balloon burst' condition).

Regarding the positive feedback, the following three conditions were identified. (1) The trial ending by a positive feedback for the second pump was used as 'no risk' condition where the balloon could never burst. (2) The positive feedback (balloon increase) for the last pump before the balloon burst was defined as 'gain before burst' condition, in which participants would have liked to take further risk and gain more reward. (3) The positive feedback (balloon increase) for the last pump before collecting the points was defined as 'gain before cash-out' condition where participants chose to avoid further risk and collected their points afterwards.

The minimum number of artifact-free epochs in a condition was 20 per participant. No restrictions were made for the minimum or maximum amount of pumps required on a given balloon to be included in the analysis. Events included in the 'no risk' condition occurred two times more frequently than the others since these events could be extracted from all balloon trials, irrespective of whether the balloon trial ended in balloon burst or cash-out. Therefore, the number of 'no risk' epochs was matched to the number of epochs in the other two conditions.

Before averaging, an additional filtering (0.5–25 Hz bandpass), re-referencing to the average of all electrodes, and baseline correction (from −200 to 0 ms) were performed on the artifact-free EEG epochs. ERP peak amplitudes were measured with the base-to-peak method. Based on the topographical characteristics of the target ERP components, a fronto-central region-of-interest (ROI) was defined for the measurement, taking into account the average of the peak amplitudes measured on the FC1, FCz, FC2, Cz, CP1, CPz, and CP2 electrodes. Measurement of the reward positivity and the related P3 for the 'no risk', 'gain before burst', and 'gain before cash-out' conditions, and the FRN and its related P3 for the 'balloon burst' condition were made within the following time windows: The reward positivity was measured as the most positive peak in the 150–300 ms time range; the FRN was defined as the most negative peak also in the 150–300 ms time range; and the related P3 components were defined as positive peaks in the 250–550 ms time range. These time windows were defined based on visual inspection of the grand averages of both groups. Peak latencies of the ERP components were not analyzed in this study.

2.4 Statistical ~~A~~analysis

2.4.1 Behavioral data

In order to characterize the progress of risk taking behavior, standard measures of the BART were calculated within each of the 3 blocks (30 consecutive balloon trials in each block), which were named as the fore-part, the middle-part, and the end-part of the experiment. Specifically, the mean adjusted number of pumps [mean number of pumps on balloons that did not explode,see 8], the number of balloon bursts, and the amount of exploratory responses [the so-called exploartion rate,see 45,46] were determined. The *mean adjusted number of pumps* indicates how far the participant went with pumps on those balloons that did not explode. The *number of balloon bursts* indicates the amount of unsuccessful trials where the task goal could not be achieved irrespective of the amount of pumps on those balloons. The calculation of the *exploration rate* was based on the method of Hassall et al. [46] and Pleskac & Wershbale [45]. This behavioral index defines a pumping response as explorative if the associated response time (RT) exceeded the level of 3 standard deviation (SD) of the participants' own mean RT. Responses executed only in the 100 ms~~—~~-3000 ms time range were included in RT analysis in order to rule out lapses and longer breaks possibly not associated with explorative behavior [47]. Exploration rate was calculated for each participant and each balloon trial (in sum 90 per participant) by dividing the pump number on a given balloon by the number of explorative pumps on that balloon (e.g., if two explorative pumps occurred in a balloon trial where 10 pumps were initiated, the exploration rate on that balloon would be 0.2). The mean of exploration rate was then determined for the 90 balloons. Group (young vs. elderly) * experimental part (fore-part, middle-part, and end-part of the experiment) mixed design ANOVA was used for the statistical analysis of the above behavioral measures.

Additionally, RTs of those pumps resulting in the 'gain before burst' and 'gain before cash-out' conditions were also compared in a group (young vs. elderly) * condition (gain before burst vs. gain before cash-out) * experimental part (fore-part, middle-part, and end-part of the experiment) mixed design ANOVA.

2.4.2 ERP data

Statistical analysis focusing on the ERP data was performed with respect to the positive and negative valence of feedback events. Analysis of the reward positivity and the following P3 ERP components for the above defined positive events ('no risk', 'gain before burst', and 'gain before cash-out' conditions) was performed in two mixed ANOVAs. First, the effect of *sequential position* was tested in an ANOVA with group (young vs. elderly) as a between-subjects factor and sequential position (early vs. late) as a within-subjects factor. Sequential position refers to the *within*-balloon positions of the pumps and the related feedback events, where the post-feedback decision is to continue pumping. Thus, while the early level refers to the 'no risk' condition, the late level refers to the 'gain before burst' condition. Second, the effect of *reward contingencies* was tested in an ANOVA with group (young vs. elderly) as a between-subjects factor and reward contingencies (expected vs. unexpected gain) as a within-subjects factor. The effect of reward contingencies refers to the post-feedback decisions based on the *between*-balloon reward contingencies. Thus, while expected gain refers to the 'gain before burst' condition, unexpected gain refers to the 'gain before cash-out' condition. The FRN and the related P3 ERP components for the negative events of balloon bursts were analyzed by one-way ANOVAs with group (young vs. elderly) as a between-subjects factor.

Greenhouse-Geisser correction was used to adjust *p*-values when violations of the assumption of sphericity made it necessary (henceforth indicated by epsilon values). Partial eta-squared values are provided as a measure for the proportion of variance explained by the independent variable(s). Post-hoc tests were performed by Bonferroni's method of pairwise comparisons.

3 Results

A summary of the ANOVAs regarding behavioral and ERP data are presented in Table 2.

Table 2 Summary of the ANOVAs regarding behavioral and ERP data.

alt-text: Table 2

		Group		Exp. part		Condition		Group~~ * Exp. partGroup * ConditionExp.part *ConditionGroup * Exp.part ~~* Exp. part		Group* Condition		Exp.part* Condition		Group* Exp. part* Condition	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Mean adjusted No. of pumps		0.14	0.7	10.72	**<0.001**	–	–	2.34	0.104	–	–	–	–	–	–
No. of balloon bursts		0.01	~~.9124.52~~0.912	**4.52**	**0.017**	–	–	**3.24**	**.049**	–	–	–	–	–	–
Exploration rate		**9.53**	**0.004**	**14.13**	**<0.001**	–	–	1.65	0.199	–	–	–	–	–	–
Response time		**4.23**	**0.048**	**15.97**	**<0.001**	**31.42**	**<0.001**	0.97	~~.3831.07.3092.69.0750.62.54~~0.383	1.07	0.309	*2.69*	*0.075*	0.62	0.54
Sequential position	rp	*3.17*	*0.084*	–	–	**50.5**	**<0.001**	–	–	2.77	0.105	–	–	–	–
	P3	2.72	0.108	–	–	**45.98**	**<0.001**	–	–	*3.34*	*0.076*	–	–	–	–
Reward contingencies	~~R~~rp~~p~~	**18.52**	**<0.001**	–	–	**53.25**	**<0.001**	–	–	**35.22**	**<0.001**	–	–	–	–
	P3	**17.40**	**<0.001**	–	–	**61.40**	**<0.001**	–	–	**24.99**	**<0.001**	–	–	–	–
Negative feedback	FRN	0.79	0.380	–	–	–	–	–	–	–	–	–	–	–	–
	P3	**34.25**	**<0.001**	–	–	–	–	–	–	–	–	–	–	–	–

~~*Note.*~~*Note*: rp = reward positivity; − = the effect is not applicable in the given analysis. *p*-values below 0.050 are **boldfaced** and *p*-values below 0.1 are *italics*.

3.1 Behavioral ~~R~~results

The analysis of the *mean adjusted number of pumps* revealed a significant main effect of experimental part ($F(2, 66) = 10.72$, $p < 0.001$, $\eta_p^2 = 0.25$), and the post-hoc pair-wise comparisons showed significant differences between the fore-part and middle-part ($p = 0.002$) and the fore-part and the end-part ($p < 0.001$) of the experiment, suggesting that the mean adjusted number of pumps increased in the middle- and the end-part of the experiment (fore-part $M = 9.26$, $SE = 0.26$; middle-part $M = 10.31$, $SE = 0.38$; end-part $M = 10.51$, $SE = 0.33$). No other main effect or interaction were found.

The analysis of the *number of balloon bursts* (Fig. 2A) showed a significant main effect of experimental part ($F(2, 66) = 4.52$, $\varepsilon = 0.94$, $p = 0.017$, $\eta_p^2 = 0.12$), where the post-hoc comparisons revealed significant difference between the fore-part and the end-part of the experiment ($p = 0.015$), showing an increase in the number of balloon burst by the end-part of the experiment (fore-part $M = 12.81$, $SE = 0.58$; middle-part $M = 14.23$, $SE = 0.66$; end-part

M = 14.8, *SE* = 0.66). Significant interaction between group and experimental part was also found ($F(2, 66) = 3.24$, $\varepsilon = 0.94$, $p = 0.049$, $\eta_p^2 = 0.09$), and the post-hoc tests showed that the number of balloon bursts differed significantly only in the young group between the fore-part and the middle-part of the experiment (fore-part *M* = 12.12, *SE* = 0.83; middle-part *M* = 15.23, *SE* = 0.95, $p = 0.032$).

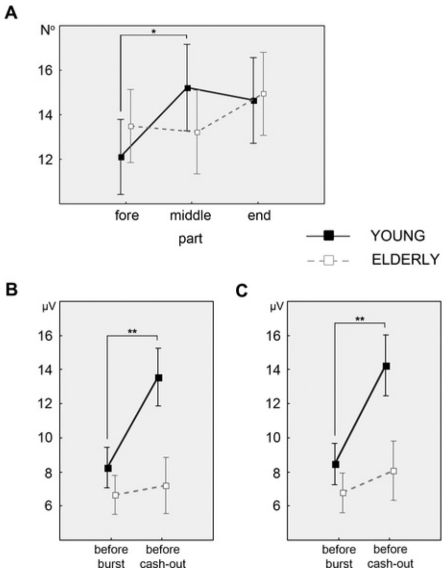

Fig. 2 Line charts show the interactions involving group factor on behavioral and ERP measures. Solid lines represent the young, whereas dashed lines represent the elderly. Part A denotes the 'number of balloon bursts' showing the interaction between the group and the experimental part. Part B and C denote the mean amplitudes of the reward positivity and P3, according to the interactions between group and condition. Significant post-hoc comparisons are indicated by asterisks. *p < 0.05; **p < 0.01.

alt-text: Fig. 2

Analysis of the *exploration rate* showed significant main effect of group ($F(1, 33) = 9.53$, $p = 0.004$, $\eta_p^2 = 0.22$), indicating increased exploratory behavior in the elderly group (young *M* = 0.07, *SE* = 0.01; elderly *M* = 0.11, *SE* = 0.01). A significant main effect of experimental part was also found ($F(2, 66) = 14.13$, $p < 0.001$, $\eta_p^2 = 0.30$), and the post-hoc comparisons showed significant differences between the fore-part and the middle-part (fore-part *M* = 0.12, *SE* = 0.01; middle-part *M* = 0.07, *SE* = 0.01, $p < 0.01$) and between the fore-part and the end-part (fore-part *M* = 0.12, *SE* = 0.01; end-part *M* = 0.08, *SE* = 0.01, $p < 0.01$) of the experiment, indicating that more exploratory behavior occurred at the beginning of the experiment in both groups. No interaction was found between these two factors.

The analysis regarding the RTs of pumps resulting in 'gain before burst' and 'gain before cash-out' conditions showed significant main effect of group ($F(1, 33) = 4.23$, $p = 0.48$, $\eta_p^2 = 0.11$), suggesting the elderly were generally slower than the young (young *M* = 574 ms, *SE* = 70.22; elderly *M* = 776 ms, *SE* = 68.24), irrespective of other experimental effects. The significant main effect of condition ($F(1, 33) = 31.42$, $p < 0.01$, $\eta_p^2 = 0.49$) indicated that responses resulting in the positive feedback of the gain before cash-out condition were slower than those of the gain before burst condition (gain before cash-out *M* = 847 ms, *SE* = 133.29; gain before burst *M* = 503 ms, *SE* = 47.43). It was also found that the experimental part had a significant main effect ($F(2, 66) = 15.97$, $p < 0.01$, $\eta_p^2 = 0.33$), showing that responses were faster as the task progressed (fore-part *M* = 789 ms, *SE* = 76.97 vs. middle-part *M* = 616 ms, *SE* = 66.43, $p < 0.001$; fore-part vs. end-part *M* = 620 ms, *SE* = 80.46, $p < 0.001$). Marginally significant interaction between condition and experimental part was also found ($F(2, 66) = 2.69$, $p = 0.75$, $\eta_p^2 = 0.7$), and the post-hoc comparisons showed that the effect of experimental part can be found only in the gain before cash-out condition (fore-part *M* = 1002 ms, *SE* = 78.24 vs. middle-part *M* = 778 ms, *SE* = 75.55, $p < 0.001$; fore-part vs. end-part M = 760 ms, *SE* = 97.6, $p < 0.001$) but not in the gain before burst condition.

3.2 Electrophysiological Rresults

3.2.1 Reward positivity and P3 for the positive feedback

The grand average waveforms obtained over the central ROI for each group and condition, and scalp distribution of the differences between conditions can be seen in Fig. 3.

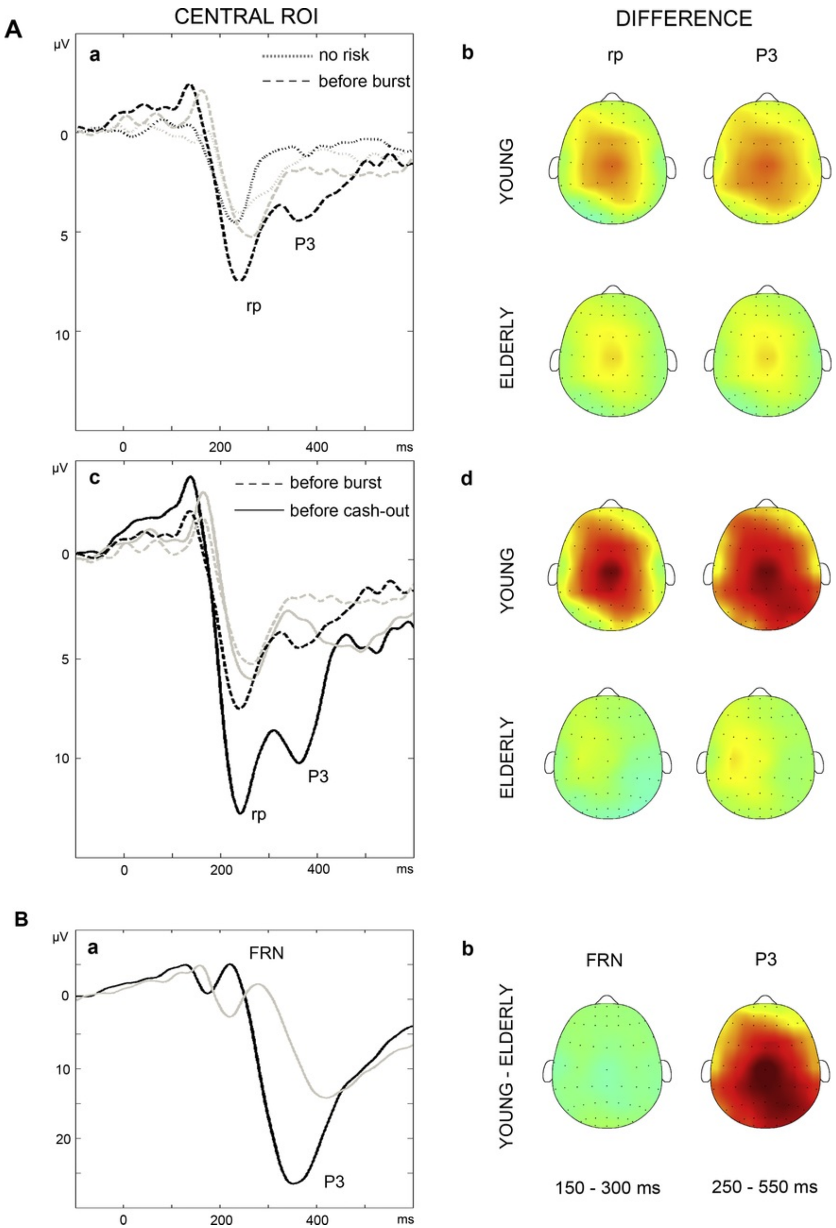

Fig. 3 Grand average ERP waveforms—Part A: Panel (a) shows reward positivity and P3 according to the effect of sequential position, and panel (b) shows the scalp distributions of the within-group differences of conditions. Panel (c) and (d) shows the ERPs and difference scalp distributions according to the effect of reward contingencies. Part B: Panel (a) shows FRN and P3 for negative feedback (balloon burst), and panel (b) contains the scalp distribution of group differences of the ERP components. Young are represented by black lines, whereas elderly are represented by grey lines on the ERP plots. Stimulus onset corresponds to 0 ms on the time scale. Scalp maps represent the differences of peak amplitude distributions within the time window of the components using −15 − 15 μV scale.

alt-text: Fig. 3

The analysis regarding the *effect of sequential position* (early ‘no risk’ vs. late ‘gain before burst’ conditions) on the *reward positivity* revealed a marginally significant main effect of group ($F(1, 33) = 3.17$, $p = 0.84$, $\eta_p^2 = 0.9$), suggesting moderately decreased amplitudes in the elderly (*M* = 5.76 μV, *SE* = 0.41) compared to those seen in the young (*M* = 6.80 μV, *SE* = 0.42). The main effect of sequential position was significant (F(1, 33) = 50.5, $p < 0.01$, $\eta_p^2 = 0.60$), indicating that in both groups the amplitudes of the reward positivity was larger at the later position ('gain before burst' *M* = 7.46 μV, *SE* = 0.41) than at the earlier one ('no risk' *M* = 5.10 μV, *SE* = 0.25). No interaction was found between these two factors.

Analysis of *reward positivity* with respect to the effect of *reward contingencies* ('gain before burst' vs. 'gain before cash-out' conditions – Fig. 2) yielded significant main effect of group (F(1, 33) = 18.52, $p < 0.01$, $\eta_p^2 = 0.36$), indicating decreased amplitudes in the elderly (*M* = 6.93 μV, *SE* = 0.64) compared to that found in the young group (*M* = 10.90 μV, *SE* = 0.66). The main effect of reward contingency was also significant (F(1, 33) = 53.25, $p < 0.01$, $\eta_p^2 = 0.62$), suggesting larger amplitudes in the trials where the expectation of gain was relatively lower ('gain before cash-out' *M* = 10.38 μV, *SE* = 0.58) than in trials where this expectation was relatively higher ('gain before burst' *M* = 7.46 μV, *SE* = 0.41). Significant interaction was also found between group and reward contingency (F(1, 33) = 35.22, $p < 0.01$, $\eta_p^2 = 0.52$), where the post-hoc analyses revealed that the significant expectancy related difference between the reward positivity amplitudes ($p < 0.01$) could be observed only in the young group ('gain before cash-out' *M* = 13.55 μV, *SE* = 0.83; 'gain before burst' *M* = 8.26 μV, *SE* = 0.59), but not in the elderly ('gain before cash-out' *M* = 7.21 μV, *SE* = 0.81; 'gain before burst' *M* = 6.66 μV, *SE* = 0.57).

The *sequential position* related analysis of the *P3* amplitudes ('no risk' vs. 'gain before burst' conditions) showed significant main effect of sequential position (F(1, 33) = 45.98, $p < 0.01$, $\eta_p^2 = 0.58$), indicating that later sequential position ('gain before burst') resulted in larger P3 amplitudes in both groups ('gain before burst' *M* = 7.63 μV, *SE* = 0.41; 'no risk' *M* = 5.07 μV, *SE* = 0.28).

The analysis of the *reward contingencies* on the *P3* amplitudes ('gain before burst' vs. 'gain before cash-out' conditions – Fig. 2) showed significant main effect of group (F(1, 33) = 17.40, $p < 0.01$, $\eta_p^2 = 0.35$): Larger amplitudes were found in the young (*M* = 11.36 μV, *SE* = 0.68) than in the elderly (*M* = 7.43 μV, *SE* = 0.66). A significant main effect of reward contingency was also found (F(1, 33) = 61.40, $p < 0.01$, $\eta_p^2 = 0.65$), indicating that the amplitude of the P3 was also larger when the expectation of gain was lower ('gain before cash-out' *M* = 11.16 μV, *SE* = 0.61) compared to that when it was higher (*M* = 7.63 μV, *SE* = 0.41). There was also a significant interaction between the group and reward contingency factors (F(1, 33) = 24.99, $p < 0.01$, $\eta_p^2 = 0.43$), and the post-hoc tests showed that significant expectancy related amplitude difference could be found only in the young group ('gain before cash-out' *M* = 14.25 μV, *SE* = 0.88; 'gain before burst' *M* = 8.47 μV, *SE* = 0.59; $p < 0.01$) but not in the elderly ('gain before cash-out' *M* = 8.07 μV, *SE* = 0.85; 'gain before burst' *M* = 6.79 μV, *SE* = 0.57).

3.2.2 FRN and P3 for the negative feedback

The analysis regarding the amplitude of the FRN ERP component (Fig. 3) did not reveal significant difference between the two groups (young *M* = −8.49 μV, *SE* = 0.92; elderly *M* = −7.35 μV, *SE* = 0.89). The analysis of the negative feedback related P3 component revealed significant difference in the amplitude of the two groups (F(1, 33) = 34.25, $p < 0.01$, $\eta_p^2 = 0.51$), showing that the P3 was larger in the young (*M* = 29.19 μV, *SE* = 1.65) than in the elderly (*M* = 15.75 μV, *SE* = 1.60) group for balloon burst events.

4 Discussion

In the present study, a probabilistic BART paradigm was used to investigate age-related characteristics of risky decision making and progressive expectation formation. Behavioral results suggest optimal adaptation to task requirements since increased risk-taking was found in both groups as the task progressed. Patterns of strategic task-solving indicated, however, that the elderly were characterized by fewer automatic responses (increased exploration rate) suggesting signs of hesitation and more deliberate decision making. ERP results of feedback processing support distinctive evaluation of rewarding events with respect to their within-balloon sequential position and to reward contingencies. This observation, however, characterized only the young. It appears that in the elderly, both the reward positivity and the P3 ERP components reflect altered evaluative processes of rewarding events preceding the decision to stop the sequential actions.

4.1 Interpretation of the risk-taking behavior

The perceived level of risk is generally thought to be influenced by the variability of outcome options and the exposure to negative consequences [48]. In most cases, this variability can be defined as an unknown probability distribution of outcomes leading to a condition in which uncertainty is guiding the individual's risk-taking behavior. In the BART, the instruction reveals that the distribution of possible positive and negative outcomes is not random but there is an increasing chance of balloon burst, thus participants already have a basic preconception about the underlying probabilistic structure of the task. Nevertheless, at the beginning of the task, it is difficult to define the exact 'optimal point' where the trade-off between reward maximization and loss minimization can be realized.

According to Hassall et al. [46], during the BART, participants have to continuously monitor their performance and explore their options in the light of previous experiences in order to decide whether to go on or to stop and keep their reward. According to previous findings concerning risk-taking behavior in conditions like the BART, people usually tend to show risk-aversion (fewer pumps on a balloon) at the beginning of the task, but as the session progresses, participants start to show more willingness to take risks, i.e., they increase the number of pumps [49]. At the same time, two types of decisions could be observed: A relatively automatic, fast response type and a so-called exploratory type when participants stop for a longer period before making the decision to keep pumping a particular balloon. Thus, participants tend to show less consideration in their responses as the task progresses [45,46], which can be viewed as a reduction in the number of decisions to be made, and suggests that participants appear to organize the action sequences into more abstract routines serving their current task goals [50]. This progressive organization of action-outcome pairs is necessarily based on prior experiences, and as such it reflects learning about reward contingencies.

Our results suggest that both age groups went through this progressive risk assessment process, although the elderly showed higher number of exploratory responses throughout the whole experiment. It can be assumed that these slower, exploratory types of responses before making the decision whether to stop or to continue in general indicate deliberative decision making in the elderly; at the same time, it could be regarded as an adaptive strategy in response to higher uncertainty about what action to take. Since all the important information about the current state and the outcome of the last balloon was provided on the screen, it would be inappropriate to assign this pattern of response to the general age-related memory decline observed in various types of experimental conditions [fore reviews,see 51,52]. Also, because this exploration rate index has been calculated on an individual level, this result is not likely the effect of a general age-related cognitive slowing [53]. However, since the explorative behavior observed in the elderly decreased through the three consecutive parts of the experiment such as in the young, it seems reasonable to suggest that learning about reward contingencies was at least similar in both groups. Additionally, as the mean adjusted number of pumps, the main index of risk-taking behavior, increased in a similar way in both groups, one can conclude that risk-taking behavior changed from cautious to more risky as the task progressed, irrespective of age.

However, regarding the number of balloon bursts, it remained relatively constant in the elderly in the first two parts of the experiment, which suggests that the behavioral switch towards taking more risk was not as fast as it was in the young group. The young group was already more oriented towards risk-taking in the second part indicated by the strategy of increasing the number of pumps, which resulted in an increased number of balloon bursts too. Meanwhile, the decision pattern of the elderly suggests that it took more time/experience to get rid of the motivation to avoid the negative outcomes. This observation agrees with the findings showing that aging is accompanied by decreased willingness to take risks [6], and that the experience with task can modify the initial risk attitudes [8].

4.2 Interpretation of the electrophysiological results

In the present study, it was found that the amplitude increase of the reward positivity for rewarding feedback diverged across different stages of the balloon inflation process, which possibly reflects the progress of expectation formation about reward contingencies. Higher reward positivity amplitudes were found in both groups for the ‘gain before burst’ (last positive feedback before the balloon burst) compared to the ‘no risk’ (second positive feedback) condition. Thus, as the balloon was inflating that involved more risk of balloon burst, the related positive feedback elicited larger reward positivity than those successful pumps at the beginning of the inflation process. This result may fit the assumption that the positive prediction error signal had a reinforcing effect on behavior by signaling that the outcome was better than expected and it promoted further steps to achieve a higher reward [15].

When the reward positivity evoked by both the ‘gain before burst’ and the ‘gain before cash-out’ trials (last positive feedback before the termination of the trial) were compared in the two age groups, higher amplitudes for ‘gain before cash-out’ were found only in the young group. In the elderly, there were no differences between the amplitudes of reward positivity observed in these two conditions. Although reward prediction error signals are assumed to provoke further reward seeking behavior, we found that the larger reward positivity in the young group was related to that level of sequential risk taking where the decision about cash-out occurred. Therefore, it could be possible that if the magnitude of the reward prediction error signal exceeds a certain threshold it may indicate that the evoking signal does not have a reinforcing value anymore [15]. This possibility would imply that participants had an internal model about the task structure and about outcome probabilities with which they could compare their current experiences [40]. According to a recent finding by Kiat, Straley and Cheadle [54], feedback-related ERP components reliably scaled with the sequential structure of the BART providing further support of the notion that continuous monitoring of the outcome contingencies are essential for the ongoing development of expectations. Furthermore, RTs of pumping responses resulting in the ‘gain before burst’ condition were faster than those resulting in the ‘gain before cash-out’ condition throughout the entire experiment. This result indicates that participants made less automatized responses before the decision to cash-out, which corroborates the reward positivity findings.

The age-dependent difference observed in reward positivity may have several implications with respect to the possible age-related alterations of feedback evaluation. On the one hand, the positive events before cash-out may have been regarded differently depending on age. This possibility implies that in the elderly, the processes related to reward prediction error signaling differed from that of the young. If one argues that the fast processing of feedback information provides the basis of decision making about upcoming actions, it is possible that different neural networks and/or extrinsic cues were used by the elderly to guide their behavior. The substantial age-related decline of the dopaminergic system is a generally accepted mechanism of aging [6,55], and as proposed by Nieuwenhuis et al. [39], the reduced phasic dopamine signaling could be behind the altered ERP correlates of evaluative feedback processing in the elderly. Thus, one possible interpretation of the group difference related to the ‘gain before cash-out’ condition could be that, as a result of inefficient dopamine signaling, these events are underrated in the neural system of the elderly compared to that seen in the young group.

On the other hand, it could be also possible that executive control processes rather than prediction-error based feedback-evaluation mechanisms had the dominant effect on risk-taking behavior and decision making irrespective of age. This possibility was supported by the findings of Helfinstein et al. [48], where, using fMRI, brain networks of cognitive control were found to be more active before making the safe choice by collecting the accumulated reward compared to those that occur before making another pump in a sequence resulting in balloon burst. In this case, it could be assumed that the early evaluative process regarding the last positive feedback has no such influence on decision making.

In the present study it was also found that the P3 component showed a similar pattern of amplitude modulation to that seen for the reward positivity in both groups, i.e., when the reward positivity was observed with larger amplitude, the amplitude of the P3 was also larger. The amplitude of the P3 is usually defined as a correlate of the depth of elaborative processing and analysis of the incoming information [27,28]. Thus, when the reward positivity was observed with larger amplitude – possibly indicating a more intensive positive prediction error signaling – it was followed by a P3 with larger amplitude presumably corresponding to a higher level of elaborative processing. This holds for both the young and the elderly since the amplitude of P3 in the elderly varied in the same way as the reward positivity did. It would suggest that elaborative processing of feedback information was constantly decreased in the elderly regarding the ‘gain before cash-out’ condition, which gives support to the notion of the underrated feedback processing as outlined above.

The magnitude of the P3 was also decreased in the elderly for the negative events, although the preceding FRN was seen with similar amplitude in the two age groups. Previous studies focusing on the age-related alterations in feedback evaluation processes found both differences and similarities in the morphology of the FRN and related P3 between young and elderly participants [35,36,39,56–60]. The finding of the present study that the magnitude of the FRN component for the negative feedback (the balloon burst itself) did not differ between the two age groups suggests that the rapid processing of negative feedback valence was equally functional in both groups emphasizing the intact sensitivity to negative events in the elderly. It is still not clear, however, whether it is reasonable to assign the neural mechanisms related to the processing of reward and punishment to one or two separate subsystems [17]. Moreover, although the effect of reward evaluation seems to be essential in shaping decision making, the present results emphasize that the specific role of external positive and negative feedback in expectation formation deserves further investigation throughout the lifespan.

In sum, the present results suggest that probabilistic circumstances provoke similar risk-taking behavior in both the young and the elderly; however, the ERP results confirm that the predictive processing of the system underlying feedback evaluation during sequential decision making appears to be altered with age. It was found that a specific reward-related component in the ERP reliably reflected expectations about outcome probabilities only in the young group. The decreased magnitude of this reward-related ERP component in the elderly implies a probable decline in the processing of probabilistic outcome contingencies, even if experience with the task have boosted risk-taking in the long run. This inefficient predictive processing sets back the organization of automatized routines resulting in a more deliberative task solving strategy. Altogether the findings of the present study may help to clarify the mechanisms contributing to the observed inflexibility of elderly not just in decision making but also in other day-to-day routines.

Acknowledgments

This research was supported by Hungarian Research Funds ~~–OTKA 77750 and OTKA 104332~~OTKA 77750 and OTKA 104332; AK was supported by the Postdoctoral Fellowship of the Hungarian Academy of Sciences. The authors thank for the technical assistance of E. Várkonyi.

References

[1] W. Hofmann, B.J. Schmeichel and A.D. Baddeley, Executive functions and self-regulation, *Trends Cogn. Sci.* **16**, 2012, 174–180, http://dx.doi.org/10.1016/j.tics.2012.01.006.

[2] K.S. DeMartini, R.F. Leeman, W.R. Corbin, B.A. Toll, L.M. Fucito, C.W. Lejuez, et al., A new look at risk-taking: using a translational approach to examine risk-taking behavior on the balloon analogue risk task, *Exp. Clin. Psychopharmacol.* **22**, 2014, 444–452, http://dx.doi.org/10.1037/a0037421.

[3] T. Schonberg, C.R. Fox and R. a. Poldrack, Mind the gap: ~~B~~bridging economic and naturalistic risk-taking with cognitive neuroscience, *Trends Cogn. Sci.* **15**, 2011, 11–19, http://dx.doi.org/10.1016/j.tics.2010.10.002.

[4] B.C. Leigh, Peril, chance, adventure: concepts of risk, alcohol use and risky behavior in young adults, *Addiction* **94**, 1999, 371–383.

[5] S.B.R.E. Brown and K.R. Ridderinkhof, Aging and the neuroeconomics of decision making: a review, *Cogn. Affect. Behav. Neurosci.* **9**, 2009, 365–379.

[6] P.N.C. Mohr, S.C. Li and H.R. Heekeren, Neuroeconomics and aging: ~~N~~neuromodulation of economic decision making in old age, *Neurosci. Biobehav. Rev.* **34**, 2010, 678–688, http://dx.doi.org/10.1016/j.neubiorev.2009.05.010.

[7] R. Mata, A.K. Josef and R. Hertwig, Propensity for ~~Risk Taking Across the Life Span and Around the G~~risk taking across the life span and around the globe, *Psychol. Sci.* 2016, 0956797615617811.

[8] J.J. Rolison, Y. Hanoch and S. Wood, Risky decision making in younger and older adults: ~~T~~the role of learning, *Psychol. Aging* **27**, 2012, 129–140, http://dx.doi.org/10.1037/a0024689.

[9] L. Zamarian, H. Sinz, E. Bonatti, N. Gamboz and M. Delazer, Normal aging affects decisions under ambiguity, but not decisions under risk, *Neuropsychology* **22**, 2008, 645–657, http://dx.doi.org/10.1037/0894-4105.22.5.645.

[10] R. Frey, R. Mata and R. Hertwig, The role of cognitive abilities in decisions from experience: ~~A~~age differences emerge as a function of choice set size, *Cognition* **142**, 2015, 60–80, http://dx.doi.org/10.1016/j.cognition.2015.05.004.

[11] C.W. Lejuez, J.P. Read, C.W. Kahler, J.B. Richards, S.E. Ramsey, G.L. Stuart, et al., Evaluation of a behavioral measure of risk taking: the Balloon Analogue Risk Task (BART), *J. Exp. Psychol. Appl.* **8**, 2002, 75–84, http://dx.doi.org/10.1037/1076-898X.8.2.75.

[12] T.S. Wallsten, T.J. Pleskac and C.W. Lejuez, Modeling behavior in a clinically diagnostic sequential risk-taking task, *Psychol. Rev.* **112**, 2005, 862–880, http://dx.doi.org/10.1037/0033-295X.112.4.862.

[13] A. Wershbale and T.J. Pleskac, Making ~~Assessments While Taking Sequential RisksTrial.~~assessments while taking sequential risks, *Trial* 2008, 326–331, http://dx.doi.org/10.1037/0278-7393.34.1.167.

[14] W. Schultz, Updating dopamine reward signals, *Curr. Opin. Neurobiol.* **23**, 2013, 229–238, http://dx.doi.org/10.1016/j.conb.2012.11.012.

[15] E.S. Bromberg-Martin, M. Matsumoto and O. Hikosaka, Dopamine in ~~Motivational Control: Rewarding, Aversive, and AlertingNeuron.~~motivational control: rewarding, aversive, and alerting, *Neuron* **68**, 2010, 815–834, http://dx.doi.org/10.1016/j.neuron.2010.11.022.

[16] R.A. Wise, Forebrain substrates of reward and motivation, *J. Comp. Neurol.* **493**, 2005, 115–121, http://dx.doi.org/10.1002/cne.20689.

[17] C.B. Holroyd and M.G.H. Coles, The neural basis of human error processing: ~~R~~reinforcement learning, dopamine, and the error-related negativity, *Psychol. Rev.* **109**, 2002, 679–709, http://dx.doi.org/10.1037//0033-295X.109.4.679.

[18] A.S. Cherniawsky and C.B. Holroyd, High temporal discounters overvalue immediate rewards rather than undervalue future rewards: ~~A~~an event-related brain potential study, *Cogn. Affect. Behav. Neurosci.* 2012, 36–45, http://dx.doi.org/10.3758/s13415-012-0122-x.

[19] C.B. Holroyd and N. Yeung, Motivation of extended behaviors by anterior cingulate cortex, *Trends Cogn. Sci.* **16**, 2012, 122–128, http://dx.doi.org/10.1016/j.tics.2011.12.008.

[20] G.R. Samanez-Larkin, D.A. Worthy, R. Mata, S.M. McClure and B. Knutson, Adult age differences in frontostriatal representation of prediction error but not reward outcome, ~~, Cogn. Affect. Behav~~*Cogn. Affect. Behav. Neurosci.* **14**, 2014, 672–682, http://dx.doi.org/10.3758/s13415-014-0297-4.

[21] S. Nieuwenhuis, N. Yeung, C.B. Holroyd, A. Schurger and J.D. Cohen, Sensitivity of electrophysiological activity from medial frontal cortex to utilitarian and performance feedback, *Cereb. Cortex* ~~.~~**14**, 2004, 741–747, http://dx.doi.org/10.1093/cercor/bhh034.

[22] W.H.R. Miltner, C.H. Braun and M.G.H. Coles, Event-~~Related Brain Potentials Following Incorrect Feedback in a Time-Estimation Task: Evidence for a Generic Neural System for Error D~~related brain potentials following incorrect feedback in a time-estimation task: evidence for a generic neural system for error detection, *J. Cogn. Neurosci.* **9**, 1997, 788–798, http://dx.doi.org/10.1162/jocn.1997.9.6.788.

[23] C.B. Holroyd and M.G.H. Coles, The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity, *Psychol. Rev.* **109**, 2002, 679–709, http://dx.doi.org/10.1037/0033-295X.109.4.679.

[24] F. Mushtaq, R.M. Wilkie, M.A. Mon-Williams and A. Schaefer, Randomised prior feedback modulates neural signals of outcome monitoring, *Neuroimage* **125**, 2016, 868–879, http://dx.doi.org/10.1016/j.neuroimage.2015.10.046.

[25] G.H. Proudfit, The reward positivity: ~~F~~from basic research on reward to a biomarker for depression, *Psychophysiology* **52**, 2015, http://dx.doi.org/10.1111/psyp.12370.

[26] C.B. Holroyd, O.E. Krigolson and S. Lee, Reward positivity elicited by predictive cues, *Neuroreport* ~~.~~**22**, 2011, 249–252, http://dx.doi.org/10.1097/WNR.0b013e328345441d.

[27] J. Polich and J.R. Criado, Neuropsychology and neuropharmacology of P3a and P3bb, *Int. J. Psychophysiol.* **60**, 2006, 172–185, http://dx.doi.org/10.1016/j.ijpsycho.2005.12.012.

[28] C. Kamarajan, B. Porjesz, M. Rangaswamy, Y. Tang, D.B. Chorlian, A. Padmanabhapillai, et al., Brain signatures of monetary loss and gain: ~~O~~outcome-related potentials in a single outcome gambling task, *Behav.*

Brain Res. **197**, 2009, 62–76, http://dx.doi.org/10.1016/j.bbr.2008.08.011.

[29] R. West, K. Bailey, S. Anderson and P.D. Kieffaber, Beyond the FN: ~~A~~a spatio-temporal analysis of the neural correlates of feedback processing in a virtual Blackjack game, *Brain Cogn.* **86**, 2014, 104–115, http://dx.doi.org/10.1016/j.bandc.2014.02.003.

[30] R. Gu, Z. Lei, L. Broster, T. Wu, Y. Jiang and Y.-J. Luo, Beyond valence and magnitude: a flexible evaluative coding system in the brain, *Neuropsychologia* ~~,~~**49**, 2011, 3891–3897, http://dx.doi.org/10.1016/j.neuropsychologia.2011.10.006.

[31] L. Lole, C.J. Gonsalvez, R.J. Barry and F.M. De Blasio, Can event-related potentials serve as neural markers for wins, losses, and near-wins in a gambling task? A principal components analysis, *Int. J. Psychophysiol.* **89**, 2013, 390–398, http://dx.doi.org/10.1016/j.ijpsycho.2013.06.011.

[32] D. Zhang, R. Gu, T. Wu, L.S. Broster, Y. Luo, Y. Jiang, et al., An electrophysiological index of changes in risk decision-making strategies, *Neuropsychologia* ~~,~~**51**, 2013, 1397–1407, http://dx.doi.org/10.1016/j.neuropsychologia.2013.04.014.

[33] S. Nieuwenhuis, G. Aston-Jones and J.D. Cohen, Decision making, the P3, and the locus coeruleus-norepinephrine system, *Psychol. Bull.* **131**, 2005, 510–532, http://dx.doi.org/10.1037/0033-2909.131.4.510.

[34] S.M.H. Hosseini, M. Rostami, Y. Yomogida, M. Takahashi, T. Tsukiura and R. Kawashima, Aging and decision making under uncertainty: behavioral and neural evidence for the preservation of decision making in the absence of learning in old age, *Neuroimage* **52**, 2010, 1514–1520, http://dx.doi.org/10.1016/j.neuroimage.2010.05.008.

[35] N.K. Ferdinand and J. Kray, Age-related changes in processing positive and negative feedback: is there a positivity effect for older adults?, *Biol. Psychol.* **94**, 2013, 235–241, http://dx.doi.org/10.1016/j.biopsycho.2013.07.006.

[36] B. Eppinger, J. Kray, B. Mock and A. Mecklinger, Better or worse than expected? Aging, learning, and the ERN, *Neuropsychologia* **46**, 2008, 521–539, http://dx.doi.org/10.1016/j.neuropsychologia.2007.09.001.

[37] N.L. Denburg and W.M. Hedgcock, Age~~-Associated Executive Dysfunction, the Prefrontal Cortex, and Complex Decision M~~associated executive dysfunction, the prefrontal cortex, and complex decision making, *Aging Decis. Mak. Empir. Appl. Perspect.* **79**, 2015.

[38] ~~L.BäckmanL.Farde~~L. Bäckman, L. Farde, The role of dopamine systems in cognitive aging, ~~in: Cogn~~Cogn. Neurosci. Aging Link. Cogn. Cereb. Aging~~20055884~~, 2005: pp. 58–84. 10.1176/appi.ajp.163.3.560

[39] S. Nieuwenhuis, K.R. Ridderinkhof, D. Talsma, M.G.H. Coles, C.B. Holroyd, A. Kok, et al., A computational account of altered error processing in older age: dopamine and the error-related negativity, *Cogn. Affect. Behav. Neurosci.* **2**, 2002, 19–36 http://www.ncbi.nlm.nih.gov/pubmed/12452582.

[40] A. Kóbor, Á. Takács, K. Janacsek, D. Németh, F. Honbolygó and V. Csépe, Different strategies underlying uncertain decision making: ~~H~~higher executive performance is associated with enhanced feedback-related negativity, *Psychophysiology* **52**, 2015, 367–377, http://dx.doi.org/10.1111/psyp.12331.

[41] D. Wechsler Manual for the Wechsler Adult Intelligence Scale. (1955).

[42] G. Fein and M. Chang, Smaller feedback ERN amplitudes during the BART are associated with a greater family history density of alcohol problems in treatment-naïve alcoholics, *Drug Alcohol Depend.* **92**, 2008, 141–148, http://dx.doi.org/10.1016/j.drugalcdep.2007.07.017.

[43] A. Delorme, T. Mullen, C. Kothe, Z. Akalin Acar, N. Bigdely-Shamlo, A. Vankov, et al., EEGLAB, SIFT, NFT, BCILAB, and ERICA: new tools for advanced EEG processing, *Comput. Intell. Neurosci.* **2011**, 2011, http://dx.doi.org/10.1155/2011/130714.

[44] J. Mognon and L. Jovicich, ADJUST: An automatic EEG artifact detector based on the joint use of spatial and temporal features, *Psychophysiology* **48**, 2010, 229–240, http://dx.doi.org/10.1111/j.1469-8986.2010.01061.x.

[45] T.J. Pleskac and A. Wershbale, Making assessments while taking repeated risks: ~~A~~a pattern of multiple response pathways, *J. Exp. Psychol. Gen.* **143**, 2014, 142.

[46] C.D. Hassall, K. Holland and O.E. Krigolson, What do I do now? An electroencephalographic investigation of the explore/exploit dilemma, *Neuroscience* ~~,~~ **228**, 2013, 361–370, http://dx.doi.org/10.1016/j.neuroscience.2012.10.040.

[47] D. Matzke and E.-J. Wagenmakers, Psychological interpretation of the ex-Gaussian and shifted Wald parameters: a diffusion model analysis, *Psychon. Bull. Rev.* **16**, 2009, 798–817.

[48] S.M. Helfinstein, T. Schonberg, E. Congdon, K.H. Karlsgodt, J. a. Mumford, F.W. Sabb, et al., Predicting risky choices from brain activity patterns, *Proc. Natl. Acad. Sci. U. S. A.* **111**, 2014, 2470–2475, http://dx.doi.org/10.1073/pnas.1321728111.

[49] S. Fecteau, A. Pascual-Leone, D.H. Zald, P. Liguori, H. Théoret, P.S. Boggio, et al., Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making, *J. Neurosci.* **27**, 2007, 6212–6218, http://dx.doi.org/10.1523/JNEUROSCI.0314-07.2007.

[50] M.M. Botvinick, Hierarchical reinforcement learning and decision making, *Curr. Opin. Neurobiol.* **22**, 2012, 956–962, http://dx.doi.org/10.1016/j.conb.2012.05.008.

[51] P. Reuter-Lorenz, New visions of the aging mind and brain, *Trends Cogn. Sci.* **6**, 2002, 394 http://www.ncbi.nlm.nih.gov/pubmed/12200182.

[52] P.A. Reuter-lorenz and D.C. Park, Human ~~Neuroscience and the Aging Mind: A New Look at Old P~~neuroscience and the aging mind: a new look at old problems, *J. Gerontol. Psychol. Sci.* **65**, 2010, 405–415, http://dx.doi.org/10.1093/geronb/gbq035.

[53] D.E. Henninger, D.J. Madden and S.A. Huettel, Processing speed and memory mediate age-related differences in decision making, *Psychol. Aging* **25**, 2010, 262–270, http://dx.doi.org/10.1037/a0019096.

[54] J. Kiat, B. Straley and J.E. Cheadle, Escalating ~~Risk and the Moderating Effect of Resistance to Peer I~~risk and the moderating effect of resistance to peer influence on the P200 and ~~Feedback Related N~~feedback related negativity, *Soc. Cogn. Affect. Neurosci.* 2015, nsv121.

[55] B. Eppinger, D. Hammerer and L. Shu-Chen, Neuromodulation of reward based learning and decision making in human aging, *Ann~~ N Y Acad~~. N. Y. Acad. Sci.* **1235**, 2011, 1–17, http://dx.doi.org/10.1111/j.1749-6632.2011.06230.x.Neuromodulation.

[56] D. Hämmerer, S.-C. Li, V. Müller and U. Lindenberger, Life ~~Span Differences in Electrophysiological Correlates of Monitoring Gains and Losses during Probabilistic Reinforcement L~~span differences in electrophysiological correlates of monitoring gains and losses during probabilistic reinforcement learning, *J. Cogn. Neurosci.* **23**, 2010, 579–592, http://dx.doi.org/10.1162/jocn.2010.21475.

[57] M. Herbert, B. Eppinger and J. Kray, Younger but not older adults benefit from salient feedback during learning, *Front. Psychol.* **2**, 2011, 1–9, http://dx.doi.org/10.3389/fpsyg.2011.00171.

[58] D.H. Mathalon, S.L. Whitfield and J.M. Ford, Anatomy of an error: ERP and fMRI, *Biol. Psychol.* **64**, 2003, 119–141, http://dx.doi.org/10.1016/S0301-0511(03)00105-4.

[59] K.J. Mathewson, J. Dywan, P.J. Snyder, W.J. Tays and S.J. Segalowitz, Aging and electrocortical response to error feedback during a spatial learning task, *Psychophysiology* **45**, 2008, 936–948, http://dx.doi.org/10.1111/j.1469-8986.2008.00699.x.

[60] M.M. Walsh and J.R. Anderson, Learning from experience: event-related potential correlates of reward processing, neural adaptation, and behavioral choice, ~~., Neurosci~~*Neurosci. Biobehav. Rev.* **36**, 2012, 1870–1884, http://dx.doi.org/10.1016/j.neubiorev.2012.05.008.

Highlights

- ~~a~~Age-dependent risk-taking behavior in sequential decision making was investigated.
- ERPs for the rewarding feedback were analyzed based on the forthcoming decisions.
- ~~r~~Reward positivity increased as a function of reward contingencies only in the young.
- ~~i~~Increased hesitation and deliberate decisions characterized the elderly.

- rReward contingencies had less effect on the elderly than on the young.

Queries and Answers

Query: The author names have been tagged as given names and surnames (surnames are highlighted in teal color). Please confirm if they have been identified correctly
Answer: The names of the authors have been identified correctly.

Query: Please check that the affiliations link the authors with their correct departments, institutions, and locations, and correct if necessary.
Answer: The affiliations are correct.

Query: “Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact m.gunasekaran@elsevier.com immediately prior to returning your corrections.”
Answer: This article does not belong to a special issue/collection.

Query: One or more sponsor names and the sponsor country identifier may have been edited to a standard format that enables better searching and identification of your article. Please check and correct if necessary.
Answer: The sponsor names are correct.

Query: Please check the presentation of Refs. [7,20,53] and amend if necessary.
Answer: The presentation of the Refs. [7,20,53] are correct.

Query: Please check all figures caption as well as artwork.
Answer: The figure captions and artworks are correct.

Query: Please provide a definition for the significance of [asterisk] in Table 2.
Answer: This asterisk does not say anything about significance, this is just the way how we represent the interaction between the two (or three) factors.