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ORIGINAL ARTICLE

Domain specificity of error monitoring: An ERP study in young and older adults

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Abstract

Metacognition refers to the ability to monitor and control one's cognitive processes, which plays an important role in decision-making throughout the lifespan. It is still debated whether metacognitive abilities decline with age. Neuroimaging evidence suggests that metacognition is served by domain-specific mechanisms. These domains may differentially decline with increasing age. The current investigates whether the error-related negativity (ERN) and the error positivity (Pe) which reflect error detection and error awareness, respectively, differ across perceptual and memory domains in young and older adults. In total, 38 young adults and 37 older adults completed a classic Flanker Task (perceptual) and an adapted memory-based version. No difference in ERN amplitude was found between young and older adults and across domains. Perceptual ERN peaked earlier than Memory ERN. Memory ΔERN was larger than Perceptual ΔERN. Pe was smaller in older adults and ΔPe was larger for perceptual than memory flanker. Memory Pe peaked earlier in young as compared to older adults. Multivariate analyses of whole scalp data supported cross-domain differences. During the task, ERN decreased in young but not in older adults. Memory Pe decreased in young adults but increased in older adults while no significant change in perceptual Pe was found. The study's findings suggest that neural correlates of error monitoring differ across cognitive domains. Moreover, it was shown that error awareness declines in old age but its within-task dynamics vary across cognitive domains. Possible mechanisms underlying metacognition impairments in aging are discussed.

KEYWORDS

aging, ERN, ERP, error monitoring, metacognition, Pe

1 | INTRODUCTION

Successful evaluation of one's actions is crucial for learning and for implementing behavioral adjustments to optimize performance. Metacognition, often defined as "thinking about thinking," refers to the ability to reflect on, monitor, and control one's own cognitive processes (Dunlosky & Metcalfe, 2009; Flavell, 1979; Fleming et al., 2012). Metacognitive abilities play an important role in promoting learning, educational achievements, and decision-making across the life span (Bryce et al., 2015; Efrati et al., 2021; Laghi et al., 2020; Ohtani & Hisasaka, 2018; Roebers et al., 2014; Weil et al., 2013). Poor metacognition is associated with dysfunctional behaviors in neurological and psychiatric conditions (Hallam et al., 2020; Lenzoni et al., 2020; Seow et al., 2021; Sun et al., 2017). However, the extent to which such abilities decline with older age remains unclear.

Neuroimaging research found that ventral and posterior regions of the medial prefrontal cortex (mPFC), including the anterior cingulate cortex (ACC), and insular regions as central nodes of an extended metacognition network, underlying self-evaluation and self-monitoring (Fleming & Dolan, 2012; Qiu et al., 2018). Recent evidence also suggests that metacognition is subserved by domain-specific processes (for a review see Rouault et al., 2018; Seow et al., 2021; Vaccaro & Fleming, 2018). In aging, metacognitive abilities might be expected to follow cognitive decline trajectories commonly associated with frontal lobe impairment (Li et al., 2015; McDonald et al., 2018). However, previous research has shown mixed findings. Some studies suggest that metacognition is preserved in older age (e.g., Halamish et al., 2011; Hertzog & Dunlosky, 2011; Sanders & Berry, 2020) while other research reported marked differences between young and older adults (e.g., Bender & Raz, 2012; Soderstrom et al., 2012; Souchay et al., 2007; Wong et al., 2012). Furthermore, a small number of studies reported domain-specific changes in metacognition (Palmer et al., 2014; Zakrzewski et al., 2021). Therefore, it is still unclear whether metacognition declines with age and whether this occurs in a domain-general or domain-specific fashion.

Event-related potentials (ERP) research identified neural markers of response monitoring, which is fundamental for the detection of errors and confidence judgments (Yeung & Summerfield, 2012). Indeed, error detection and confidence judgments share neural substrates and rely on similar neural computations (Boldt & Yeung, 2015; Yeung & Cohen, 2006; Yeung & Summerfield, 2012). The error-related negativity (ERN; Falkenstein et al., 1991; Gehring et al., 1993) is a frontocentral negative potential, peaking between 0 and 100 ms after error commission, with a larger amplitude than the correct responses potential, the correct-related negativity (CRN or correct-trial ERN; Falkenstein et al., 2000). The neural source of ERN has been localized in the ACC (e.g., Brázdil et al., 2005; Debener, 2005; Dehaene et al., 1994; Reinhart & Woodman, 2014; Van Veen & Carter, 2002). The ERN has been proposed to reflect a prediction error conveyed via the dopaminergic system (Holroyd & Coles, 2002), post-response conflict (Botvinick et al., 2001; Yeung et al., 2004), or mismatch between expected and actual responses (Dehaene, 2018; Falkenstein et al., 2000). The CRN has been generally less investigated, and it is believed to represent a basic post-response behavioral monitoring process (Klawohn et al., 2014; Roger et al., 2010).

The error positivity (Pe; Falkenstein, Hielscher, et al., 2001; Overbeek et al., 2005) is a posterior positive component occurring between 200 and 400 ms after a response, being larger for errors than for correct trials. The neural origin of the Pe is less clear, but possible roles for insula (Dhar et al., 2011), ACC (Herrmann et al., 2004), and posterior-cingulate/precuneus (O'Connell et al., 2007) have been suggested. Previous research found a relationship between Pe and conscious perception of errors (Endrass et al., 2007; Murphy et al., 2012; Nieuwenhuis et al., 2001). According to the *evidence accumulation*, Pe reflects error awareness, which emerges from a post-decisional process of evidence accumulation about the erroneous response (Steinhauser & Yeung, 2012; Ullsperger et al., 2010; Wessel et al., 2011). Indeed, Pe amplitude was shown to be associated with confidence judgments (Boldt & Yeung, 2015), and behavioral adjustments (Desender et al., 2019), thus supporting the idea that Pe tracks a metacognitive decision variable (Desender et al., 2021). Correct positivity resembles Pe for scalp topography and time course (Nieuwenhuis et al., 2001; Overbeek et al., 2005) but its functional significance has not been previously investigated.

Past research on neurophysiology of error monitoring in aging, showed inconsistent findings. Several studies found that ERN amplitude was reduced in older adults (Beste et al., 2009; Dywan et al., 2008; Endrass et al., 2012; Eppinger & Kray, 2011; Falkenstein, Hoormann, et al., 2001; Harty et al., 2017; Herbert et al., 2011; Hoffmann & Falkenstein, 2011; Mathalon et al., 2003; Mathewson et al., 2005; Schreiber et al., 2011; Themanson et al., 2006; Thurm et al., 2020; West, 2004). However, other studies reported no ERN differences between young and older adults (Capuana et al., 2012; Clawson et al., 2017; Eppinger et al., 2008; Larson et al., 2016; Pietschmann, Endrass, Czerwon, et al., 2011; Pietschmann, Endrass, & Kathmann, 2011; Thurm et al., 2013) and one study found larger ERN in older adults (Staub et al., 2014). Fewer studies reported the CRN, showing larger (Larson et al., 2016; Schreiber et al., 2011) or smaller (Eppinger et al., 2007; Harty et al., 2017; Mathalon et al., 2003) amplitude in older adults as compared to young adults, while other studies reported no age group differences (Clawson et al., 2017; Endrass et al., 2012; Falkenstein, Hoormann, et al., 2001; Pietschmann, Endrass, Czerwon, et al., 2011; Staub et al., 2014; Thurm et al., 2013). Finally, limited research explored aging effects on Pe, which was found to be attenuated in older adults (Capuana et al., 2012; Clawson et al., 2017; Larson et al., 2016; Mathewson et al., 2005; Thurm et al., 2020). However, one study showed no differences in Pe between young and older adults (Mathalon et al., 2003) and another study did not clarify the effect of age on Pe (Staub et al., 2014). It is therefore still unclear whether and how aging may affect these neurophysiological processes, reinforcing the need for further investigation.

One factor that may contribute to the discrepancy in the findings is the heterogeneity of experimental paradigms. It has been previously discussed that the presence of task-specific effects may limit our understanding of self-monitoring neurophysiology in clinical populations (Lenzoni et al., 2022; Mathews et al., 2012; Riesel, 2019). However, few studies explored task effects on performance monitoring. For example, error-related ERPs were observed to vary across tasks in undergraduate students (Flanker, Stroop, Go/NoGo; Riesel et al., 2013), as a function of obsessive–compulsive symptomatology (Flanker, Probabilistic learning; Gründler et al., 2009), and in children and adolescents (Flanker, Go/NoGo; Meyer et al., 2014). One study only investigated task effects in aging, showing smaller ERN and Pe in older as compared to young adults, no ERN differences between Flanker and Source Monitoring Tasks, but larger Pe in the Flanker Task (Mathewson et al., 2005). It could be argued that task dissociations do not necessarily reflect patters of self-monitoring impairments, but instead they may be a by-product of diverse experimental procedures that modulate such components, for instance task difficulty (Falkenstein, 2004; Hoffmann & Falkenstein, 2010; Johannes et al., 2002; Pailing & Segalowitz, 2004), instructions (Morris et al., 2006), or number of trials (Fischer et al., 2017). Critically, although current evidence on metacognitive abilities supports the existence of underlying domain-specific processes, this issue has not been yet investigated by ERP research. Moreover, a better understanding of error monitoring across cognitive domains in aging may throw light upon the inconsistency of the existing literature and provide relevant insights into age-related decline in metacognition.

Considering the above, the current study aimed at (i) investigating whether it is possible to differentiate neurophysiological markers of performance monitoring across cognitive domains; (ii) exploring whether age-related changes (if any) occur at a global level (domain-general) or are specific to certain cognitive domains (domain-specific). To this end, a group of young and older adults performed two versions of the Flanker Task (Eriksen & Eriksen, 1974): the classic arrow version (perceptual domain) and an adapted memory version that was developed to test the domain-specificity hypothesis. The task design was the same for both perceptual and memory versions (e.g., for stimuli-flanker configuration, number of trials, presentation time, interval duration, and instructions) and many control procedures were employed to ensure that the core difference was how errors occurred (i.e., perceptual interference vs. memory interference) in order to best investigate differences and similarities between monitoring of errors in perceptual and memory decisions.

Different novel approaches were employed to understand whether ERN and Pe differed across domains and whether the alteration of these neurophysiological processes were present in older adults. In line with fMRI and behavioral evidence of domain-specific mechanism of metacognition, it was hypothesized that multilevel model analyses (MLM) would indicate an effect of task domain on ERN and Pe. However, we did not have evidence in support of a directional hypothesis. Domain-specific decline of monitoring processes would be indicated by the interaction between domain and age. Additionally, MLM was used to explore trial-to-trial variations and within-task changes in ERPs (Volpert-Esmond et al., 2018), thus allowing us to explore whether different brain dynamics can be identified between age groups and task domains. Similar to fMRI analyses, multivariate pattern analysis (MVPA) can provide meaningful information about differences and similarities of neural activity patterns and can be used to investigate domain-general and domain-specific (Morales et al., 2018). Good classifier's performance in discriminating between perceptual and memory post-response activity would support the domain-specificity hypothesis. Additionally, poor cross-domain classification performance in young adults and good performance in older adults could be interpreted as evidence in support for domain generality of metacognitive processes which undergo domain-specific cognitive decline in aging.

2 | METHODS

2.1 | Participants

A total of 42 young adults and 41 older adults were recruited through the Psychology Division Research participation schemes at Nottingham Trent University. Inclusion criteria were normal/corrected-to-normal vision and fluency in English. Participants were excluded if they have history of neurological and/or psychiatric disorders. Four participants were excluded due to current diagnosis of psychiatric disorders and four participants were excluded from the analyses because they had a low error rate in at least one of the experimental tasks (number of errors <5). The final enrolment included 38 younger adults (24 females, 14 males) between the ages of 19–34 years ($M = 22.45$, $SD = 4.38$) and 37 older adults (23 females, 14 males) between the ages of 60–90 years ($M = 70.95$, $SD = 10.56$). Both young and older adult groups had similar sex ratios ($\chi^2(1) < .01$, $p = .929$) and educational levels ($W = 572$, $p = .141$). In the young adult group, the ethnic group that participants identified with was White English/Welsh/Scottish/Northern Irish/British ($n = 22$), White ($n = 8$), White/Black African ($n = 1$), Asian/Asia British ($n = 4$), Black/African/Caribbean/Black British ($n = 2$), and one did not report it. In the older adult group, the ethnic group that participants identified with was White English/Welsh/Scottish/Northern Irish/British ($n = 35$) White Irish ($n = 2$). All participants provided written consent and all procedures were approved by Nottingham Trent University College of Business, Law and Social Sciences Ethics Committee.

2.2 | Experimental tasks

Participants completed two versions of the Eriksen Flanker Task (Eriksen & Eriksen, 1974): (i) the classic arrow version exploring performance monitoring in perceptual decision; herein termed the Perceptual Flanker Task and (ii) a modified version developed to investigate performance monitoring in memory decisions, herein termed the Memory Flanker Task. The tasks were created using PsychoPy2 (v1.90.1; Peirce et al., 2019). All stimuli were 2D icons generated from Freepik (www.flaticon.com). All stimuli were displayed on a white background, approximately 60 cm from participants' forehead, with a 19-inch LCD monitor displaying 1600 × 900 pixels at 60 Hz. The order of the Flanker Tasks was counterbalanced to control for possible effects of learning and fatigue.

2.2.1 | Perceptual flanker task

In each trial, participants were presented with five horizontal arrows stimuli either pointing all to the same directions (i.e., congruent), or with the central arrow pointing to the opposite direction relative to the others (i.e., incongruent). This resulted in four conditions: congruent left (all arrows pointing to the left, <<<<<), congruent right (all arrows pointing to the right, >>>>>), incongruent left (the target arrow points to the left and the flanker arrows point to the right, >><>>) and incongruent right (the target arrow points to the right and the flanker arrows point to the left, <<><<). Figure 1 displays an example of congruent and incongruent trials. Participants were asked to identify by button press whether the central arrow (target) was pointing to the left or to the right and were instructed to respond as quickly and as accurately as possible, while ignoring the direction of the other arrows (flankers). For both congruent and incongruent conditions, in half of the trials, the target was pointing to the left and in the other half to the right. Each set of stimuli filled 2.46° of visual angle vertically and 12.36° horizontally. Trial order was randomized. Each stimulus was presented for 100 ms and preceded by a 500 ms fixation cross (500 ms). Participants were then given 1200 ms to respond. The inter-trial interval (ITI) varied between 500 and 900 ms. In each block, half of the trials were congruent, and the other half were incongruent. Participants completed 12 practice trials and six blocks of 96 trials for the actual task. At the end of each block, participants were asked to rate, on a scale of 1–5, where 1 is not confident and 5 is very confident, how confident they were about their task performance.

2.2.2 | Memory flanker task

In the learning phase, participants memorized four icons, which will be referred to as old icons (chicken, shoe, mushroom, and love heart, see Figure 2). The learning phase procedures consisted of the following steps: (i) each of the four icons was presented at the center of the screen for 2 s

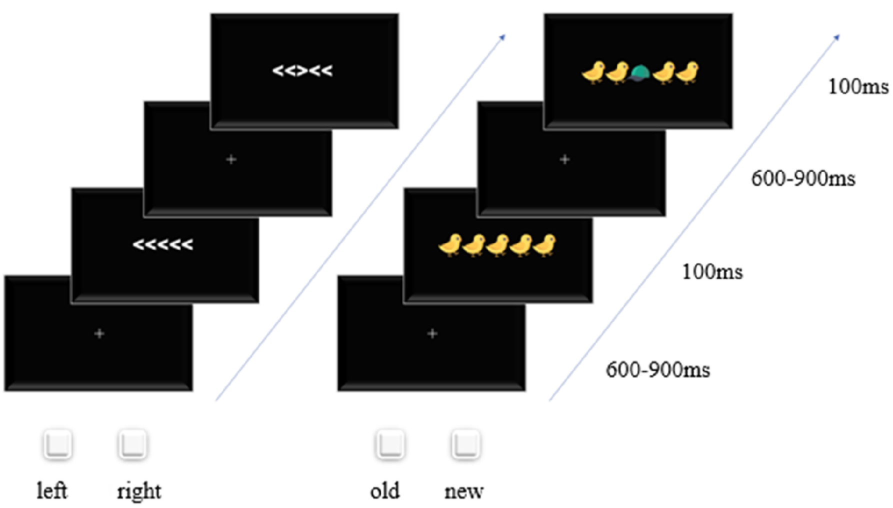

FIGURE 1 Graphical representation of experimental tasks: perceptual domain (on the left) and memory domain (on the right).

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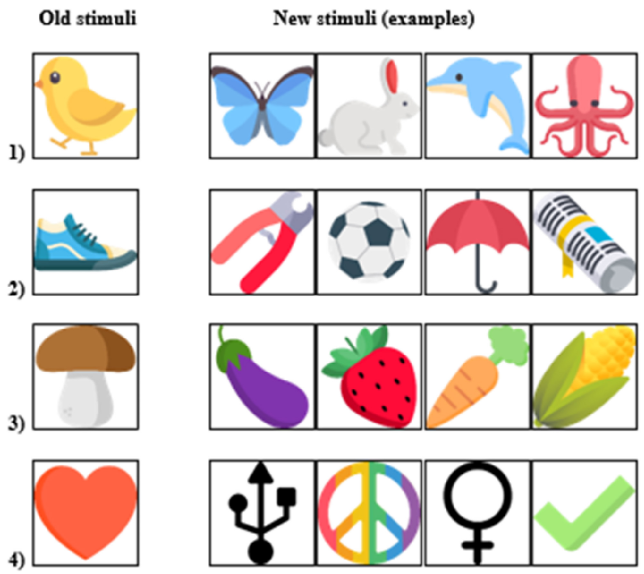

FIGURE 2 Memory Flanker task stimuli. In each row, old icons and examples of new icons are displayed by category: animals (1), objects (2), fruit and vegetables (3), and symbols (4).

(2.46°–2.46°); (ii) participants were asked to recall the four icons; (iii) participants performed a recognition task in which they saw eight icons, one by one (2.46°–2.46°), and they had to decide by button press whether they have just seen the icon or not. The eight icons included four old icons and four distractors (seal, corn, eggplant, and flame); and (iv) the four old icons were displayed one last time and participants were asked to try to remember them. The experimental task (actual task) took place 20 mins following the end of the learning phase to ensure transfer into long-term memory. Before the beginning of the task, participants were asked to recall, by verbal labelling, the four icons they were asked to remember in the learning phase to ensure that retrieval issues would not confound task execution and memory monitoring (i.e., all participants were able to recall the four icons before the start of the experimental tasks). The experimental task was an adapted Flanker Task as it maintained the interference characteristic based on a central target to focus on, surrounding distractors (flankers) to ignore and two possible responses executed by button press. However, whilst in the classic arrow version, the response was based on a perceptual decision, in the memory-adapted version, the response was based on a memory decision. In each trial, participants were presented with five icons that could either be all the same (i.e., congruent), or with the central icon being different from the other four icons (i.e., incongruent). Similar to the perceptual flanker, this resulted in 4 conditions: congruent old (all the icons are old stimuli, e.g., all chicken icons), congruent new (all icons are new, e.g., all dolphin icons), incongruent new (the target icon is new and the flankers are old icons, e.g., the target is the cap icon and the flanker are all chicken icons) and incongruent old (the target icon is old and the flankers are new icons, e.g., the target is the shoe icon and the flanker are all octopus icons). An example of congruent and incongruent trials is displayed in Figure 1. Participants were asked to identify by button press whether the central icon (target) was old (one of the four icons memorized in the learning phase) or new and were instructed to respond as quickly and as accurately as possible, while ignoring other icons (flankers). All the new icons were displayed only once and non-target stimuli of the learning phase were not included in the experimental task. For both congruent and incongruent conditions, in half of the trials the target was an old icon and, in the other half, a new icon. Stimuli were classified as belonging to four categories: animals, food, objects, and symbols. To avoid the possibility that the interference effects in incongruent trials could be caused by perceptual interference, rather than memory interference, we controlled for physical similarities between target and flanker, by avoiding flanker and target of similar color and shape within the same incongruent trial. Moreover, to avoid semantic relatedness in incongruent trials, within each trial, target and flanker stimuli were chosen from different categories. Finally, to avoid possible semantic associations within natural/artificial from different categories (e.g., target: rabbit, flanker: carrot) that may modulate interference effects within the same incongruent trial, possible stimuli combinations were animal–object; animal–symbol, food–object, food–symbol. Each set of stimuli filled 2.46° of visual angle vertically and 12.36° horizontally. Trial order was randomized. Each stimulus was presented for 100 ms and preceded by a 500 ms fixation cross (500 ms). Participants were then given 1200 ms to respond. The ITI varied between 500 and 900 ms. In each block, half of the trials were congruent and half of the trials were incongruent. For incongruent trials (incongruent old and incongruent new), the target was an old icon in half of the trials and a new icon in the other half, the categories stimuli combination was equal in number in both cases. Participants completed 12 practice trials and 6 blocks of 96 trials for the actual task. The number of trials for each old icon was equal across conditions, and within each block, each old icon was used in 6 out of 24 congruent old trials, 6 out of 24 incongruent old trials, and 6 out of 24 incongruent old trials. This resulted in 12 old–new different combinations for each old icon by block, 72 combinations for each old icon in the whole task, and 432 old–new combinations in total. At the end of each block, participants were asked to rate how confident they were about their performance on a scale between 1 and 5.

2.3 | EEG recordings, preprocessing, and ERP extraction

A BioSemi Active II system (Biosemi, Amsterdam, The Netherlands) was used to record continuous EEG.

Recordings were taken from 64 active scalp electrodes based on the 10/20 system with two external electrodes placed on the right and left mastoids. Data were sampled at 2048 Hz, digitized at 24 bits and referenced online with a CMS/DRL feedback loop. Electrodes offset was kept within the absolute value of 20 μV. EEGLAB (Delorme & Makeig, 2004) and MATLAB (Mathworks, Natick, Massachusetts, USA) were used for offline analyses. Data were downsampled to 256 Hz and processed through a 0.1 Hz high-pass filter and a 30 Hz low-pass filter. Data were re-referenced to average mastoids. Bad channels were removed and interpolated. Epochs of 1200 ms (200 ms baseline before response and 1000 ms after) were extracted. Independent component analysis (ICA) was used to remove ocular artifacts. The interval between −200 and 0 ms was chosen for baseline correction, as it was showed to be associated with large effect sizes (Clayson et al., 2021) and good internal consistency (Klawohn et al., 2020). Epochs exceeding 100 μV and −100 μV were removed. Response-locked ERPs were averaged separately for each type of response (correct responses and errors). The ERN/CRN was quantified as mean amplitude in the interval 0–80 ms at Fz, F1, F2, FCz, FC1, and FC2 and the Pe/Correct Positivity was quantified as mean amplitude in the interval 200–400 ms at CPz, CP1, CP2, Pz, P1, and P2. Latencies were extracted at the maximal values in the selected intervals (most negative peak for ERN/CRN and most positive peak for Pe/Correct Positivity). ΔERN and ΔPe (error minus correct) were also calculated because difference waveforms are commonly computed to isolate an error-specific activity (Simons, 2010). Split-half reliability analyses were performed to obtain internal consistency measures of ERN/CRN and Pe/Correct Positivity. Correlations of averaged even and odd trials were corrected using the Spearman–Brown coefficient prediction formula. Internal consistency of all ERPs by group, domain, and electrodes is summarized in Table S1 of Supplementary Materials.

2.4 | Statistical analysis

All analyses were performed using R (R Core Team, 2020). Trials with RTs lower than 200 ms were excluded. MLM was chosen as it presents multiple advantages for ERP analysis, such as robustness to missing trials and unbalanced designs, the inclusion of categorical and continuous variables as independent variables and electrodes as random factors rather than predictors (Volpert-Esmond et al., 2021). Maximal model structures included all random slopes and their interaction by participant (Barr et al., 2013). Response (correct, error), Domain (perceptual, memory), and Group (younger, older) were entered as predictors. The models included electrodes as a crossed random factor. Fixed effects were effect coded (categorical variables; −0.5, 0.5). In the case of convergence problems, models would include random slopes but not their interactions. In order to explore neurophysiological variations that occur during the task, we reproduced the approach used by Volpert-Esmond et al. (2018) and examine ERN and Pe changes as a function of the number of errors. Errors trials were sequentially numbered (i.e., error 1 is the first error regardless of the trial number). In order to explore the relationship between ERPs and confidence about performance, mean confidence was used as the fixed effect. Mean confidence was grand-mean centered (Enders & Tofighi, 2007). Participants and electrodes were included as random factors, and the domain was allowed to vary by participant. To fit the models, lme4 package (Bates et al., 2015) was used and lmerTest (Kuznetsova et al., 2017) was used to derive p-values using the Satterthwaite's degrees of freedom. Interactions were tested using post-hoc tests adjusting with Tukey's correction for multiple comparisons for categorical variables and simple slope analysis for continuous variables.

Considering that the current study included a novel task, classical analysis (mixed ANOVAs) on ERP components averaged across the target electrodes was also performed. Because of the low error rate in congruent trials, it was not possible to run separate analyses for congruent and incongruent trials. These analyses were then repeated on incongruent trials to exclude that effects of interest were driven by the inclusion of correct trials (Supplementary Table S5). Secondary analyses included the examination of behavioral performance. Considering the novelty of the *Memory Flanker task*, it was important to evaluate whether it induced the classic interference effect (i.e., congruency effects) and whether behavioral performance was similar within and between age groups. Accuracy was calculated as the proportion of correct responses. In order to explore whether there were differences in behavioral performance within-task and between cognitive domains, a 2 (Group: Younger, Older) ×2 (Domain: Perceptual, Memory) ×6 (Block:1, 2, 3, 4, 5, 6) ×2 (Congruency: Congruent, Incongruent) mixed ANOVA were conducted on accuracy and RTs. Confidence judgments were participant rating at the end of each block. Considering that confidence was evaluated at the end of each block, and not at the trial level, a 2 (Group: Younger, Older) ×2 (Domain: Perceptual, Memory) ×6 (Block:1, 2, 3, 4, 5, 6) mixed ANOVA was performed. Post-error slowing (PES) was calculated using the mean-based correct robust measurement approach, as it reduces bias in interference tasks (Derrfuss et al., 2022), and therefore a 2 (Group: Younger, Older) ×2 (Domain: Perceptual, Memory) mixed ANOVA was used to test group and domain differences. For all analyses, Tukey's adjustment for multiple comparisons was used.

2.5 | Multivariate pattern analysis

Multivariate pattern analysis (MVPA) analysis applied to EEG data is an optimal method to investigate brain response patterns based on single-trial data as compared to univariate, average-based methods (Grootswagers et al., 2017; Hebart & Baker, 2018), and to explore differences between experimental conditions without a priori channel selection (Fahrenfort et al., 2017). MVPA was applied on the raw EEG data using the ADAM toolbox (Fahrenfort et al., 2018). EEG epochs time-locked to response were classified according to task domain (perceptual, memory) within response correctness (error, correct). A backward decoding model was used to perform a leave-one-out cross-validated multivariate classification analysis. The linear discriminant classifier was trained on 90% of the data and tested on 10% of the data for each participant, across all electrodes. The area under the receiver operating characteristics curve (AUC; Bradley, 1997) was used as classifier accuracy. AUC is a metric derived from signal detection theory (Wickens, 2010), which was obtained by plotting the cumulative true positive rates against the cumulative false positive rates, and varies between 0 and 1, where 0.5 indicates chance performance and 1 indicates maximum classification accuracy. Group analyses were performed using two-sided *t* tests against chance accuracy across subjects. Cluster-based permutation testing was used to control for multiple comparisons. To visualize topographical maps of neural activity underlying classification performance, ADAM transforms the weight vectors from BDM analyses to weights that would result from a forward model, by taking the product of the classifier weights and the data covariance matrix. Finally, correlations between RT difference scores between task domains (memory—perceptual) and AUC at the participant level were performed to evaluate whether differential overlap between stimulus-locked and response-locked brain activity contributed to classification performance.

3 | RESULTS

3.1 | Behavioral performance

Descriptive statistics of accuracy, RTs and confidence are summarized in Table S2 of the Supplementary Materials. Both task domains produced the congruency effect that characterizes the classic Flanker task (Eriksen & Eriksen, 1974). As shown in Figure 3a,b, both age groups were more accurate and faster for congruent trials relative to incongruent trials over the course of the task. For accuracy, the main effect of Congruency was statistically significant, $F_{(1,73)} = 156.38$, $p = <.001$, $\eta^2 = .100$, and was qualified by the Domain × Congruency interaction, $F_{(1,73)} = 93.68$, $p < .001$, $\eta^2 = .037$. Post-hoc tests showed that accuracy was higher in congruent than incongruent trials for both perceptual ($p < .001$) and memory ($p < .001$) domains. Moreover, accuracy in congruent trials was higher for perceptual than memory ($p < .001$) while accuracy in incongruent trials was higher for memory than perceptual domains ($p < .001$). There was a Group × Block interaction, $F_{(3.39,247.80)} = 3.12$, $p = .022$, $\eta^2 = .008$. Post-hoc tests did not reveal any statistically significant differences. Main effects of Group, Domain, and Block, and all other two-way interactions and three-way interactions were not statistically significant.

Older adults were overall slower than the young group, despite no differences in accuracy in both perceptual and memory domains. For RTs, the main effect of Group, $F_{(1,73)} = 86.84$, $p = < .001$, $\eta^2 = .449$, the main effect of Domain, $F_{(1,73)} = 109.62$, $p = < .001$, $\eta^2 = .170$, the main effect of Block, $F_{(2.79,203.79)} = 21.87$, $p = < .001$, $\eta^2 = .021$, and the main effect of Congruency, $F_{(1,73)} = 693.15$, $p = < .001$, $\eta^2 = .117$, were statistically significant. These were qualified by two- and three-way interactions. The Group × Congruency interaction was statistically significant, $F_{(1,73)} = 23.02$, $p = <.001$, $\eta^2 = .004$. Post-hoc test showed that young adults were faster than older adults in congruent ($p < .001$) and incongruent ($p < .001$) trials, responses in congruent trials were faster than in incongruent trials for young ($p < .001$) and older adults ($p < .001$). Figure 3b shows that responses became slightly faster over the course of the task and this improvement was mostly noticeable in the memory domain after completing the first block. The Domain × Block interaction, $F_{(3.46,252.70)} = 21.34$, $p = < .001$, $\eta^2 = .018$, and the Domain × Congruency interaction, $F_{(1,73)} = 242.88$, $p = <.001$, $\eta^2 = .023$, were statistically significant and were qualified by the Domain × Block × Congruency, $F_{(4.15,303.02)} = 4.05$, $p = .003$, $\eta^2 < .001$. Post-hoc tests revealed that responses were slower for incongruent than congruent trials during all the blocks (1–6) of both perceptual and memory Flanker Tasks (all $ps < .001$). Responses were faster in incongruent trials for perceptual than memory domain in Blocks 1, 2, and 3 (all $ps < .001$), in Block 4 ($p = .021$), in Block 5 ($p = .046$) but not in Block 6 ($p = .871$). Responses were faster in congruent trials for perceptual than memory domain in all the blocks ($ps < .001$) In the memory flanker, responses for congruent and incongruent trials in Block 1 were slower than the rest of the blocks (2–6; all $ps < .001$) and in Block 5 were

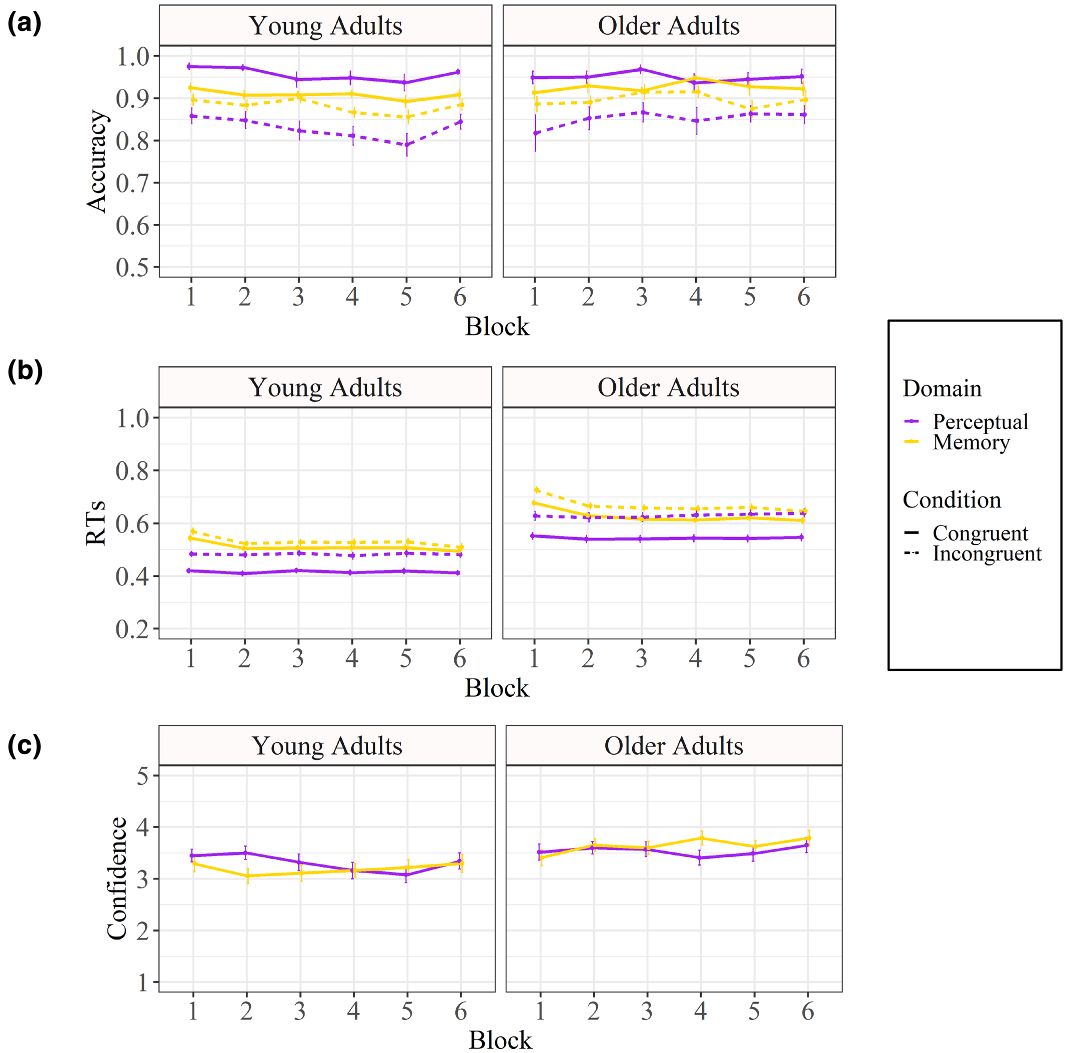

FIGURE 3 Behavioral performance across age groups and task domains. Mean accuracy (a), RTs (b), confidence ratings (c). Error bars represent standard errors.

slower than Block 6 for incongruent ($p = .001$) and congruent trials ($p = .032$).

In terms of confidence ratings, older adults were overall more confident throughout the course of the task for both perceptual and memory domains (see Figure 3c), as demonstrated by the main effect of Group, $F_{(1,72)} = 6.66$, $p = .012$, $\eta^2 = .04$. There was also a Group × Block interaction, $F_{(4.32,310.89)} = 2.35$, $p = .049$, $\eta^2 < .01$. However, post-hoc tests did not reveal any significant differences.

Post-error behaviors were also similar across task domains for both young and older adults. Mean PES for young adults was 0.050 (*SD* 0.042) during the perceptual flanker and 0.059 (0.048) during the memory flanker while for older adults was 0.068 (*SD* 0.074) during the perceptual flanker and 0.071 (0.054) during the memory flanker. No main effect of Group, $F_{(1,65)} = 1.16$, $p = .288$, $\eta^2 < .01$, no main effect of Domain, $F_{(1,65)} = 0.00$, $p = .992$, $\eta^2 < .01$, no interaction between Group and Domain, $F_{(1,65)} = 0.79$, $p = .377$, $\eta^2 < .01$.

3.2 | ERP amplitudes and latencies

First, we examined ERP differences between age groups and task domains. Grand-average waveforms as a function of age group and task domain are presented in Figure 4a,b. Topographical distributions for correct responses and errors are displayed in Figure 4c. Full models for ERN/CRN amplitude[1] can be found in Table 1. The highest intraclass correlation coefficient (ICC) was for response variability, accounting for approximately 57% (amplitude model) and 47% (latency model) of the ERN variability. As shown in Figure 4a, different neural responses to correct and incorrect responses could be observed for both versions of the Flanker task in both age groups. This difference was evident in earlier and later post-response intervals at anterior and posterior

[1]Wilkinson notation: ERN_amp ~ response * domain * group + (domain*response|id) + (1|channel).

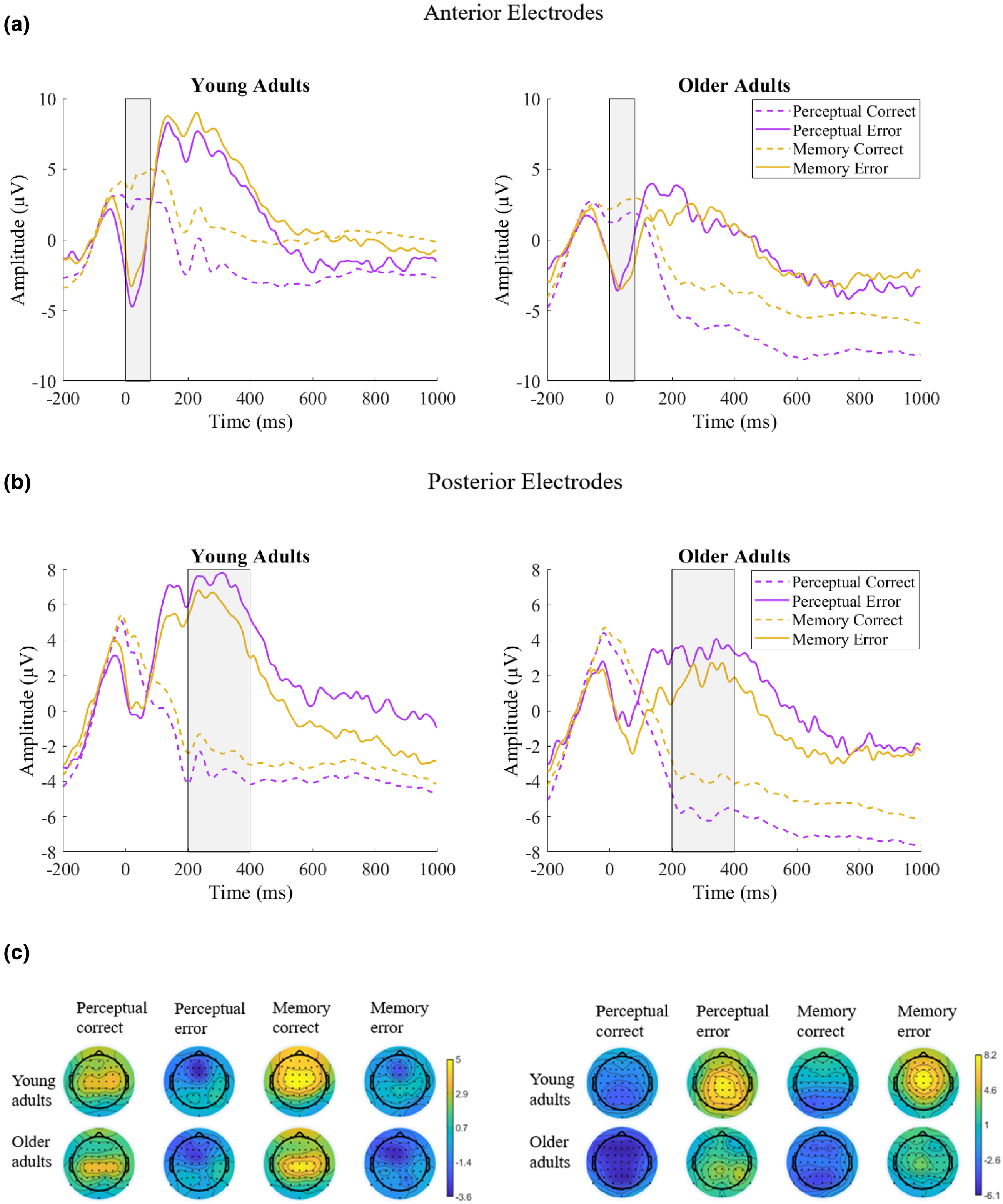

FIGURE 4 (a) Grand-average waveforms for ERN/CRN as average activity over anterior electrodes (F1, F2, FCz, FC1, FC2, FC2). (b) Grand-average waveforms for error positivity (Pe) s as average activity over posterior electrodes (P1, P2, Pz, CP1, CP2, CPz). (c) Topographical distribution for response type in each domain between 0 and 80 ms (left) and 200–400 ms (right).

electrode sites. Indeed, there was a main effect of Response, with a larger amplitude (more negative) for errors than correct responses. There was also a main effect of Domain, with a larger amplitude for the perceptual domain than the memory domain. The main effects were qualified by a Response × Domain interaction,

TABLE 1 MLM for ERN/CRN amplitude 95% CI.

Intercept-only	b	95% CI	df	t	p
(Intercept)	1.42	0.67 to 2.18	65.82	3.77	**<.001**
Random effects	Variance	SD	ICC		
Subject	11.67	3.41	0.13		
Response	52.29	7.23	0.57		
Domain	7.87	2.80	0.09		
Response × Domain	17.76	4.21	0.19		
Channel	0.14	0.38	0.002		
Residual	1.19	1.09			
	b	95% CI	*df*	*t*	*p*
Intercept	0.36	−0.45 to 1.16	69.29	0.88	.382
Response	4.91	3.67 to 6.15	73.00	7.90	**<.001**
Domain	0.80	0.18 to 1.42	73.00	2.57	**.012**
Group	−0.98	−2.48 to 0.51	73.00	−1.31	.193
Response × Domain	1.14	0.18 to 2.11	72.99	2.37	**.020**
Response × Group	−0.89	−3.36 to1.59	73.00	−0.72	.477
Domain × Group	−1.20	−2.44 to 0.04	73.00	−1.94	.057
Response × Domain × Group	0.98	−0.95 to 2.90	72.99	1.01	.315

Note: 95% confidence interval.

Abbreviation: ICC, intraclass correlation coefficient.

Bold values denote statistical significance at the $p < .05$ level.

$b = 1.14$, 95% CI [0.18. 2.11], t (72.99) = 2.37, $p = .020$. Post-hoc tests revealed a larger amplitude for errors compared to correct responses in both task domains (all $ps < .001$) and a larger CRN amplitude in the perceptual domain than the memory domain ($p < .001$). Cross-domain differences in amplitude therefore were more specific to correct responses. Greater differentiation between memory and perceptual errors may be present in young adults, as it can be observed in Figure 4a (solid lines) and in the Response × Domain trend ($p = .057$) in Table 1. There was no main effect of the group and the other 2-way, and the 3-way interactions were not statistically significant.

In MLM for ΔERN,[2] between-person variability accounted for approximately 59% of the total variance (ICC = 0.588), while ICC was 0.369 for the domain and 0.005 for the electrode. There was a main effect of Domain, $b = -1.14$, 95% CI [−2.11. 0.18], t (73.00) = −2.37, $p = .020$, with larger ΔERN for the memory domain than the perceptual domain. The main effect of Group and the Group × Response interaction were not statistically significant. Thus, the error-specific activity was more pronounced for the memory domain.

Full models for ERN/CRN latency[3] are displayed in Table 2. There were main effects of Domain, and a main effect of Group. The main effect of Domain was qualified by a Response × Domain interaction, $b = -5.17$, 95% CI [−5.80. −4.54], t (1568.00) = −16.10, $p < .001$. Post-hoc test revealed that ERN peaked earlier in the perceptual domain than the memory domain ($p < .001$), but there was no difference for correct trials ($p = .045$). Moreover, only in the perceptual domain, ERN peaked earlier than CRN ($p = .005$). There was also a Response × Group interaction, $b = -3.43$, 95% CI [−6.63. −0.23], t (73.01) = −2.14, $p = .036$. Young adults ERN peaked earlier than older adults ($p = .021$), but there was no difference for CRN ($p = .988$). Moreover, for young adults only, ERN peaked earlier than CRN ($p = .030$).

Full models for Pe/Correct Positivity amplitude[4] are displayed in Table 3. The highest intraclass correlation coefficient (ICC) was for response variability, accounting for approximately 65% (amplitude model) and 48% (latency model) of the Pe variability. There was a main effect of Response, with higher amplitude (more positive) for

[2]Wilkinson notation: ΔERN ~ group * domain + (domain|id) + (1|channel).

[3]Wilkinson notation: ERN_lat ~ response * domain * group + (domain + response|id) + (1|channel); maximal model did not converge.

[4]Wilkinson notation: Pe_amp ~ response * domain * group + (domain * response|id) + (1|channel).

TABLE 2 MLM for ERN/CRN latency 95% CI.

Intercept-only	***b***	**95% CI**	**df**	***t***	***p***
(Intercept)	39.07	38.08 to 40.06	78.99	69.67	**<.001**
Random effects	Variance	SD	ICC		
Subject	16.38	4.05	0.15		
Response	49.99	7.07	0.47		
Domain	25.87	5.09	0.24		
Channel	0.15	0.38	0.001		
Residual	13.48	3.67			
	b	**95% CI**	**df**	***t***	***p***
Intercept	38.96	37.98 to 39.93	68.99	79.63	**<.001**
Response	1.47	−0.13 to 3.07	73.01	1.83	.071
Domain	1.69	0.52 to 2.85	72.99	2.88	**.005**
Group	2.10	0.25 to 3.94	73.00	2.27	**.026**
Response × Domain	−5.17	−5.80 to −4.54	1568.00	−16.10	**<.001**
Response × Group	−3.43	−6.63 to −0.23	73.01	−2.14	**.036**
Domain × Group	1.07	−1.26 to 3.40	72.99	0.91	.364
Response × Domain × Group	−0.18	−1.44 to 1.08	1568.00	−0.28	.778

Note: 95% confidence interval.

Abbreviation: ICC, intraclass correlation coefficient.

Bold values denote statistical significance at the $p < .05$ level.

TABLE 3 MLM for Pe/Pc amplitude 95% CI.

Intercept-only	***b***	**95% CI**	**df**	***t***	***p***
(Intercept)	0.48	−0.30 to 1.25	45.19	1.24	.221
Random effects	Variance	SD	ICC		
Subject	8.82	2.97	0.06		
Response	101.52	10.09	0.65		
Domain	13.05	3.61	0.08		
Response × Domain	30.22	5.50	0.19		
Channel	0.24	0.48	0.001		
Residual	1.92	1.38			
	b	**95% CI**	**df**	***t***	***p***
Intercept	0.36	−0.38 to 1.09	39.44	0.99	.332
Response	−8.31	−9.63 to −6.98	73.00	−12.51	**<.001**
Domain	0.10	−0.75 to 0.95	73.00	0.24	.811
Group	−2.81	−4.03 to −1.60	73.00	−4.61	**<.001**
Response × Domain	2.98	1.88 to 4.09	73.00	5.38	**<.001**
Response × Group	1.80	−0.85 to 4.45	73.00	1.36	.179
Domain × Group	0.30	−1.40 to 2.00	73.00	0.35	.726
Response × Domain × Group	0.86	−1.35 to 3.07	73.00	0.78	**.439**

Note: 95% confidence interval.

Abbreviation: ICC, intraclass correlation coefficient.

Bold values denote statistical significance at the $p < .05$ level.

TABLE 4 MLM for Pe/Pc latency 95% CI.

Intercept-only	***b***	**95% CI**	**df**	***t***	***p***
(Intercept)	296.44	293.88 to 299.01	24.46	238.4	**<.001**
Random effects	Variance	SD	ICC		
Subject	107.10	10.35	0.16		
Response	307.36	17.53	0.48		
Domain	148.46	12.18	0.23		
Channel	3.69	1.92	0.005		
Residual	73.18	8.55			
	b	**95% CI**	**df**	***t***	***p***
Intercept	297.01	294.11 to 299.90	36.65	207.83	**<.001**
Response	−1.34	−5.41 to 2.72	73.00	−0.66	.513
Domain	−1.12	−3.94 to 1.71	73.00	−0.79	.433
Group	4.39	−0.37 to 9.15	73.00	1.84	.070
Response × Domain	2.81	1.25 to 4.37	1568.00	3.53	**<.001**
Response × Group	−7.55	−15.68 to 0.58	73.00	−1.85	.068
Domain × Group	7.18	1.54 to 12.83	73.00	2.54	**.013**
Response × Domain × Group	−8.38	−11.51 to −5.26	1568.00	−5.26	**<.001**

Note: 95% confidence interval.

Abbreviation: ICC, intraclass correlation coefficient.

Bold values denote statistical significance at the $p < .05$ level.

errors than correct responses and a main effect of Group, with reduced amplitude in older adults as compared to young adults, as it can be clearly seen in Figure 4b (solid lines). There was a Response × Domain interaction, $b=2.98$, 95% CI [1.88–4.09], t (73.00) = 5.38, $p<.001$. The memory Correct Positivity was larger than the Perceptual Correct Positivity ($p<.001$). No statistically significant difference in Pe amplitude was found across task domains ($p=.115$).

In MLM for ΔPe,[5] between-person variability accounted for approximately 51% of the total variance (ICC = 0.508), while ICC was 0.469 for domain and 0.001 for electrode revealed a main effect of Domain, $b=-2.98$, 95% CI [−4.09–1.88], t (73.00) = −5.38, $p<.001$, with larger ΔPe for the perceptual domain than the memory domain. The main effect of Group and the Domain × Group interaction was not statistically significant.

Model estimates for Pe/Correct Positivity latency[6] are summarized in Table 4. No main effect was statistically significant. There was a Response × Domain interaction, $b=2.81$, 95% CI [1.25. 4.37], t (1568.00) = 3.53, $p<.001$, and a Domain × Group interaction, $b=7.18$, 95% CI [1.54. 12.83], t (73.00) = 2.54, $p=.013$, that were qualified by statistically significant a three-way interaction Response × Domain × Group, $b=-8.38$, 95% CI [−11.14. −5.26], t (1568.00) = −5.26, $p<.001$, Memory Pe peaked earlier than Perceptual Pe in young adults ($p=.004$). Memory Pe peaked earlier in young as compared to older adults ($p=.021$).

Mean ERN/CRN and Pe/Correct Positivity amplitudes and latencies at each electrode are presented in Table S3 of Supplementary Materials mixed ANOVAs in Table S4 of Supplementary materials.

3.3 | ERP changes within task

We also examined ERP changes as a function of a number of errors, and therefore the analyses were limited to ERN and Pe. In the ERN model, the ICC was 0.176 for the participant, 0.098 for the domain and 0.003 for the electrode while in the Pe model, the ICC was 0.106 for the participant, 0.182 for the domain and 0.004 for the electrode. As displayed in Figure 5a, ERN amplitude tended to decrease as a function of error number. ERN trial-level analysis[7] revealed a main effect of Error Number, the Error Number × Domain and the Error Number × Group interactions

[5]Wilkinson notation: ΔPe ~ group * domain + (domain|id) + (1|channel).

[6]Wilkinson notation: Pe_lat ~ response * domain * group + (domain + response|id) + (1|channel); maximal model did not converge.

[7]Wilkinson notation: ERN ~ error number * domain * group + (domain|id) + (1|channel).

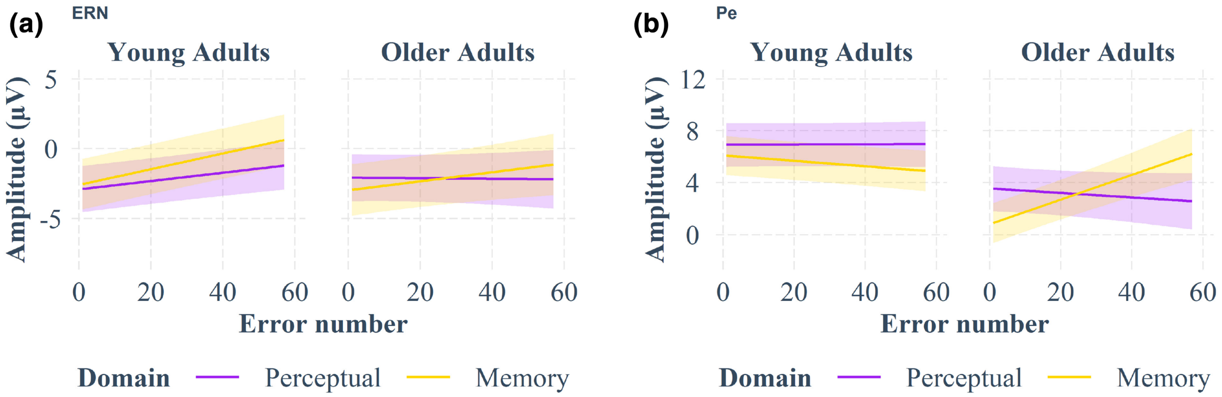

FIGURE 5 Slopes associated with change in ERN amplitude (a) and Pe amplitude (b) during the task plotted by group and task domain.

TABLE 5 Model estimates for ERN and Pe as a function of number of errors.

	ERN				
	b	**95% CI**	**df**	***t***	***p***
Intercept	−2.64	−3.86 to −1.42	68.54	−4.31	**<.001**
Error Number	0.03	0.02 to 0.04	27,019.40	5.13	**<.001**
Domain	−0.29	−1.21 to 0.64	90.64	−0.62	.539
Group	0.22	−2.02 to 2.47	75.67	0.20	.844
Error Number × Domain	0.03	0.01 to 0.05	21,053.51	2.70	**.007**
Error Number × Group	−0.03	−0.05 to −0.01	27,019.40	−2.45	**.014**
Domain × Group	−1.21	−3.06 to 0.63	90.64	−1.31	.195
Error Number × Domain × Group	0.01	−0.04 to 0.05	21,053.51	0.34	.733
	Pe				
	b	**95% CI**	**df**	***t***	***p***
Intercept	4.34	3.30 to 5.39	54.44	8.34	**<.001**
Error Number	0.01	0.00 to 0.03	27,347.50	2.46	**.014**
Domain	−1.78	−3.05 to −0.51	82.67	−2.79	**.006**
Group	−4.33	−6.17 to −2.49	77.53	−4.69	**<.001**
Error Number × Domain	0.05	0.02 to 0.07	25,713.54	3.86	**<.001**
Error Number × Group	0.05	0.03 to 0.07	27347.50	4.17	**<.001**
Domain × Group	−1.93	−4.47 to 0.61	82.67	−1.51	.134
Error Number × Domain × Group	0.13	0.09 to 0.18	25,713.54	5.73	**<.001**

Abbreviations: 95% CI, 95% confidence interval; ERN, error-related negativity; Pe, error positivity.
Bold values denote statistical significance at the $p < .05$ level.

were statistically significant, meaning that the association between the number of errors and ERN amplitude was stronger for the memory flanker (see Table 5). Simple slope analysis indicated a significant decrease in ERN only for the memory domain ($b = 0.04$, $p < .001$), while the slope for the perceptual domain was not statistically significant. Moreover, there was a significant ERN decrease in young adults ($b = 0.04$, $p < .001$) while the slope for older adults was not statistically significant. At first glance, it can be noticed that Pe dynamics across domains presented a more pronounced group-specific pattern (see Figure 5b). Pe trial-level analysis[8] revealed a main effect of Error Number, a main effect of Domain. and a main effect of Group. There were also an Error Number × Domain interaction and an Error Number × Group interaction. Main effects and interactions were qualified by an Error Number × Domain × Group interaction. Follow-up slope

[8]Wilkinson notation: Pe ~ error number * domain * group + (domain|id) + (1|channel).

TABLE 6 Model estimates for ERN and Pe in relation to confidence.

	ERN				
	b	95% CI	df	*t*	*p*
Intercept	−2.15	−3.36 to −0.93	72.85	−3.51	**.001**
Confidence	−1.39	−2.55 to −0.24	126.28	−2.38	**.019**
Domain	0.16	−0.75 to 1.07	69.87	0.35	.728
Group	0.06	−2.21 to 2.33	75.70	0.05	.957
Confidence × Domain	−1.10	−2.59 to 0.39	73.90	−1.47	.145
Confidence × Group	0.21	−2.10 to 2.53	126.28	0.18	.856
Domain × Group	−0.87	−2.70 to 0.95	69.87	−0.96	.342
Confidence × Domain × Group	−0.24	−3.22 to 2.74	73.90	−0.16	.871
	Pe				
	b	95% CI	df	*t*	*p*
Intercept	4.34	3.29 to 5.38	60.47	8.29	**<.001**
Confidence	0.40	−0.86 to 1.66	134.51	0.63	.532
Domain	−1.44	−2.71 to −0.18	73.25	−2.27	**.026**
Group	−3.73	−5.61 to −1.85	75.50	−3.96	**<.001**
Confidence × Domain	−0.68	−2.70 to 1.33	86.68	−0.67	.502
Confidence × Group	1.79	−0.73 to 4.31	134.51	1.40	.162
Domain × Group	0.19	−2.35 to 2.73	73.25	0.15	.882
Confidence × Domain × Group	−1.45	−5.49 to 2.58	86.68	−0.72	.475

Abbreviations: 95% CI, 95% confidence interval; ERN, error-related negativity; Pe, error positivity.

Bold values denote statistical significance at the $p < .05$ level.

analysis indicated a significant decrease in memory Pe in young adults ($b = -0.02$, $p = .005$) and a significant increase in memory Pe in older adults ($b = 0.09$, $p < .001$). The other slopes were not statistically significant.

3.4 | ERPs and confidence

Additionally, we assessed the association between ERP amplitude and confidence ratings. In the ERN intercept-only model, approximately 59% of the variance was accounted by between-participant variance (ICC = 0.591), while ICCs were 0.359 for the domain and 0.007 for the electrode. In the Pe intercept-only model, approximately 37% of the variance was accounted by between-participant variance (ICC = 0.374), while ICCs were 0.569 for the domain and 0.051 for the electrode. MLM for the association between ERPs and confidence[9,10] are summarized in Table 6. ERN was associated with higher confidence ratings as indicated by the main effect of Confidence. However, the association did not vary in relation to task domain or age group. No association between Pe and confidence was found.

3.5 | Multivariate pattern analysis

MVPA showed that the two conditions (task domains) could be successfully decoded from one another in young and older adults for correct responses and errors. As displayed in Figure 6, when the classifier was trained to discriminate between perceptual correct responses and memory correct responses (green lines), decoding accuracy was significantly above chance for the entire epoch in both young and older adults. Similarly, decoding performance for error trials (blue lines) was above chance for almost the entire epoch (young adults: 0–996 ms, $p < .001$; older adults: −199 to −137 ms, $p = .008$, −129 to −82 ms, $p = .019$, −35 to 35 ms, $p = .007$, 43–996 ms, $p < .001$). The activation patterns resulting from the product of the forward transformed decoding weights topographical maps can be found in Figure 7. The correlation between RTs difference scores and AUC were not statistically significant for neither young (correct responses, $r = .109$, $p = .513$; errors, $r = .282$, $p = .086$) nor older adults (correct responses $r = .146$, $p = .388$; errors $r = .253$, $p = .131$), thus suggesting

[9]Wilkinson notation: ERN ~ confidence * domain * group + (domain|id) + (1|channel).

[10]Wilkinson notation: Pe ~ confidence * domain * group + (domain|id) + (1|channel).

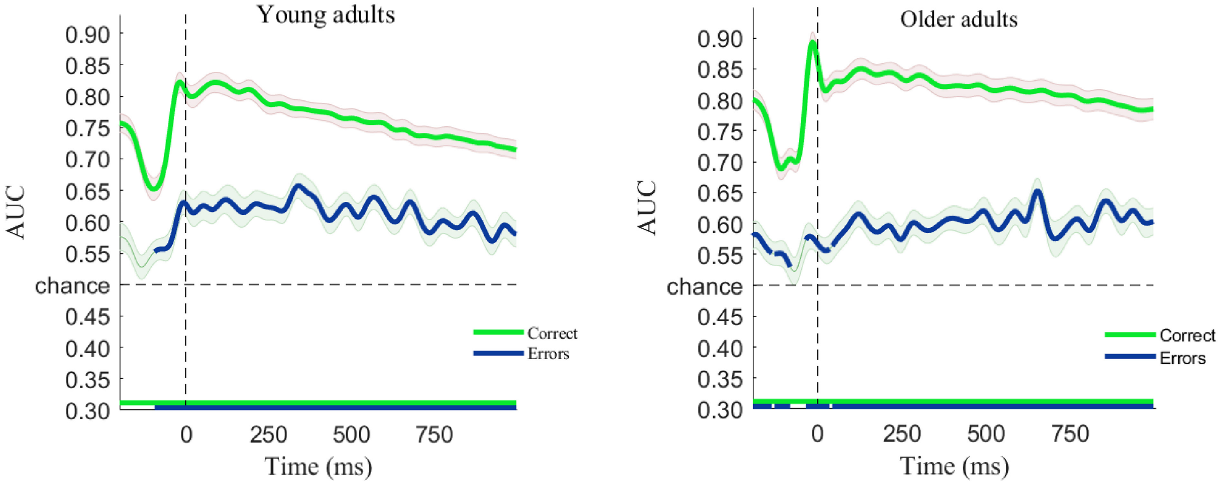

FIGURE 6 Decoding performance (AUC) for domain contrasts. Chance-level decoding = 0.5. Color bars below indicate significant differences.

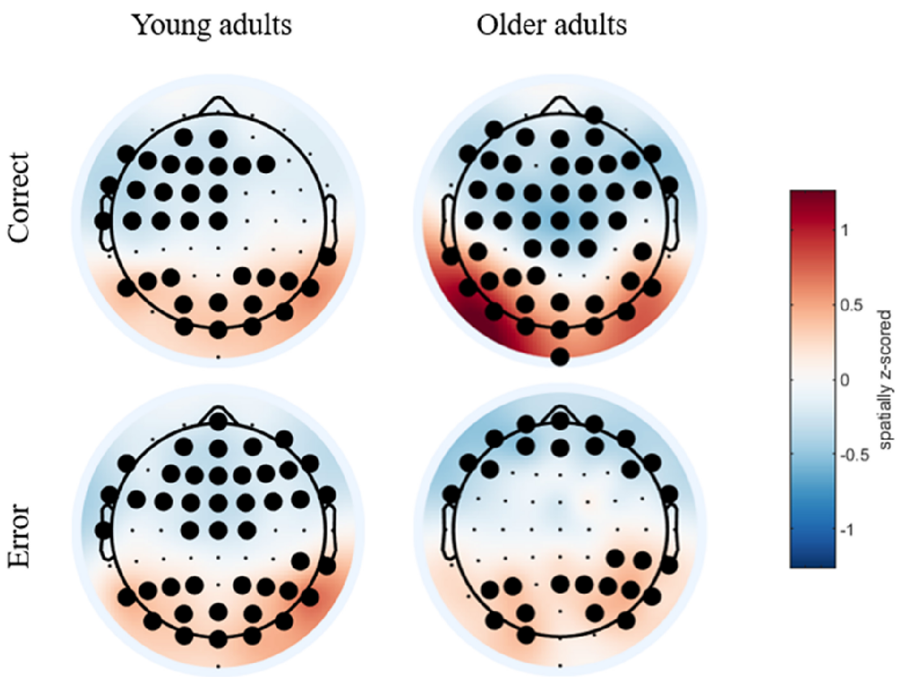

FIGURE 7 Post-response activation patterns spatially normalized (z scored) for every participant. Thick electrodes indicate $p < .05$ under two-sided cluster-based permutation.

that classification accuracy was not associated with RT difference between task domains.

4 | DISCUSSION

The current study investigated domain-specific mechanisms underlying error monitoring in young and older adults. A novel memory version of the classic Flanker task was used to explore differences between perceptual and memory domains. First, we demonstrated that neurophysiological correlates of error monitoring differ across task domains using classic and modern statistical approaches. Our analyses revealed differences in brain responses to both errors and correct responses between perceptual and memory domains. Mean perceptual CRN was larger, and perceptual ERN peaked earlier as compared to the memory domain. However, ΔERN was larger during the memory flanker. The memory Correct Positivity was larger than perceptual Correct Positivity, memory Pe peaked earlier than perpetual Pe in young adults, but no difference in Pe amplitude was found across domains. However, ΔPe was larger for the perceptual domain, thus highlighting marked error-specific differences. Moreover, trial-based analyses provided further support to the domain specificity hypothesis. First, within-task changes of ERN and Pe were found to be specific to the memory Flanker Task, while perceptual ERPs tended to be more stable during the course of the task. Second, multivariate analyses with no a priori region of interest confirmed the presence of distinct patterns of neural activity between perceptual and memory domains in both young adults.

Overall, our findings are consistent with behavioral and fMRI evidence of domain-specific processes underlying metacognition. Notably, we showed that cross-domain differences can be observed at the neurophysiological level since the earliest stages of behavioral monitoring. Crucially, this does not imply that the neural origin of the processes varies by cognitive domain. In fact, the neural source of error monitoring ERPs has been consistently shown to be localized in the ACC (Brázdil et al., 2005; Debener, 2005; Dehaene et al., 1994; Reinhart & Woodman, 2014; Van Veen & Carter, 2002) and to be common across different tasks (Mathewson et al., 2005). Instead, it is possible that domain-specific activity derives from discrete neural activation within the ACC, or within a more widespread overlapping neural network, as suggested by recent fMRI-MVPA research (Morales et al., 2018). Further investigations combining EEG and fMRI should attempt to decode regional and network activity associated with error monitoring ERPs across cognitive domains. Taken together, the findings support models of cognitive awareness which postulated the existence of local and global processes of performance monitoring contributing to the emergence of self-awareness (Morris & Mograbi, 2013), and are in line with recent neuroanatomical models in which metacognitive functions are believed to rely on domain-specific and -general hubs (Seow et al., 2021; Vaccaro & Fleming, 2018).

The second aim of the study was to examine the effect of age on error monitoring and whether age-related changes may occur at a global or specific level. ERN latencies were longer for older than for young adults, while no group differences were found for ERN/CRN amplitude, and CRN latency. In older adults, Pe/Correct Positivity amplitude was reduced, and memory Pe latencies were longer, thus suggesting a decline in processes underlying error awareness despite efficient implicit error detection. ERN and Pe results replicate the most recent studies on aging using a Flanker Task (Clawson et al., 2017; Larson et al., 2016), while inconsistent with previous research with lower sample size ($n \leq 20$; Beste et al., 2009; Hoffmann & Falkenstein, 2011; Mathewson et al., 2005; Nieuwenhuis et al., 2002; Schreiber et al., 2011) as highlighted by Larson et al. (2016). Thus, these findings suggest that aging may not be characterized by a general decline in monitoring mechanisms. Instead, older adults seem to be less aware of error commission. Error awareness is believed to emerge through a process of evidence accumulation about response correctness (Steinhauser & Yeung, 2012; Ullsperger et al., 2010; Wessel et al., 2011), which therefore may be impaired in old age. With increasing age, is it typical to observe sensorimotor decline, encompassing a series of changes in sensory encoding and, integration, which are likely to diminish the quality of the evidence used in decisional processes (McGovern et al., 2018).

When exploring within-task changes, we found that ERN amplitude decreased throughout task performance in young adults but not in older adults. It has been proposed that ERN attenuation may reflect that errors tend to become less salient or that motivation decreases (Volpert-Esmond et al., 2018). This seems to be the case in our study, considering the slight decrease of accuracy over time in young adults. Interestingly, memory Pe decreased in young adults while increasing in older adults as a function of a number of errors. Instead, perceptual Pe remained stable during the memory Flanker Task performance. This suggests that improvement in conscious processing of errors was specific to memory in older adults, because this change was not observed during the perceptual Flanker Task. Perceptual decisions are based on tracking stimuli sensory properties and their expectations (Summerfield & De Lange, 2014), which are possibly inefficient in the elderly as a result of age-related sensory difficulties (McGovern et al., 2018). However, in tasks that involved higher-order processes, older adults may benefit from using elaborative alternative strategies (Zakrzewski et al., 2021), not merely based on sensory properties of the stimuli to monitor performance, leading to a boost in error awareness. Pe has been previously associated with affective responses and error salience (Overbeek et al., 2005), and an alternative interpretation may be that memory errors may be motivationally or personally more relevant in aging, as consequence of memory concerns. Older adults commonly experience "dementia worry" (Kessler et al., 2012), or fear of forgetting, thus increasing personal relevance of memory failures and memory performance in aging (Reese & Cherry, 2004). Consequently, changes in Pe during memory performance may be mediated by increasing frustration or emotional reactivity as more errors are committed.

These findings have implications for interpreting past research findings. Domain-dependent factors need to be considered when exploring age-related differences in error monitoring, and probably contribute to the heterogeneity with past findings. However, it is important to note that other factors may contribute to the inconsistency of the past studies results. One example is the age cut-off defining young and older age groups. For instance, in Harty et al. (2017) age ranges were between 18 and 35 in the young group ($n=28$) and between 65 and 88 in the older group ($n=23$). In the study by Larson et al. (2016), the age range was between 18 and 30 in the young group ($n=89$) and between 55 and 85 ($n=48$) in the older group. In the study by Thurm et al. (2013), age ranged between 20 and 26 in young adults ($n=16$) and between 63 and 78 in older adults ($n=16$). Indeed, the age range of both young and older adults varied considerably across previous research studies and, importantly, no guidelines have been yet elaborated for the definition of age cut-off in ERP research. Future studies should evaluate this and other methodological choices (e.g., sample size) and their impact on the results so far reported by this area of research.

Self-reported confidence about performance was found to be similar across domains and stable during the task performance. In line with past research, older adults were more confident than young adults, despite similar task performance, suggesting that older adults tend to overestimate their abilities (Cauvin et al., 2019; Dodson et al., 2007; Hansson et al., 2008; Hertzog et al., 2021). Overall, ERN but not Pe was found to be associated with performance confidence. These findings may seem to diverge from previous evidence on the relation between error awareness and Pe (Desender et al., 2021; Murphy et al., 2012; Nieuwenhuis et al., 2001). However, in the current study participants were asked to rate their performance at the end of each block, therefore confidence judgments refer to the global performance rather than response correctness. Nonetheless, the association between larger ERN and higher confidence may suggest that ERN reflects indirect effects of trait-like characteristics of error monitoring, in line with previous research describing the association with anxiety and depression (Clayson et al., 2020; Weinberg et al., 2015), while Pe is more likely to reflect trial-based metacognitive processes (Desender et al., 2021). However, including confidence ratings after each trial in the study is more appropriate for tasks with a smaller number of trials because of time-related issues such as attention and fatigue. Future research should investigate performance monitoring and individual differences in relation to both global and trial-level measures of confidence (e.g., metacognitive efficiency; Fleming, 2017; Maniscalco & Lau, 2012) to confirm this dissociation.

Another methodological limitation is the use of different stimuli in the two versions of the Flanker Task. The perceptual Flanker includes only symbol-like stimuli (i.e., arrows) while the memory-adapted version employs more complex stimuli like objects and animals as well as symbols. Therefore, even though our analyses were conducted on response-locked activity, the differential overlap between stimulus-locked and response-locked activity patterns may have biased our cross-domain findings. It is important to note that the Flanker Task consisted of a large number of trials and the memory domain required a large set of stimuli, because all new stimuli are presented only once. Although different shapes could have been created using the dashes forming the arrowheads segments from the perceptual domain, it was important to obtain stimuli that are clearly distinguishable. This was crucial to avoid similarity issues in order to ensure that errors were induced by memory interference in the memory flanker. Nonetheless, one of the strengths of the study is investigating error monitoring in two domains of the same behavioral task (i.e., flankers-induced interference inhibition), while previous research compared very different experimental paradigms, comprising of very different cognitive processes (e.g., Go/NoGo vs. Flanker Task or source monitoring vs. Flanker Task) and with different tasks characteristic that may have biased these studies' findings (Falkenstein, 2004; Fischer et al., 2017; Hoffmann & Falkenstein, 2010; Johannes et al., 2002; Morris et al., 2006; Pailing & Segalowitz, 2004). Nonetheless, future ERP research should attempt at designing an experimental paradigm that is suitable for manipulations of certain stimuli features, rather than using different stimuli, to test the domain specificity of error monitoring.

In summary, the current study's findings demonstrate the presence of domain-specific mechanisms underlying performance monitoring. It was found that implicit processes of performance monitoring were preserved in older adults with an age-related decline in error awareness, as reflected by reduced Pe. Moreover, neural dynamics underlying error awareness were found to differ across domains over time and we speculated that within-task Pe changes may reflect domain-specific compensatory strategies to overcome sensory deficits in older age. Our findings provide relevant insights into neurophysiological bases of self-monitoring which contribute to better understanding metacognitive processes and may have relevant implications for clinical assessment and intervention of domain-specific cognitive impairments.

AUTHOR CONTRIBUTIONS

Sabrina Lenzoni: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Alexander Sumich:** Conceptualization; methodology; project administration; resources; supervision; writing – review and editing. **Daniel Mograbi:** Conceptualization; methodology; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

TABLE S1. ERP internal consistency.

TABLE S2. Descriptive statistics of behavioral performance, mean (*SD*).

TABLE S3. Mean (*SD*) response-locked ERP amplitude (μV), and latency (ms) summary data as a function of age group and task domain.

TABLE S4. Mixed ANOVAs for ERPs amplitude and latency.

TABLE S5. Mixed ANOVAs for ERPs amplitude and latency, including only incongruent trials.

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