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Registered Report

Neurophysiological examination of the affect–integration–motivation framework of decision-making in the aging brain: A registered report

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ABSTRACT

The Affect–Integration–Motivation (AIM) framework was proposed to clarify how brain circuits that support decision-making are altered by aging (Samanez-Larkin & Knutson, 2015). According to this framework, choices are preceded by affective, integrative, and motivational processes, which may all be affected by aging. The Monetary Incentive Delay (MID) task allows tapping into several mechanisms proposed by the AIM framework, and the present registered report aimed to explore the temporal resolution of the EEG to find the neural correlates of age differences in such mechanisms, including gain/loss anticipation, value integration, motivational processes underlying motor choice, as well as processing of positive/negative rewards. The electrophysiological data were recorded from 77 participants (20–80 years old), and we analyzed the Cue-P3, Contingent Negative Variation, target-P3, Feedback-related Negativity, and the Feedback-P3. The results support the AIM framework, suggesting that aging altered affective processes (as shown by a significant reduced cue-P3 in the older group), while preserved integration and motivation processes. However, despite a general lack of significant group by domain interactions across the ERPs analyzed, the results of the planned comparisons are suggestive of a preserved processing of gains and affected processing of losses during aging. This conclusion requires further replication with larger samples, but our study shows that future research may profit from decomposing decision processes to understand how biological aging affects decision making.

1. Introduction

Aging influences economic decision-making, with potentially wide-ranging consequences for older adults' health and well-being (for a review, see Mata et al., 2011). The Affect–Integration–Motivation (AIM) framework was proposed to clarify how the brain circuits that support decision-making are altered by aging, thus providing a mechanistic account of age-related decision-making changes (Samanez-Larkin and Knutson, 2015). According to this framework, three sequential and hierarchical processes precede choices. First, *affective processes* potentiate anticipation of gains (via mesolimbic dopaminergic projections to the nucleus accumbens) and losses (via noradrenergic and dopaminergic projections from the locus coeruleus to the anterior insula). This anticipation of gains and losses induces positive and negative arousal, and motivates approach and avoidance behaviors, respectively. Second, the output of the affective anticipation is integrated (*integration processes*) with further evaluative considerations, via glutamatergic projections from the ventral tegmental area, locus coeruleus, and ventral striatum to the medial prefrontal cortex (mPFC), and back to the ventral striatum. Finally, the outcome of this integration feeds in *motivation processes* that promote subsequent actions (approach or avoidance) and motor responses (via glutamatergic projections from the dorsal striatum and anterior insula to the pre-supplementary motor area; Samanez-Larkin and Knutson, 2015).

Previous literature suggests that some of these processes are affected by aging. For instance, evidence shows that aging preserves gain but reduces loss anticipation (Samanez-Larkin et al., 2007). Older adults show reduced reinforcement learning, probably due to the diminished responsiveness of the nucleus accumbens to violations of reward expectations, as well as degraded connectivity from this region to the mPFC (Samanez-

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Larkin and Knutson, 2015). Finally, aging may degrade glutamatergic projections from the mPFC to the striatum, compromising value integration (Samanez-Larkin and Knutson, 2015).

In the present study, we aim to explore the temporal resolution of EEG to identify age-related differences in neural correlates associated with the processes proposed by the AIM framework. To this purpose, younger and older adults performed a version of the Monetary Incentive Delay (MID) task (Knutson et al., 2000), adapted to the event-related potential (ERP) technique of EEG (Broyd et al., 2012). The MID task allows the identification of core brain networks involved in different stages of anticipatory and reward processing. During this task, participants are presented with a cue that signals possible gains and losses. This cue is followed by a perceptually undemanding target detection, which requires a button press to win or avoid losses. Then, feedback reveals the success or failure of the performance (Knutson et al., 2000). Thereby, the MID task allows studying the mechanisms that precede choice proposed by the AIM framework. The cue signaling gains or losses elicits anticipatory affective processes, which are integrated with further considerations to influence motivation processes that promote the motor response required by the target.

A number of recent studies further showed the utility of the electrophysiological version of the MID task (e-MID) for the temporal decomposition of the brain activity during anticipatory, target, and outcome stages of decision-making (Broyd et al., 2012; Flores et al., 2015; Hill et al., 2018; Novak and Foti, 2015; Oumeziane et al., 2017; Pfabigan et al., 2014). Moreover, one of these studies used the e-MID task to show that several ERPs related to reward anticipation and feedback processing deteriorate with age (Hill et al., 2018).

In our work, we used the e-MID task and EEG to further identify age-differences in the neural correlates of the main components of the AIM framework, in particular, gain/loss anticipation, value integration, and motivational processes linked to motor responses, as well as the processing of positive/negative rewards. In what follows, we introduce our main components of interest and expected patterns of age differences that we derive from the AIM framework and related aging literature. We see our work as a contribution to establishing AIM as a helpful framework to understand age differences in decision-making.

First, to examine the anticipatory neural responses, we analyzed the P3 evoked by cues (cue-P3), that is a centroparietal positivity correlated with the engagement of proactive cognitive control (Bekker et al., 2004), which increases in function of the reinforcement amount (Goldstein et al., 2006). Concerning the effects of aging, the cue-P3 of older adults typically exhibits less differentiation based on the significance of the cue (Hämmerer et al., 2010; Kropotov et al., 2016), and increased latencies (Kray et al., 2005).

Second, to examine the integration process of the value, we analyzed the contingent negative variation (CNV), a frontocentral negative potential induced by a cue signaling the future presentation of an imperative stimulus. It can be divided into an earlier component ('orienting' O wave), related to the alerting properties of the cue, and a later component ('expectancy' E wave), associated with the engagement of effortful processes to future motor responses (Brunia et al., 2011; Brljnia and Vingerhoets, 1981; Van Boxtel and Bocker, 2004). The CNV appears to be modulated by motivation (Cant and Bickford, 1967; Irwin et al., 1966), cognitive effort (Falkenstein et al., 2003; Gómez et al., 2007) and salience of the stimuli (Baas et al., 2002; Klorman and Ryan, 1980). It is modulated by the presence of monetary incentives, being larger for incentive than for non-incentive cues (see, for instance, Schevernels et al., 2016, 2014). The CNV is more negative in older adults than younger adults, particularly during demanding tasks (Kray et al., 2005; Wild-Wall et al., 2007).

Despite the studies cited above, only Schmitt et al. (2015) examined the effects of monetary incentives on the cue-P3 and CNV in younger and older adults. The authors found that gains and losses elicited more positive cue-P3 than neutral cues in both groups, but this effect was larger in younger adults. Regarding the CNV, only younger adults showed amplitudes more negative after cues anticipating losses than after neutral cues, while cues anticipating gain and neutral trials induced similar amplitudes in both groups. Building upon this study (Schmitt et al., 2015), we hypothesized a more positive cue-P3 after cues anticipating gains and losses than after neutral cues, both in younger and older adults (H1). We also hypothesized a more negative CNV after cues anticipating losses than cues anticipating neutral and gain trials in younger adults, while predicting similar CNV amplitudes for cues anticipating the three conditions in older adults (H2).

Third, to examine the motivational processes behind motor choices, we analyzed the Lateralized Readiness Potential (LRP) and the target-P3. The LRP reflects a voluntary motor response after a decision has been taken, signaling a decision threshold (Van Vugt et al., 2014). To the best of our knowledge, the effect of aging on LRP was not previously studied using incentivized tasks. However, the results of target detention tasks evidenced more negative LRP in older than in younger adults. This result was interpreted as a decline in inhibitory control (Roggeveen et al., 2007) or as an increased threshold of response activation due to dysregulation in high-level control systems (Wild-Wall et al., 2008; Yordanova et al., 2004). The target-P3 is a centroparietal ERP elicited by the target, which was previously considered a robust index of task-relevance and motivated attention (Groom et al., 2010). The target-P3 seems to be delayed and more frontally distributed in older adults (Wild-Wall et al., 2008; Williams et al., 2016; 2018). Due to the lack of literature about the effect of monetary tasks on these ERP components (LRP and target-P3), we formulated our hypothesis based on the evidence provided by the AIM framework, which argues that aging may degrade glutamatergic projections from mPFC to the striatum, reducing value integration and motivational processes (Samanez-Larkin and Knutson, 2015). Thus, we predicted similar LRP and target-P3 amplitudes for gain, loss, and neutral conditions in older adults, while predicting more negative LRP and more positive target-P3 for gain and loss than neutral conditions in younger adults (H3 for LRP and H4 for target-P3).

Finally, concerning the processes following the decision, the e-MID task allows the study of the neural correlates of feedback processing. Thereby, we analyzed two ERP components that play a crucial role in processing rewards (Martín, 2012): the frontocentral feedback-related negativity (FRN) and the parietal feedback-P3.

The FRN is a frontocentral negative-going ERP typically larger for negative than positive outcomes (Martín, 2012; Miltner et al., 1997). On the other side, the feedback-P3 appears to be sensitive to the expectancy (Donaldson et al., 2016), probabilistic, arousing, motivational, and emotional nature of the feedback (Nieuwenhuis, 2011). Regarding the effects of aging on these components, while one study found that both younger and older adults had more negative FRN after losses than after gains (Di Rosa et al., 2017), another study found that only younger adults had more negative FRN after losses, whereas older adults had similar amplitudes after both conditions (Kardos et al., 2017). Another study found that, in comparison with younger adults, older adults had reduced FRN amplitudes after gains, losses, and busts (West et al., 2014). Finally, a recent study analyzed age-related differences in the FRN elicited by feedbacks delivered in loss and gain domains. The results showed that groups differed only in the loss domain, in which older adults were insensitive to the feedback valence, while younger adults had a more negative FRN after non-losses (zero-value outcome) than after losses (Fernandes et al., 2018). In the gain domain, both groups had more negative FRN after non-gains (zero-value outcome) than after gains. Considering the similarity in design, we based our hypothesis on the results of Fernandes et al. (2018). Therefore, in younger adults, we hypothesize more negative FRN after non-losses than after losses and more negative component amplitudes after non-gains than after gains. Regarding older adults, we predict more negative FRN after non-gains than after gains, while predicting similar amplitudes after non-losses and losses (H5).

Regarding feedback-P3, while one study found that younger and older adults had similar amplitudes after gains, but older adults had reduced feedback-P3 after losses (Di Rosa et al., 2017), another study

found that older adults had reduced amplitudes after gains, losses and bust (West et al., 2014). Other study showed that, while younger adults had more positive feedback-P3 after gains than after losses, older adults had similar amplitudes after both conditions (Kardos et al., 2017). The study from Fernandes et al. (2018), which analyzed differences in the feedback-P3 after positive and negative feedbacks delivered in loss and gain domains, and showed that groups only differed in the gain domain. While younger adults had more positive feedback-P3 after gains than after non-gains (zero-value outcome), older adults had similar amplitudes after both conditions. In the loss domain, both groups had similar amplitudes after losses and non-losses (zero-value outcome). Consequently, we predicted more positive feedback-P3 for gains than non-gains in younger adults, while we predicted similar amplitudes for losses and non-losses. Regarding older adults, we predict similar amplitudes after all conditions (gains, non-gains, losses, non-losses) (H6).

In this study, we measured age continuously instead of in dichotomous groups. Based on Hill and colleagues' result, we predicted that ERP amplitudes would decrease with age, which would be reflected in higher amplitudes for younger adults compared with middle-aged and older adults, and higher amplitudes for middle-aged adults compared with older adults (H7). This study is a registered report, and all the procedures of the confirmatory analysis are described a priori. The protocol associated with this Registered Report received in-principle acceptance (IPA) on 10 Sep 2019, prior to data collection and analysis. The approved Stage 1 manuscript, unchanged from the point of IPA, may be downloaded from https://osf.io/knx63/. We analyzed the data collected according to procedures designed to reduce spurious effects and family-wide and experiment-wide error rates in ERP data (Pasion et al., 2018).

2. Method

2.1. Participants

2.1.1. Sample size calculation

Although this research was focused on the investigation of several ERP components, only the CNV, cue-P3, FRN and feedback-P3 were investigated with economic decision-making tasks (Di Rosa et al., 2017; Fernandes et al., 2018; Kardos et al., 2017; West et al., 2014) or with monetary incentives (Schmitt et al., 2015). Therefore, we based our power analysis on the reported effect sizes in these studies. Effect sizes ranged from medium (η_p^2=0.114; Fernandes et al., 2018) to large (η_p^2=0.71; Schmitt et al., 2015; see Table 1 a summary). Considering this range and accounting for possible publication bias, we adopted a conservative approach and selected a small effect size for our sample size calculation.

The sample size was calculated with GPower 3.1 (Faul et al., 2007). We assumed an effect of $f = 0.15$ ($\alpha = 0.05$, 1-$\beta = 0.80$) for the main effects and interactions of a repeated measure ANOVA with three within-subject factors (gain, loss, and neutral conditions), three groups (younger, middle-aged, and older adults), and moderate correlation among amplitudes ($r = 0.60$). Correlation between measures was estimated from the database provided by Fernandes et al. (2018), in which all correlations between FRN and feedback-P3 were larger than $r = 0.64$. The statistical power analysis revealed that a sample size of 75 participants would be adequate. As participants with less than 20 valid trials in each ERP component were excluded (see Section 2.1.3. for exclusion criteria), more participants were recruited to ensure the analysis was sufficiently powered.

2.1.2. Inclusion criteria

We recruited healthy participants between 20 and 80 years of age, both men and women, with more than four years of formal education, to be included into two age groups: younger adults (20 – 40 years), middle-aged adults (40–60 years), and older adults (60 – 80 years). We aimed for, at least, 25 participants per group.

Table 1
An overview of the results of previous studies investigating the effects of aging on anticipation of gains and losses and feedback processing.

Study	Task	ERP component	*n*	*F*	*p*	BS η_p^2	Interaction η_p^2	WS η_p^2	Comparison
Schmitt et al. (2015)	AXE-CPT	Cue-P3	YA = 18 OA = 18	40.9 12.5	< 0.001 < 0.01	0.19		.71 .42	losses > neutral; gains > neutral losses > neutral; gains > neutral
Schmitt et al. (2015)	AXE-CPT	CNV	YA = 18 OA = 18	12.6	< 0.01	0.16		.43	losses > neutral; gains = neutral losses = neutral; gains = neutral
Di Rosa et al. (2017)	Iowa Gambling Task	FRN	YA = 21 OA = 15						losses > gains losses > gains
Kardos et al. (2017)	Two-choice single-outcome gambling task	FRN	YA = 18 OA = 17	6.09	.018		.15		losses > gains losses = gains
West et al. (2014)	Backjack game	FRN	YA = 20 OA = 20						OA < YA
Fernandes et al. (2018)	Risky task	FRN	YA = 29 OA = 26	6.95	.011	0.010	0.088	.118	Non-losses > losses; non-gains > gains Non-losses = losses; non-gains > gains
Di Rosa et al. (2017)	Iowa Gambling Task	Feedback-P3	YA = 21 OA = 15	4.31	.001		.11		OA < YA only for losses
Kardos et al. (2017)	Two-choice single-outcome gambling task	Feedback-P3	YA = 18 OA = 17	6.34	.017	0.52	.16		gains > losses gains = losses
West et al. (2014)	Backjack game	Feedback-P3	YA = 20 OA = 20						OA < YA
Fernandes et al. (2018)	Risky task	Feedback-P3	YA = 29 OA = 26	6.69	.013	0.026	0.092	.114	gains > non-gains; losses = non-losses gains = non-gains; losses = non-losses

Note: OA = older adults; MA = middle-aged adults; YA = younger adults; BS = Between-subjects; WS = Within-subjects; CNV = Contingent Negative Variation; LRP = Lateralized Readiness Potential; FRN = Feedback-related Negativity.

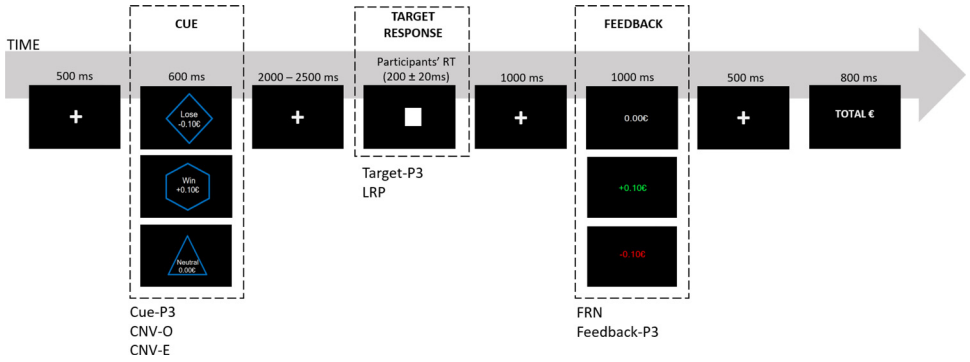

Fig. 1. Depiction of each trial of the e-MID task. Note: ISI = inter-stimulus interval; RT = Reaction Time; CNV = Contingent Negative Variation; LRP = Lateralized Readiness Potential; FRN = Feedback-related Negativity.

2.1.3. Exclusion criteria

The recruited participants were assessed according to neurocognitive and affective tests during the first data collection session. After this session, participants were excluded if they scored below the cutoff score (22 points) for mild cognitive impairment in the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005; Freitas et al., 2014), if they reported uncorrected visual impairments, use of psychotropic medication, history of brain injury, as well as neurological or psychiatric diagnosis. The participants who meet the inclusion criteria were invited to the second session of data collection, in which they performed the e-MID task during the EEG recording. After this session, we also excluded participants with less than 20 valid trials per condition in each ERP, which is the number of trials needed for reliable ERP components (Broyd et al., 2012).

2.2. Instruments and tasks

2.2.1. Neuropsychological measures

The MoCA was used to assess general cognitive abilities. The fluid intelligence was measured by the Test of Non-Verbal Intelligence (TONI-4; Brown et al., 2019), a test of inductive and analytic reasoning, and by the short form of the Wisconsin Card Sorting Test (WCST), a test of reward-based learning and executive function (Kongs et al., 2000). Crystallized abilities were be assessed by the Comprehension and Vocabulary tests of the Wechsler Adult Intelligence Scale (Wechsler, 2008). The aging positivity effect was assessed by the Positive Affect Negative Affect Schedule (PANAS; Watson et al., 1988; Galinha and Pais-Ribeiro, 2005;).

2.2.2. Electrophysiological version of the monetary incentive delay (e-MID) task

The e-MID task (Broyd et al., 2012) was presented in E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA, USA). Each trial started with one of three cue stimuli, followed by a target stimulus (a white square). Participants were instructed to respond to the target as quickly as possible, pressing a button with the thumb of their dominant hand. After, feedback was provided.

The task comprised three domains - neutral, gains and losses – whose trials were presented in random order. In the neutral trials (blue triangle labeled "0.00€"), participants were instructed that they would neither win nor lose money based on their performance, and they would be shown neutral feedback at the end of each trial ("0.00€" in white). In the gain trials (blue hexagon cue labeled "Win +0.10€"), participants were instructed that successful responses (button presses while the target is still displayed) would result in positive feedback of a gain ("+0.10€" in green). Unsuccessful responses (responses either before the target onset or after the target offset) will result in negative feedback of no gains ("0.00€" in white). In the loss trials (blue diamond cue labeled "Lose −0.10€"), successful responses would result in positive feedback of no loss ("0.00€" in white), and unsuccessful responses in a negative feedback indicating a loss ("−0.10€" in red). A summary of the time course of the e-MID task is presented in Fig. 1. The task was composed of 150 trials (60 trials of gains, 60 trials of losses, and 30 neutral trials).

Participants were instructed that their final payoff depended on the success rate of their choices. However, unbeknownst to the participants, the task difficulty was adjusted throughout the task. The accuracy rate of each participant was manipulated by altering the average duration of the target with an adaptive timing algorithm set at the individual's mean reaction time in a practice block of 10 trials that occurred before the EEG data collection. This algorithm made the task easier (target duration = +20 ms) or harder (target duration = −20 ms) after each trial if the participant's success rate was inferior or superior to 50% of the trials already played, respectively. Participants received a fixed fee of 2.50€, plus a performance-dependent bonus. However, as the accuracy rate is set at 50%, the bonus was equal to 2.50€, and participants were compensated in the end with a 5€ (gift card) for their time.

2.3. Procedure

The participants were tested individually in two experimental sessions. The first session aimed to confirm the remaining inclusion/exclusion criteria and collect sociodemographic, neurocognitive, and affective data. The MoCA was administered first, followed by the remaining tests in random order. Participants who fulfilled the inclusion criteria were recruited for the second session, in which the experimental tasks were administered during an EEG recording. Participants were seated inside an EEG chamber, with ~115 cm between them and a 17″ screen where the task was displayed. The current study is part of a larger project approved by the local Ethics Committee.

2.4. EEG recording and processing

The EEG was recorded using a 128-electrode Hydrocel Geodesic Sensor Net, with a Net Amps 300 amplifier (Electrical Geodesics Inc., Eugene, U.S.), at a digitizing rate of 500 Hz. Impedances were kept below 50 kOhm for all electrodes (since this is a high impedance EEG system). The electrodes were referenced to the Cz during recording and re-referenced offline to the average of the electrodes placed in the left and right mastoids (E57, E100). EEG data was be pre-processed in EEGLAB version 14 (Delorme & Makeig, 2004), a MATLAT® toolbox. EEG recordings were downsampled to 250 Hz, band-pass filtered (0.1–30 Hz) and submitted to an Independent Components Analysis (ICA). Eye blink, saccade, alpha waves, and heart rate artifacts were corrected by subtracting the independent component activity from the data. Afterward, bad channels were interpolated (maximum of 10% of the sensors), all segments were visually inspected, and the remaining artifactual epochs were rejected. All epochs were baseline corrected (200 ms pre-stimulus) and averaged by domain (neutral, gain, loss).

On each trial of the e-MID task, we examined ERP components induced by the cue, target, motor response, and feedback stimuli. The stimuli in which each ERP component were examined are presented in Fig. 1. The epoch to the cue began 200 ms prior to stimulus onset

and ended 2600 ms post-stimulus presentation. The epoch to the target stimulus began 200 ms prior to stimulus onset and ended 800 ms post-stimulus presentation. The epoch to the motor response began 700 ms prior to response and ended with the response. Finally, the epoch to the feedback stimulus began 200 ms pre-stimulus and ended 1500 ms post-stimuli. Epochs were corrected to the mean voltage of the baseline (−200 to 0 in stimulus-locked ERP components and −700 to −500 in response-locked ERP components).

According to the literature, the cue-P3 is a centroparietal positivity, which emerges between 300 and 600 ms post-stimulus (Goldstein et al., 2006). The CNV is a slow negative potential, maximal over frontocentral sites, which typically emerges between 600 and 1600 ms (O–CNV), and between 1600 and 2600 ms post-stimulus (E-CNV; Broyd et al., 2012; Novak and Foti, 2015). The target-P3 is a centroparietal component typically elicited approximately 300–400 ms following target stimuli (Polich and Kok, 1995). The LRP is obtained through the formula [(C4 - C3) non-dominant hand movements + (C3 - C4) dominant hand movements]/2], between 350 and 150 ms before the motor response (Cespón et al., 2013). The FRN is typically measured over the frontocentral region, at 250–350 ms after the feedback onset, while the feedback-P3 is typically measured over the centroparietal region between 300 and 500 ms after the feedback onset (Martín, 2012).

However, considering that older adults have typically broader topographies (Friedman, 2012), the electrodes of interest for each component were those with more positive/negative amplitudes (for positive/negative components, respectively), within the region of interest described in the literature. Once we selected the electrode of interest, the cluster of the surrounding electrodes was used to measure each ERP component to increase the signal-to-noise ratio of the data (Luck and Gaspelin, 2017). Moreover, older adults also have delayed latencies (see, Cespón et al., 2013; Eppinger et al., 2008; Ferdinand and Kray, 2013; Fernandes et al., 2018; Friedman, 2012). Considering this, the time window of the targe-P3 and FRN amplitudes were ±50 ms around the peak latency of each group. The time window of the cue-P3, LRP, and feedback-P3 were ±100 ms around the peak latency of each group. Finally, the time window of the CNV-O and CNV-E amplitudes were ±500 ms around the latency of the minimal amplitude of each group. Once the time windows of interest were defined, all the ERPs were measured as the mean amplitude of that time window.

2.5. Statistical analysis

2.5.1. Manipulation check

Participants were instructed that the neutral cue does not anticipate gains or losses. Thus, they would receive neutral feedback in these trials, and this condition served as a manipulation check. It allows the contrast of the ERPs induced by gain/loss trials with those obtained in the neutral condition. The manipulation check was confirmed through the main effect of condition in the mixed reported-measures ANOVAs conducted during the confirmatory statistical analysis. Specifically, we hypothesize significant differences between ERP amplitudes obtained in gain/loss conditions compared to the ERPs elicited by the neutral condition.

2.5.2. Confirmatory statistical analysis

The confirmatory analysis to test the effects of aging on anticipatory (Cue-P3, CNV), integration (LRP) and motivation processes (Cue-P3) was conducted through mixed repeated-measures ANOVA, using *age group* (younger, middle-aged, older adults) as a between-subjects factor, and *domain* (gains, losses, neutral) as a within-subjects factor. The comparisons of interest are observed through the main effects of age and within the age group*domain interaction, comparing each group on the modulation of the ERPs induced by gains vs neutral and loss vs. neutral domains. The confirmatory analysis to test the effects of aging on feedback processing (FRN and Feedback-P3) were conducted through mixed repeated-measure ANOVAs, using *age group* (younger, middle-aged, older adults) as a between-subjects factor, and *domain* (gains, losses) and feedback (gains, non-gains, losses, non-losses) as within-subjects factors. The comparisons of interest are observed within the age group*domain*feedback interaction, comparing, by group, the modulation of these ERP components induced by gains versus non-gains, losses versus non-losses. The planned comparisons to test our hypotheses are described in Table 2.

The threshold for statistical significance was set at $\alpha = 0.05$ for all analyses. Violations of sphericity were corrected via the Greenhouse-Geisser method. Statistical analysis was performed using SPSS 27 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Participants

One hundred and forty-five participants were recruited from the local community. According to the inclusion criteria, two participants were excluded for uncorrected visual impairments, eight participants were excluded for psychotropic medication use, and 17 participants were excluded for history of brain injury, neurological or psychiatric diagnosis. Moreover, during the COVID-19 lockdowns, 37 participants dropped out of the study after the neuropsychological assessment and before the EEG data collection. Therefore, we collected EEG data of 81 participants from three age groups 28 younger adults (age range = 20 – 39 years old), 27 middle-aged adults (age range = 40 – 59 years old), and 26 older adults (age range = 60 – 80 years old). After data treatment, one younger adult, two middle-aged adults, and one older adult were excluded for having less than 20 valid trials per condition in each ERP component. Thus, the final sample was composed of 77 participants: 27 younger adults (16 female; $M_{age} = 28.52$, $SD = 6.30$; $M_{education} = 17.15$, $SD = 2.18$), 25 middle-aged adults (15 female; $M_{age} = 47.72$, $SD = 5.83$; $M_{education} = 17.00$, $SD = 4.42$), and 25 older adults (14 female; $M_{age} = 67.68$, $SD = 4.79$; $M_{education} = 13.80$, $SD = 5.34$). Groups were statistically matched for sex, $\chi 2\ (2, 77) = 0.094$, $p = .954$, and differed significantly for years of education, $F(2,76) = 5.27$, $p = .007$.

3.2. Electrophysiological results

3.2.1. Anticipatory processes – cue-P3 (H1 and H7.1)

The cue-P3 was analyzed based on each group's morphology and topographical maps. As predicted in our pre-registration, the component's latency slightly varied between groups. Based on the morphology of the wave, the cue-P3 had the peak latency at the parietal region, at 260 ms for younger adults, 280 ms for middle-aged adults, and 260 ms for older adults. Thereby, the cue-P3 was measured at Pz Cluster (composed by the electrodes 54, 55, 61, 62 [Pz], 78, 79), and it was quantified as the mean amplitude in the time-window of 210 – 310 ms after the cue onset in the younger group, 230 – 330 ms in the middle-aged group, and 210 – 310 ms in the older group (Fig. 2).

3.2.1.1. Manipulation check. We found a main effect of *domain*, $F(2, 148) = 20.59$, $p < .001$, $\eta^2_p = 0.218$, $\varepsilon = 0.923$, showing that cues anticipating gain and loss trials elicited higher cue-P3 amplitudes than cues anticipating neutral trials ($p < .001$ in both cases).

3.2.1.2. Confirmatory statistical analysis. The planned comparison to test H7.1 (group comparison regarding the amplitude of the cue-P3) revealed a main effect of *age group*, $F(2, 74) = 8.40$, $p < .001$, $\eta^2_p = 0.185$. The younger ($p < .001$) and middle-aged adults ($p = .025$) had significantly higher amplitudes than older adults, but the comparison between younger and middle-aged adults was marginally significant ($p = .83$). The age group*domain interaction was not significant, $F(4, 148) = 1.98$, $p = .101$, $\eta^2_p = 0.051$, but the planned comparisons to test H1 revealed

Table 2
The planned comparisons for each hypothesis.

Trial Event	Neural Process	ERP	Hypothesis no.	Hypothesis	Planned Comparison
Cue	Anticipatory	Cue-P3	H1	YA: losses > neutral; gains > neutral; OA: losses > neutral; gains > neutral	YA: losses vs neutral; gains vs neutral; OA: losses vs neutral; gains vs neutral
Cue	Integration	CNV	H2	YA: losses > neutral; gains = neutral; OA: losses = neutral; gains = neutral	YA: losses vs neutral; gains vs neutral; OA: losses vs neutral; gains vs neutral
Target	Motivation	LRP	H3	YA: losses > neutral; gains > neutral; OA: losses = neutral; gains = neutral	YA: losses vs neutral; gains vs neutral; OA: losses vs neutral; gains vs neutral
Target	Motivation	Target-P3	H4	YA: losses > neutral; gains > neutral; OA: losses = neutral; gains = neutral;	YA: losses vs neutral; gains vs neutral; OA: losses vs neutral; gains vs neutral
Feedback	Feedback	FRN	H5	YA: non-losses > losses; non-gains > gains; OA: losses = non-losses; non-gains > gains	YA: losses vs non-losses; gains vs non-gains; OA: losses vs non-losses; gains vs non-gains
Feedback	Feedback	Feedback-P3	H6	YA: gains > non-gains; losses = non-losses; OA: gains = non-gains; losses = non-losses;	YA: losses vs non-losses; gain vs non-gains; OA: losses vs non-losses; gain vs non-gains
		All ERPs	H7	OA < MA < YA	Main effects of OA vs MA vs YA

Note: OA = older adults; MA = middle-aged adults; YA = younger adults; CNV = Contingent Negative Variation; LRP = Lateralized Readiness Potential; FRN = Feedback-related Negativity.

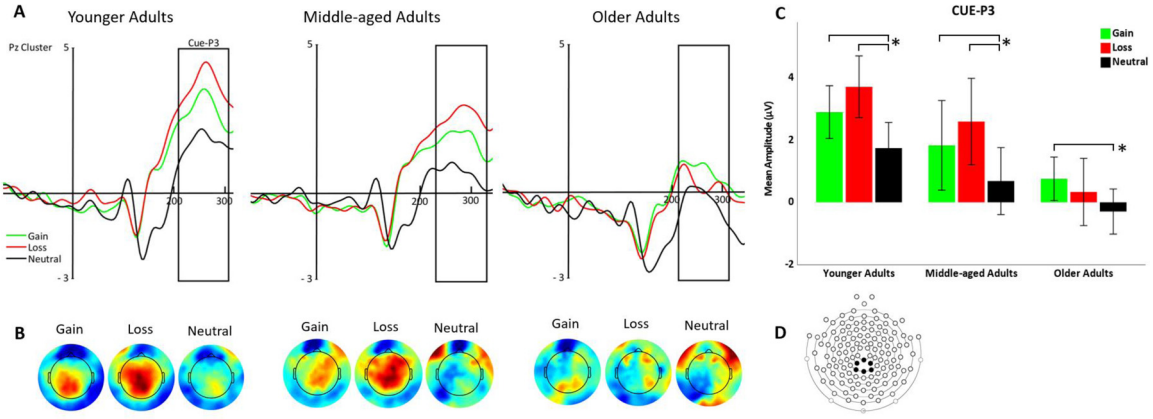

Fig. 2. A: Grand averages of the cue-P3 mean amplitude for younger, middle-aged, and older adults, evoked by cues anticipating gain, loss, and neutral trials. B: Topographical maps for the cue-P3 elicited for each condition and group. C: Means of the cue-P3 amplitudes (μV) evoked by condition. Error bars indicate 95% confidence intervals and * represent the significant planned comparisons. D: Electrode locations in the 128-channel HydroCel Geodesic Sensor Net (EGI) where the cue-P3 was measured.

that, for younger adults, cues anticipating gain (p = .004) and loss trials (p < .001) elicited higher amplitudes than cues anticipating neutral trials. Regarding older adults, cues anticipating gain trials elicited higher amplitudes than cues anticipating neutral trials (p = .012), but cues anticipating loss and neutral trials elicited similar amplitudes (p = .197). The results of the confirmatory statistical analysis are presented in Table 3.

3.2.1.3. Exploratory statistical analysis. The planned comparisons used test to H1 were analyzed for middle-aged adults, revealing that cues anticipating gain (p = .006) and loss trials (p < .001) elicited higher amplitudes than cues anticipating neutral trials.

3.2.2. Integration processes – CNV (H2 and H7.2)

The CNV was analyzed based on each group's morphology and topographical maps. As anticipated in the pre-registration methodology, the CNV emerged at FCz Cluster (composed of electrodes 5 6 [FCz] 7 12 13 106 112). The O–CNV was measured between 600 and 1600 ms, while E-CNV emerged between 1600 ms post-stimulus (Fig. 3).

3.2.2.1. Manipulation check. We found a main effect of *domain* for O–CNV, $F(2, 148) = 4.60$, $p = .017$, $\eta^2_p = 0.059$, $\varepsilon = 0.864$, showing that cues of gain trials elicited higher O–CNV than cues of neutral trials ($p = .008$). However, cues anticipating loss and neutral trials elicited similar amplitudes (p = .121). We also found a main effect of *domain* for E-CNV, $F(2, 148) = 7.90$, p < .001, $\eta^2_p = 0.096$, $\varepsilon = 0.935$, showing that cues of gain and loss trials elicited higher E-CNV amplitudes than neutral trials (both ps < 0.015).

3.2.1.2. Confirmatory statistical analysis. The planned comparison to test H7.2 (group comparison regarding the amplitude of O–CNV and E-CNV) did not reveal a main effect of *age group* for O–CNV, $F(2, 74) = 0.316$, $p = .730$, $\eta^2_p = 0.008$, or for E-CNV, $F(2, 74) = 1.138$, $p = .326$, $\eta^2_p = 0.030$. The age group*domain interaction was not significant for O–CNV, $F(4, 148) = 0.400$, $p = .808$, $\eta^2_p = 0.011$, or for E-CNV, $F(4, 148) = 1.624$, $p = .171$, $\eta^2_p = 0.042$. However, for younger adults, the planned comparisons to test H2 revealed that cues of gain trials elicited higher O–CNV than cues of neutral trials (p = .024). The remaining planned comparisons were not significant for younger and older adults (all ps >0.147). Regarding E-CNV, for younger adults, the planned comparisons revealed that cues of gain (p < .001) and loss trials ($p = .019$) elicited higher amplitudes than cues anticipating neutral trials. For older adults, these planned comparisons were not significant (both ps > 0.572).

3.2.1.3. Exploratory statistical analysis. The planned comparisons to test H2 were conducted for middle-aged adults, showing non-significant differences for the comparison between cues of gain ($p = .196$) and loss trials ($p = .236$) with cues of neutral trials for the O–CNV. Regarding the E-CNV, cues of gain ($p = .029$) and loss trials ($p = .042$) elicited higher amplitudes than cues of neutral trials.

Table 3
Results of the statistical analysis conducted to test hypotheses H1 to H6 (within-subjects hypothesis) and H7 (between-subjects hypothesis).

Hypothesis no.	Description of hypotheses	Mathematical representation of hypotheses	*p*(Main effect)	*p*(BS planned comparison)	*p*(Interaction)	*p*(WS planned comparison)	Evidence interpretation
H1.1	For YA, cues anticipating losses will elicit larger Cue-P3 than neutral cues	YA: losses > neutral	–	–	.101[1]	< *0*.001	Evidence for H1
H1.2	For YA, cues anticipating gains will elicit larger Cue-P3 than neutral cues	YA: gains > neutral		–		.004	Evidence for H1
H1.3	For OA, cues anticipating losses will elicit larger Cue-P3 than neutral cues	OA: losses > neutral		–		.197	Lack of evidence for H1
H1.4	For OA, cues anticipating gains will elicit larger Cue-P3 than neutral cues	OA: gains > neutral		–		.012	Evidence for H1
H7.1	Cue-P3 amplitudes will decrease with age	Cue-P3: OA < MA < YA	< *0*.001	YA vs MA: 0.083 YA vs OA: < 0.001 MA vs OA: 0.025	–	–	Partial evidence for H1: OA < (MA = YA)
H2.1.1	For YA, cues anticipating losses will elicit larger O–CNV than neutral cues	YA: losses > neutral	–	–	.808[1]	.178	Lack of evidence for H1
H2.2.1	For YA, cues anticipating gain and neutral trials will elicit similar O–CNV amplitudes	YA: gains = neutral		–		.024	Lack of evidence for H1
H2.3.1	For OA, cues anticipating loss and neutral trials will elicit similar O–CNV amplitudes	OA: losses = neutral		–		.253	Evidence for H1
H2.4.1	For OA, cues anticipating gain and neutral trials will elicit similar O–CNV amplitudes	OA: gains = neutral		–		.859	Evidence for H1
H7.2.1	O-CNV amplitudes will decrease with age	O–CNV: OA < MA < YA	.730	YA vs MA: 0.979 YA vs OA: 0.497 MA vs OA: 0.488	–	–	Lack of evidence for H1: OA = MA = YA
H2.1.2	For YA, cues anticipating losses will elicit larger E-CNV than neutral cues	YA: losses > neutral	–	–	.171[1]	.019	Evidence for H1
H2.2.2	For YA, cues anticipating gain and neutral trials will elicit similar E-CNV amplitudes	YA: gains = neutral		–		< 0.001	Lack of evidence for H1
H2.3.2	For OA, cues anticipating loss and neutral trials will elicit similar E-CNV amplitudes	OA: losses = neutral		–		.907	Evidence for H1
H2.4.2	For OA, cues anticipating gain and neutral trials will elicit similar E-CNV amplitudes	OA: gains = neutral		–		.572	Evidence for H1
H7.2.2	E-CNV amplitudes will decrease with age	E-CNV: OA < MA < YA	.326	YA vs MA: 0.690 YA vs OA: 0.282 MA vs OA: 0.150	–	–	Lack of evidence for H1: OA = MA = YA
H4.1	For YA, targets of loss trials will elicit larger Target-P3 than neutral targets	YA: losses > neutral	–	–	.011[1]	< *0*.001	Evidence for H1
H4.2	For YA, targets of gain trials will elicit larger Target-P3 than neutral targets	YA: gains > neutral		–		< *0*.001	Evidence for H1
H4.3	For OA, targets of loss and gain trials will elicit similar Target-P3 amplitudes	OA: losses = neutral		–		.006	Lack of evidence for H1
H4.4	For OA, targets of gain and gain trials will elicit similar Target-P3 amplitudes	OA: gains = neutral		–		.006	Lack of evidence for H1
H7.4	Target-P3 amplitudes will decrease with age	Target-P3: OA < MA < YA	.067	YA vs MA: 0.021 YA vs OA: 0.334 MA vs OA: 0.176	–	–	Partial evidence for H1: MA < YA
H5.1	For YA, non-losses will elicit larger FRN amplitudes than losses	YA: non-losses > losses	–	–	.870[1] .274[2]	.038	Evidence for H1
H5.2	For YA, non-gains will elicit larger FRN amplitudes than gains	YA: non-gains > gains		–		< *0*.001	Evidence for H1
H5.3	For OA, losses and non-losses will elicit similar FRN amplitudes	OA: losses = non-losses		–		.088	Evidence for H1
H5.4	For OA, non-gains will elicit larger FRN amplitudes than gains	OA: non-gains > gains		–		.044	Evidence for H1
H7.5	FRN amplitudes will decrease with age	FRN: OA < MA < YA	.079	YA vs MA: 0.233 YA vs OA: 0.025 MA vs OA: 0.289	–	–	Partial evidence for H1: OA < YA
H6.1	For YA, non-losses and losses will elicit similar Feedback-P3 amplitudes	YA: losses = non-losses	–	–	.951[1]	.075	Lack of evidence for H1
H6.2	For YA, gains will elicit larger Feedback-P3 amplitudes than non-gains	YA: gains > non-gains		–	.349[2]	< *0*.001	Evidence for H1
H6.3	For OA, losses and non-losses will elicit similar FRN amplitudes	OA: losses = non-losses		–		.379	Lack of evidence for H1
H6.4	For OA, gains and non-gains will elicit similar Feedback-P3 amplitudes	OA: non-gains = gains		–		.017	Lack of evidence for H1
H7.6	Feedback-P3 amplitudes will decrease with age	Feedback-P3: OA < MA < YA	.127	YA vs MA: 0.310 YA vs OA: 0.043 MA vs OA: 0.312	–	–	Partial evidence for H1: OA < YA

Note: Evidence is interpreted for the alternative hypothesis (H1) compared with the null (H0) and vice versa. The *p* (main effect) reports the results for the main effect of age group. The *p* (interaction) reports [1]age group*domain interaction and [2]age group*feedback interaction. The *p* (planned comparisons) reports the results obtained from the confirmatory analysis conducted to test each registered hypothesis (see Table 2). BS = Between-subjects; WS = Within-subjects; CNV = Contingent Negative Variation; LRP = Lateralized Readiness Potential; FRN = Feedback-related Negativity; OA = older adults; MA = middle-aged adults; YA = younger adults.

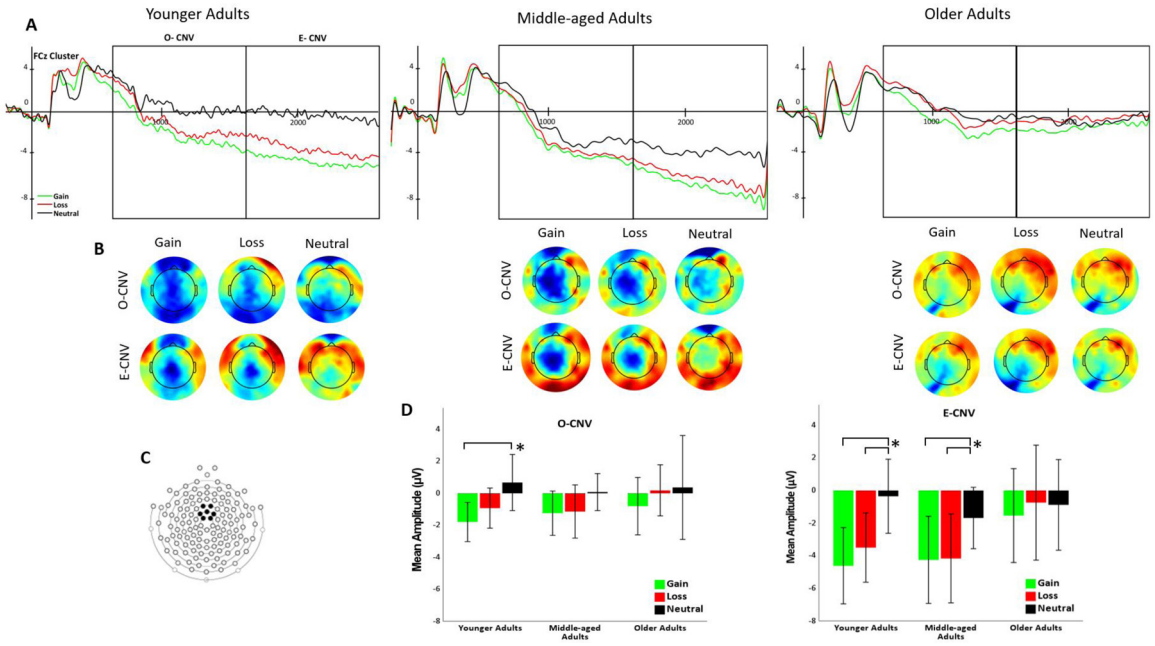

Fig. 3. A: Grand averages of the CNV mean amplitude for younger, middle-aged, and older adults, evoked by cues anticipating gain, loss, and neutral trials. B: Topographical maps for the CNV elicited for each condition and group. C: Electrode locations in the 128-channel HydroCel Geodesic Sensor Net (EGI) where the CNV was measured. D: Means of the O–CVN and E-CNV amplitudes (μV) evoked by condition. Error bars indicate 95% confidence intervals and * represent the significant planned comparisons.

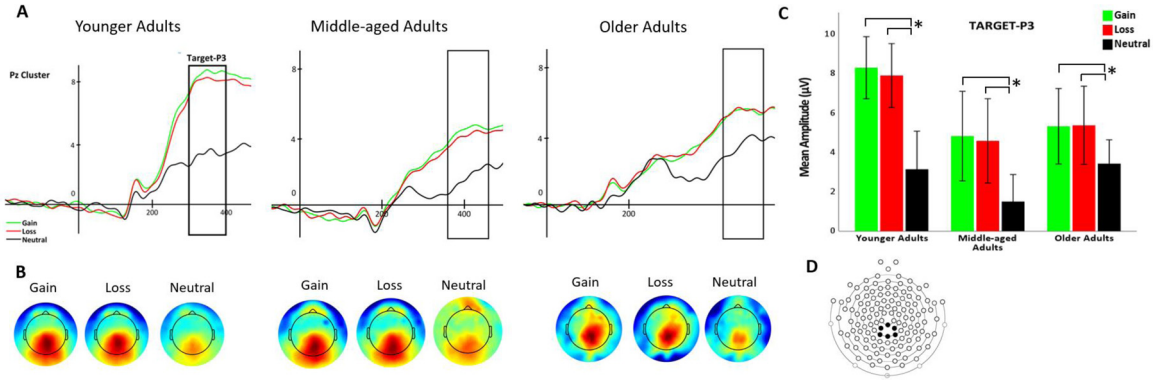

Fig. 4. A: Grand averages of the target-P3 mean amplitude for younger, middle-aged, and older adults, evoked by targets present in gain, loss, and neutral trials. B: Topographical maps for the target-P3 elicited for each condition and group. C: Means of the O–CVN and E-CNV amplitudes (μV) evoked by condition. Error bars indicate 95% confidence intervals and * represent the significant planned comparisons. D: Electrode locations in the 128-channel HydroCel Geodesic Sensor Net (EGI) where the target-P3 was measured.

3.2.3. Motivation processes – LRP (H3 and H7.3)

Participants were instructed that the neutral cue would not anticipate gains or losses and would receive neutral feedback in these trials. As a consequence of this instruction, participants did not respond to the target in the neutral trials, precluding the extraction of an ERP component time-locked to the motor response in this condition. As a result, we could not conduct the confirmatory nor exploratory analyses for this ERP.

3.2.4. Motivation processes – target-p3 (H4 and H7.4)

Based on the morphology of the wave, the target-P3 had the peak latency at the parietal region, at 350 ms for younger adults, 410 ms for middle-aged adults, and 480 ms for older adults. Thereby, the target-P3 was measured at Pz Cluster (composed by the electrodes 54, 55, 61, 62 [Pz], 78, 79), and it was quantified as the mean amplitude in the time-window of 300 – 400 ms after the target onset in the younger group, 430 – 530 ms in the middle-aged group, and 430 – 530 ms in the older group (Fig. 4).

3.2.4.1. Manipulation check. We found a main effect of *domain* for target-P3, $F(2, 148) = 53.49$, $p < .001$, $\eta^2_p = 0.420$, $\varepsilon = 0.833$), showing that targets of gain and loss trials elicited higher amplitudes than targets of neutral trials (both *ps* < 0.001).

3.2.4.2. Confirmatory statistical analysis. The planned comparison to test H7.4 (group comparison regarding the amplitude of target-P3) revealed a marginally significant main effect of *age group*, $F(2, 74) = 2.81$, $p = .067$, $\eta^2_p = 0.071$. The age group*domain interaction was significant, $F(2, 148) = 3.37$, $p = .011$, $\eta^2_p = 0.084$, and the planned comparison to test H4 revealed that targets of gain and loss trials elicited higher amplitudes than targets of neutral trials, both for younger (both *ps* < *0*.001) and older adults (both *ps* = 0.006).

3.2.4.3. Exploratory statistical analysis. The planned comparisons to test H4 were conducted for middle-aged adults, revealing that targets of gain and loss trials elicited higher amplitudes than targets of neutral trials (both *ps* < *0*.001).

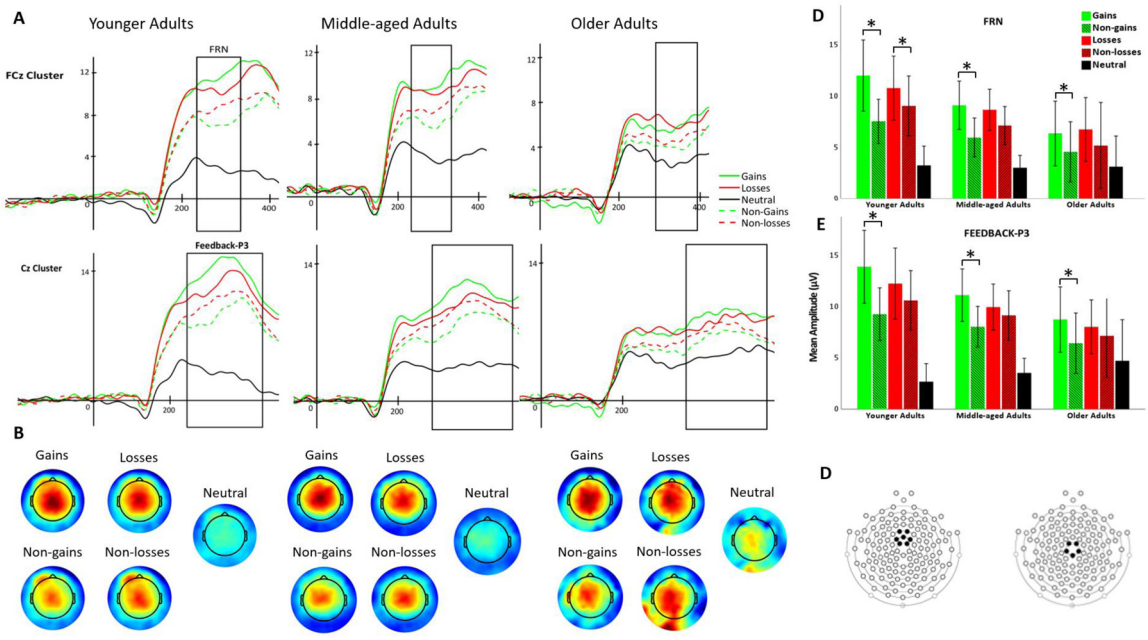

Fig. 5. A: Grand averages of the FRN (above) and feedback-P3 (below) mean amplitude for younger, middle-aged, and older adults, evoked by gains, non-gains, losses, non-losses, and neutral feedbacks. B: Topographical maps for the feedback-P3 elicited for each condition and group. C: Means of the FRN (above) and feedback-P3 (below) evoked by condition. Error bars indicate 95% confidence intervals and * represent the significant planned comparisons. D: Electrode locations in the 128-channel HydroCel Geodesic Sensor Net (EGI) where the FRN (left) and feedback-P3 (right) were measured.

3.2.5. Feedback processes – FRN (H5 and H7.5)

Based on the morphology of the wave, the FRN had the peak latency at the parietal region, at 280 ms for younger adults, 280 ms for middle-aged adults, and 330 ms for older adults. Thereby, the FRN was measured at FCz Cluster (composed by the electrodes 5, 6 [FCz], 7, 12, 112, 106), and it was quantified as the mean amplitude in the time-window of 230 – 330 ms after the feedback onset in the younger and middle-aged groups, and 280 – 380 ms in the older group (Fig. 5).

3.2.5.1. Manipulation check. We found a main effect of *domain* for FRN, $F(4, 148) = 37.11$, $p < .001$, $\eta^2_p = 0.334$, $\varepsilon = 0.686$, showing that feedback of gains, non-gains, losses, and non-losses elicited higher FRN than neutral feedbacks (all *ps* < 0.001).

3.2.5.2. Confirmatory statistical analysis. The planned comparison to test H7.5 (group comparison regarding the amplitude of FRN) revealed a marginally significant main effect of *age group*, $F(2, 74) = 2.63$, $p = .079$, $\eta^2_p = 0.066$. Both the age group*domain, $F(2, 74) = 0.139$, $p = .870$, $\eta^2_p = 0.004$, and the age group*feedback interactions, $F(2, 74) = 1.32$, $p = .274$, $\eta^2_p = 0.034$, were not significant. However, the planned comparison to test H5 revealed that non-gains elicited higher amplitudes than gains ($p < .001$) for younger adults, as well as losses elicited higher amplitudes than non-losses ($p = .038$). For older adults, non-gains elicited higher amplitudes than gains ($p = .044$), while the difference between losses and non-losses was marginally significant ($p = .088$).

3.2.5.3. Exploratory statistical analysis. The planned comparisons to test H5 were repeated for middle-aged adults, revealing that non-gains elicited higher amplitudes than gains ($p < .001$), whereas the difference between losses and non-losses was marginally significant ($p = .092$).

3.2.6. Feedback processes – feedback-p3 (H6 and H7.6)

Based on the morphology of the wave, the feedback-P3 had the peak latency at the parietal region, at 350 ms for younger adults, 400 ms for middle-aged adults, and 460 ms for older adults. Thereby, the feedback-P3 was measured at Cz Cluster (composed by the electrodes 7, 31, 55, 80, 106), and it was quantified as the mean amplitude in the time-window of 250 – 450 ms after the feedback onset in the younger group, 290 – 490 ms in the middle-aged group, and 360 – 560 ms in the older group (Fig. 5).

3.2.6.1. Manipulation check. We found a main effect of *domain* for feedback-P3, $F(4, 148) = 42.04$, $p < .001$, $\eta^2_p = 0.362$, $\varepsilon = 0.591$, showing that feedback of gains, non-gains, losses, and non-losses elicited higher feedback-P3 than neutral feedbacks (all *ps* < 0.001).

3.2.6.2. Confirmatory statistical analysis. The planned comparison to test H7.5 (group comparison regarding the amplitude of feedback-P3) revealed a not significant main effect of *group*, $F(2, 74) = 2.12$, $p = .127$, $\eta^2_p = 0.054$. Neither the age group*domain, $F(2, 74) = 0.050$, $p = .951$, $\eta^2_p = 0.001$, nor the age group*feedback interactions, $F(2, 74) = 1.07$ $p = .349$, $\eta^2_p = 0.028$, were significant. However, the planned comparison to test H5 revealed that gains elicited higher amplitudes than non-gains ($p < .001$) for younger adults, while the difference between losses and non-losses was marginally significant ($p = .075$). For older adults, gains elicited higher amplitudes than non-gains ($p = .017$), but the difference between losses and non-losses was not significant ($p = .379$).

3.2.6.3. Exploratory statistical analysis. The planned comparisons to test H6 were conducted for middle-aged adults, revealing that gains elicited higher amplitudes than non-gains ($p = .002$), whereas the difference between losses and non-losses was not significant ($p = .399$).

The data collected, as well as the experimental task, the MatLab® scripts, the SPSS syntaxes, and the logs of the data processing may be freely downloaded from https://osf.io/knx63/.

4. Discussion

Aging may affect economic decision-making by changing brain circuits that support reward anticipation and outcome processing (for a review, see Samanez-Larkin and Knutson, 2015). This registered study aimed to investigate age-related differences in the neural correlates of mechanisms that precede and succeed economic decisions, using a decision task developed to decompose different aspects of decision-making

process. To this purpose, younger, middle-aged, and older adults performed a version of the MID task (Knutson et al., 2000) adapted to an ERP methodology (Broyd et al., 2012). This task is composed of events designed to elicit neural correlates of reward anticipation and integration, as well as motivational processes associated with motor responses and outcome processing.

Age-related differences in reward anticipation were assessed through the P3 elicited by cues (cue-P3) anticipating gain, loss, and neutral trials. Based on previous studies, we hypothesized higher amplitudes for cues anticipating loss and gain trials compared to cues anticipating neutral trials, both in younger (H1.1 and H1.2, respectively) and older groups (H1.3 and H1.4, respectively). We also hypothesized that ERP amplitudes would decrease with age, which would be reflected in higher amplitudes for younger adults compared to middle-aged and older adults, and higher amplitudes for middle-aged adults compared to older adults (H7.1). In line with the literature, enhanced cue-P3 for salient or rewarded cues might indicate updating of task-relevant information and attentional resources available to process these stimuli (Donchin and Coles, 1988; Polich, 2007).

For the cue-P3, we found a main effect of group that partially supports H7.1 as younger and middle-aged adults had significantly higher cue-P3 than older adults, despite the comparison between younger and middle-aged being marginally significant. Regarding the within-subjects hypothesis, despite the non-significant age group*domain interaction, as this article is a registered report with hypothesis and procedures described a priori, we conducted the planned comparisons described on Table 2. This analysis revealed that, in the younger group, cues anticipating gain and loss trials elicited larger cue-P3 than cues anticipating neutral trials, which is in accordance with our hypotheses. These hypotheses were also proposed for older adults. However, in this group, cues anticipating gain trials elicited larger amplitudes than cues anticipating neutral trials, while cues anticipating loss and neutral trials evoked similar cue-P3 amplitudes. Such result may suggest that aging compromises the voluntary allocation of attention to update information about cues anticipating losses, while preserving the processing of cues anticipating gains. Nonetheless, given the lack of a significant interaction between age group and domain, these results have to be interpreted with caution and require further replication with a larger sample.

These results are consistent with previous findings (Hämmerer et al., 2010; Kropotov et al., 2016; Schmitt et al., 2015), including a neuroimaging study previously conducted with the MID Task (Samanez-Larkin et al., 2007). In this study, the authors did not find differences between younger and older adults in ventral striatal activation during gain anticipation, while older adults showed less activation of the insula and caudate during loss anticipation. Importantly, these results were not explained by a lack of response of these regions in the older group as they were significantly activated during gain anticipation. Moreover, they are consistent with behavioral data showing that older adults experienced less negative arousal than younger adults during loss anticipation, without differences during gain anticipation (Samanez-Larkin et al., 2007). In our study, despite the lack of a significant age group by domain interaction, our planned comparisons showed a pattern of results consistent with the one found in the literature, suggesting that larger sample size might be needed to find a significant interaction.

Age-related differences in integration processes were assessed through the CNV, an ERP component elicited by a cue signaling the future presentation of imperative stimuli. The CNV can be divided into an earlier (O–CNV) and a later component (E-CNV), respectively related to the neural processing of alerting properties of the cue and to the engagement of effortful processes to future motor responses (e.g., Brunia et al., 2011). There is evidence that the amplitude of the CNV is related to the short-term mobilization of effort benefiting fast responding to an upcoming task (Falkenstein et al., 2003), which is modulated by motivation and salience of the stimuli (e.g., Baas et al., 2002). Based on a previous study (Schmitt et al., 2015), we hypothesized a more negative CNV after cues anticipating losses than cues anticipating neutral and gain trials in younger adults (H2.1 and H2.2, respectively), and similar CNV amplitudes for the three conditions in older adults (H2.3 and H2.4, respectively). We also hypothesized larger CNV amplitudes for younger adults compared to middle-aged and older adults, and higher amplitudes for middle-aged adults compared to older adults (H7.2).

The results showed that the amplitude of the CNV (both in the O–CNV as in the E-CNV time-window) did not differ between groups, which does not support H7.2. As before, regarding the within-subjects hypothesis, despite the lack of a significant age group*domain interaction, we conducted the planned comparisons described on Table 2. This analysis revealed that, in the younger group, cues anticipating gain trials elicited higher amplitudes than cues anticipating neutral trials at the O–CNV time window, while the difference between cues anticipating loss and neutral trials was not significant. At the E-CNV time window, cues anticipating gain and loss trials elicited higher amplitudes than cues anticipating neutral trials. This pattern of results was absent for the older group, which had similar CNV amplitudes for all conditions according to was hypothesized.

Once again, these results should be interpreted with caution considering they followed a non-significant age group by domain interaction. However, the results of younger adults showed that their E-CNV was modulated by the valence of the cue, suggesting that the CNV is stronger for incentive than for non-incentive cues (see, for instance, Schevernels et al., 2014, 2016). The absence of this modulation in the older group leads us to hypothesize that aging may compromise attentional neural processes associated with the cue and the subsequent engagement of effortful processes needed to prepare motor responses. However, these results need to be replicated in a future study conducted with a larger sample.

To examine the motivational processes behind motor choice, we analyzed the LRP elicited by motor responses given to gain, loss, and neutral trials. However, our task failed to elicit the LRP time-locked to neutral responses. Since participants were instructed they would receive neutral feedback in the neutral trials independently of their performance, they did not respond to the neutral targets. As a result, we could not conduct confirmatory or exploratory analyses for this ERP component. This is a limitation of the present research and may be overcome in future studies through an instruction that makes the motor response to neutral trials mandatory.

Nonetheless, motivation processes were further assessed through the target-P3, which is considered a robust index of task-relevance and motivated attention (Groom et al., 2010). Due to the lack of literature about the effect of aging on monetary tasks eliciting target-P3, we based our hypothesis on the evidence provided by the AIM framework. According to this framework, aging may degrade glutamatergic projections from mPFC to the striatum, diminishing value integration and motivational processes (Samanez-Larkin and Knutson, 2015). Thereby, we predicted similar target-P3 amplitudes for loss, gain, and neutral conditions in the older group (H4.3 and H4.4, respectively), while predicting an enhanced target-P3 for gain and loss than neutral conditions in the younger group (H4.1 and H4.1, respectively). We also hypothesized larger target-P3 amplitudes for younger adults compared to middle-aged and older adults, and higher amplitudes for middle-aged adults compared to older adults (H7.4).

The results showed a marginally significant main effect of group, showing that younger adults had higher target-P3 amplitudes than middle-aged adults. However, older adults did not significantly differ from younger and middle-aged adults, partially refuting H7.4. Regarding the within-subjects hypothesis, we found a significant age group by domain interaction, showing that both younger and older adults had significantly higher P3 amplitudes for gain and loss targets compared to neutral trials.

These results partially contrast with our hypothesis and with several studies that reported an age-related decline in the amplitude of the target-P3 (e.g., Kok, 2000). However, a deep exploration of the literature revealed a non-negligible number of studies showing that older adults

may be as effective as younger and middle-aged individuals in detecting target stimuli, as evidenced by their equivalent or enhanced target-P3 in tasks demanding motivated sustained attention (e.g., Daffner et al., 2005; Staub et al., 2015).

These results allow different interpretations since older adults had increased amplitudes for neutral (e.g., Riis et al., 2008), standard (e.g., Daffner et al., 2005) or non-target conditions (e.g., Alperin et al., 2014). They may suggest that older adults had increased attentional processes to nonspecific stimuli, and focused on the general approach to the task (Riis et al., 2008). In line with this interpretation, these results may reflect an age-related decline in the capacity to withdraw attentional resources from irrelevant stimuli or, alternatively, an age-related dedifferentiation that reduces the difference between the neural responses to targets and non-targets (Mott et al., 2014).

Our results contribute to this debate, suggesting that aging may preserve the capacity to differentiate between target and non-target, such as those that will result in a monetary gain/loss versus those that will result in neutral feedback. Coherently with the AIM framework (Samanez-Larkin and Knutson, 2015), our results may suggest that the effects of aging on glutamatergic projections from mPFC to the striatum could diminish value integration (according to our CNV results), while preserving motivational processes related to approach/avoidance of specific targets.

In addition to the anticipation, integration, and motivation processes that precede an economic decision, the e-MID task allowed the study of the neural correlates of feedback processing. To this purpose, we analyzed the FRN, associated with the neural processing of the reward prediction error (Martín, 2012; Miltner et al., 1997), and the feedback-P3, associated with the neural processing of probability, arousing, motivational, and emotional nature of the feedback (Nieuwenhuis, 2011).

Considering previous results conducted with a similar study design (Fernandes et al., 2018), we hypothesized higher FRN amplitudes after non-gains than after gains for younger and older adults (H5.2 and H5.4, respectively) and higher amplitudes after non-losses than after losses only for younger adults (H5.1 and H5.3, respectively). Also, we hypothesized larger FRN amplitudes for younger adults compared to middle-aged and older adults, and higher amplitudes for middle-aged adults compared to older adults (H7.5).

The results showed a marginal main effect of group, explained by significant differences between younger and older adults that partially support H7.5. Regarding the within-subjects hypothesis, despite the lack of a significant age group*domain interaction, we conducted the planned comparisons described on Table 2. All of the planned comparisons supported the proposed hypothesis. In gain domain, both younger and older adults had a more negative FRN for unfavorable (non-gains) than for favorable feedbacks (gains), coherently with the reward prediction error hypothesis (Milner et al., 1997). In the loss domain, younger adults had a higher FRN after favorable (non-losses) than after unfavorable feedbacks (losses), whereas older adults had similar FRN amplitudes after both types of feedback.

According to the reward prediction error hypothesis (Milner et al., 1997), the modulation of the FRN after negative outcomes appears to reflect the decreasing dopaminergic activity after events that are worse than expected, allowing the adaptation of the motor system control according to the feedback contingencies (Holroyd and Coles, 2002). However, as in the loss domain, younger adults had larger FRN after favorable (non-losses) than after unfavorable feedbacks (losses), we hypothesize that loss domains elicited negative instead of positive reward prediction errors. While more studies are needed to investigate the domain-related inconsistent modulation found for the FRN, we hypothesize that such modulation is absent in the older group. However, these results need to be replicated in a future study conducted with a larger sample.

Regarding feedback-P3, we hypothesized a higher feedback-P3 after gains than after non-gains for younger adults (H6.2) and a similar amplitude of this component after losses and non-losses (H6.1). For older aduts, we predicted similar amplitudes after all conditions (gains, non-gains, losses, non-losses; H6.3 and H6.4). Regarding the group comparison, we hypothesized larger feedback-P3 amplitudes for younger adults compared to middle-aged and older adults, and higher amplitudes for middle-aged adults compared to older adults (H7.6).

At the later stage of feedback processing, we did not find a main effect of group nor a significant age group by domain interaction, but the planned comparisons showed that younger adults had significantly larger feedback-P3 amplitudes than older adults, which partially support our hypothesis. Regarding the age group by domain interaction, the majority of planned comparisons did not support our hypotheses since both younger as older adults showed higher feedback-P3 amplitudes after gains than after non-gains, and similar amplitudes after losses and non-losses.

Despite these results partially contradicting our H6.1, H6.2, and H6.4, the results obtained in the P3 time window are consistent with the results obtained in the FRN time window and suggest that aging does not affect later stages of the feedback processing when the feedback is received in the gain domain. Moreover, aging does not appear to affect later stages of the feedback processing when the feedback is received in the loss domain, as the lack of modulation of feedback-P3 during losses was similar between younger and older adults.

Of note, the lack of an outcome valence effect in the loss domain was previously found (Fernandes et al., 2018; Zheng et al., 2017), being interpreted as a manifestation of an increased relevance attributed to the gain versus the loss domain. This is a plausible explanation considering that the P3 modulation may change depending on the task goal and, particularly, depending on the arousal levels of the stimuli (Martín, 2012). Participants were instructed to win as many points as possible, and thus feedback received in the loss domain (losses and non-losses) could evoke similar levels of arousal, contrary to what happens in the gain domain, in which gains might be more arousing than non-gains.

In conclusion, despite the overall dearth of significant group differences in the amplitude of the ERPs, our results showed that the effects of aging emerged in the comparison between the conditions of the task. Specifically, older adults appear to engage similar neural resources to process events presented in the loss versus neutral (or non-loss) conditions, as shown by similar amplitudes found for all ERPs, except for the target-P3. These results contrast with the results of younger adults but, more interestingly, contrast with the results that older adults obtained in the gain domain. In this domain, gain trials elicited higher amplitudes than neutral trials, except the CNV time window.

These results provide further evidence of differential age effects at the attentional, integration, and motivational levels as proposed by the AIM framework and suggest that future work will profit from employing research paradigms and strategies that allow the decomposition of decision processes to investigate the effects of aging on decision-making.

It is important to highlight that these results only emerged due to the planned comparisons conducted to test each a priori proposed hypothesis. With the exception of the target-P3, we did not find a significant age-group by domain interaction for the remaining ERPs, suggesting that a larger sample size is needed to reach more robust conclusions.

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