

Adult Age Differences in the Temporal Dynamics of Motivated Attention

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Abstract

■ Reward-based motivation modulates attention and cognitive control across the life span, but little is known about age differences in the temporal dynamics of motivated attention. The current study examined the effects of financial incentives on visual attention using ERPs. Participants (26 younger, aged 18–33 years; 24 older, aged 65–95 years) completed an incentivized flanker task in which trial-level incentive cues signaled the availability of performance-contingent reward, and subsequent alerting cues signaled the onset of the flanker target. ERP components of interest included cue-related components (incentive-cue P2 and contingent negative variation, and alerting-cue N1) as well as target-related components (target N1 and P3). Transient effects of incentives were assessed by comparing ERP amplitudes across incentive and non-incentive

trials from mixed-incentive blocks. Sustained effects of incentives were assessed by comparing ERP amplitudes across non-incentive trials from mixed-incentive blocks and non-incentive trials from pure non-incentive blocks. Younger adults showed transient effects of incentives on all components, whereas older adults showed these effects for incentive-cue P2 and alerting-cue N1 only. Both age groups showed sustained effects of incentives on cue-locked ERPs, but only younger adults showed sustained effects on target-locked ERPs. RT patterns mirrored the ERP findings, in that younger adults showed greater incentive-based modulation than older adults, but at a greater cost to accuracy. Overall, these findings reveal widespread age differences in the dynamics of incentive-motivated attention and cognitive control, particularly at longer timescales. ■

INTRODUCTION

Age-related declines in attention and cognitive control are consequential for complex everyday tasks, such as avoiding distractions while driving (Adrian, Moessinger, Charles, & Postal, 2019). A growing literature suggests that, despite age-related dopaminergic decline (Bäckman et al., 2000), cognitive performance remains sensitive to motivational incentives in older adulthood (Mather, 2016). However, the nature and temporal dynamics of incentive effects on cognitive control in younger and older adults are not fully understood (Ferdinand & Czernochowski, 2018). In particular, although incentives sometimes enhance cognitive control, they can also have the opposite effect (e.g., Chiew & Braver, 2016). Incentives may also shift speed-accuracy trade-off settings, and these shifts may differ for younger and older adults (e.g., Williams, Kudus, Dyson, & Spaniol, 2018; Schmitt, Ferdinand, & Kray, 2015). Finally, existing studies suggest that the timescale of incentive effects may be shorter for older than for younger adults (e.g., Williams et al., 2018). In the current study, we sought to investigate the nature and time course of incentive effects on attention and cognitive control in younger and older adults using an incentivized flanker task. We examined both cue-locked

and target-locked ERP components to disentangle early (“proactive”) and late (“reactive”) mechanisms of cognitive control, and we investigated trial-level and block-level effects to shed light on the timescale on which incentives impact neural and behavioral measures of cognitive control. Before describing the study in more detail, we briefly review the relevant literature.

Incentive Effects on Early versus Late Components of Attention and Cognitive Control

Several studies have used the Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) to explore age differences in incentive effects on attention. The ANT, which combines the flanker task (Eriksen & Eriksen, 1974) and the attentional cueing paradigm (Posner, 1980), separates attention into three distinct networks (alerting, orienting, and executive control). Although the orienting network is preserved in older adults, findings are mixed regarding the alerting and executive control networks (Gamboz, Zamarian, & Cavallero, 2010; Jennings, Dagenbach, Engle, & Funke, 2007; Fernandez-Duque & Black, 2006). Using the ANT task, Williams and colleagues (2016) found posterior N1 amplitude, an early attentional component occurring between 150 and 250 msec, was more negative for trials with a double cue versus no cue (i.e., alerting effect) at both

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the cue and the target, with no differences between age groups. An alerting effect was also present for ANT cue-locked contingent negative variation (CNV) amplitude, but age group differences did not emerge until the target. At the target, older adults, but not younger adults, demonstrated a typical flanker congruency effect, with reduced P3 amplitude for incongruent versus congruent trials (Galvao-Carmona et al., 2014; Neuhaus et al., 2010), whereas only younger adults showed larger frontocentral N2 amplitude for incongruent versus congruent targets. Thus, younger and older adults showed similar neural processing patterns for early, proactive/preparatory processes at the alerting cue, but not in terms of late, reactive processes at the target. Importantly, research with younger and older adults have shown that the addition of an incentive condition to the ANT decreases overall RTs, particularly for younger adults (Williams, Biel, Dyson, & Spaniol, 2017). However, this incentive-related speed-up was associated with greater flanker interference. These results suggest that incentives may shift speed-accuracy trade-off settings, rather than boost cognitive control, in younger adults.

Prior research has examined both earlier and later occurring ERP components to shed light on the temporal dynamics of age differences in incentive effects on attention and cognitive control. The P2 is an early positive component peaking approximately 200 msec poststimulus, involved in automatic visual selective attention (Carretié, Hinojosa, Martín-Loeches, Mercado, & Tapia, 2004; Wastell & Kleinman, 1980). The P3 component at ~300 msec poststimulus is involved in a range of cognitive processes, including attention, memory, and context updating (Neuhaus et al., 2010; Polich, 2007), and its amplitude is typically smaller in older than in younger adults (Porcaro et al., 2019). The CNV is a slow negative potential elicited at frontocentral sites that occurs between a warning cue and target onset (Wild-Wall, Hohnsbein, & Falkenstein, 2007). Schmitt and colleagues (2015) examined incentive-based modulation of P2, P3, and CNV components in an incentivized AX continuous-performance task (Braver & Barch, 2002). In this version of the task, an incentive cue preceded a task-informative cue, which in turn preceded the response target. Incentive cues (i.e., gains or losses) as opposed to neutral, non-incentive cues elicited larger P2 and P3 amplitudes in both age groups, with a larger P3 incentive effect present for younger versus older adults. At the task-informative cue, younger adults also showed a more pronounced CNV amplitude for losses. In contrast, at this stage, older adults showed larger task-informative cue-locked P3 amplitude, but also an extended target-locked P3, indicative of increased demands on working memory. These results support the idea that incentive effects are similar between younger and older adults for early, but not late-stage, attentional processes.

In summary, when incentive cues are presented ahead of upcoming cognitive tasks that require interference

resolution, responses are faster, particularly in younger adults. Younger and older adults show similar patterns of neural activity at early stages of automatic attentional processes (P2 component) in relation to the incentive cue and at the alerting cue (posterior N1 component, CNV), but age differences emerge at later stages of processing at the incentive cue and the target (via P3 components). Despite similar alerting effects at the neural level between age groups, younger adults show greater alerting effects behaviorally. Younger adults show reduced flanker interference in their RTs, but at a cost to accuracy, whereas older adults prioritize accuracy and also display greater congruency effects for P3 amplitude.

Transient versus Sustained Effects of Incentives

On a broader timescale, incentives have been shown to elicit shifts in behavior (Marini, van den Berg, & Woldorff, 2015; Savine, Beck, Edwards, Chiew, & Braver, 2010) and in the temporal dynamics of cognitive control via both transient (i.e., trial-level) and sustained (i.e., block-level) effects (Kostandyan et al., 2019; Chiew & Braver, 2013; Jimura, Locke, & Braver, 2010). Transient effects of incentives are typically examined as changes in behavior or neural activity between incentive and non-incentive trials within reward blocks, whereas sustained effects of incentives represent differences between non-incentive trials embedded in reward blocks versus neutral/baseline blocks (Williams et al., 2018; Chiew & Braver, 2013).

In terms of age differences in transient and sustained incentive effects, Williams and colleagues (2018) examined ERP correlates of anticipatory and target processing in an incentivized flanker task with younger and older adults. Different patterns emerged for each age group during the earlier time window of the incentive cue-P3 component, with younger adults showing both transient and sustained effects of incentives, whereas incentive effects were limited to sustained effects for older adults. During late-stage anticipatory processing, both age groups showed a similar pattern of transient incentive effects for CNV amplitude. At the level of the target, only older adults showed a congruency effect, with larger P3 amplitude for congruent versus incongruent trials. Incentive effects were more prominent in younger adults, with both transient and sustained effects of incentives shown for target-P3 amplitude, whereas incentive effects were absent for older adults. In addition, younger adults had larger cue- and target-locked P3 amplitude for incentive trials in relation to older adults. Incentives were associated with transient and sustained increases in response speed, but at a greater cost to accuracy for younger adults versus older adults. Thus, although certain aspects of incentive effects were similar between age groups for anticipatory processing, at the time of the target and during reactive control processing, only younger adults showed incentive effects.

In summary, trial-wise presentation of incentive cues within a mixed reward context elicits both transient and sustained effects on the temporal dynamics of cognitive control. Transient effects of incentives are conducive to preparatory processing and faster response speed, which is more detrimental to accuracy in younger adults. At the neural level, when older adults show incentive effects, they tend to be present earlier within the preparatory phase of the trial, but are absent by the time of the target. In addition, for older adults, these effects are more sustained in nature such that they persist across trial types. In contrast, younger adults demonstrate more robust effects of incentives, showing transient and sustained effects during anticipatory processing and conflict resolution at the time of the target.

The Current Study

Previous research has explored the relationship between incentives and alerting and between incentives and cognitive control. However, no prior studies have investigated age differences in early and late stages of the neural time course of incentive processing for both alerting and cognitive control networks. The present study sought to extend previous behavioral (Williams et al., 2017) and neural findings (Williams et al., 2016, 2018) to characterize age differences in behavioral and neural responses at the level of the (1) incentive cue, (2) ANT alerting cue, and (3) target. Younger and older adult participants completed an incentivized flanker task that involved gain, loss, and neutral (i.e., non-incentivized) trials, with or without a preceding visual alerting cue, while ERPs were continuously recorded. Similar to prior studies investigating transient (i.e., trial-level) and sustained (i.e., block-level) effects of incentives, motivational states were manipulated on a trial-by-trial basis through a mixed-block/event-related design (Williams et al., 2018; Chiew & Braver, 2013; Jimura et al., 2010).

To investigate age differences in incentive processing earlier on in the trial, at the time of the incentive cue, we examined three components at frontocentral and centroparietal sites representing early visual attention and preparatory processes: (1) P2 amplitude, (2) an early negative component amplitude,¹ and (3) later occurring CNV amplitude. Our analysis of early attention processes at the P2 was a novel approach, whereas the following two components corresponded to the analyses conducted by Williams and colleagues (2018). At the time of the ANT cue, corresponding to Williams and colleagues (2016), we examined posterior N1 amplitude, a negative early visual component associated with the alerting network. At the target and later stages of incentive processing within the trial, we examined both posterior N1 amplitude, to assess later occurring alerting effects (Galvao-Carmona et al., 2014; Neuhaus et al., 2010), as well as frontocentral and centroparietal target-P3 amplitude to investigate age-related processing differences in cognitive control. These

set of analyses are the first to examine the time course of incentive effects on both altering and cognitive control.

Overall, we expected larger effects of incentives on neural processing and behavior in younger versus older adults. We specifically predicted that age differences in incentive-based modulation of attention and cognitive control would emerge at later stages of preparatory and target processing, rather than at earlier stages associated with more automatic attentional processes. We also expected that the incentive cue-locked P2 amplitude would increase with incentives and that the posterior N1 amplitude time-locked to both the ANT cue and target would increase with alerting, and that both components should be largely age-invariant. CNV amplitude was expected to increase with incentives, but we had no specific predictions for age differences given mixed findings of prior studies (Williams et al., 2016, 2018; Schmitt et al., 2015). At the time of the target, P3 amplitude was expected to be larger in younger versus older adults. In addition, in line with Williams and colleagues (2016, 2018), older adults but not younger adults were expected to show an effect of congruency on P3 amplitude. We predicted that younger adults would show transient and sustained effects of incentives on ERP components during anticipatory and target processing. Older adults were expected to show sustained effects of incentives during anticipatory processing, but not at the time of the target. We expected larger incentive-based modulation of behavior in younger versus older adults, and greater prioritization of accurate performance by older adults. In addition, we explored whether incentives would affect the temporal dynamics of alerting and the potential relationships between behavioral performance and electrophysiological markers of alerting effects (i.e., ANT cue-N1 amplitude) and preparatory incentive effects (i.e., CNV amplitude) for each age group.

METHODS

Participants

Twenty-six younger adults and 25 older adults participated in the current study. These group sample sizes were chosen to match those of prior studies in the literature (e.g., Williams et al., 2016, 2017, 2018). One older adult was excluded for having an accuracy level of < 60% in each experimental block. Included participants reported normal or corrected-to-normal hearing and vision, and were free of any major medical, neurological, or psychological problems. Participants had to be native speakers of English or possess native-like English language proficiency, and have a minimum of 12 years of education. We aimed to recruit equal numbers of men and women in both age groups, and to match average years of education of both age groups. Group characteristics for this sample show typical age-related differences (see Table 1). All participants received \$25 in cash in compensation for completing the study, which lasted 2–2.5 hr. Participants could win

Table 1. Group Characteristics

	<i>Younger Adults</i>		<i>Older Adults</i>		<i>t</i> (48)	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
<i>n</i>	26	–	24	–	–	–
<i>n</i> (female)	14	–	15	–	–	–
Age, years	23.27	4.57	72.38	6.61	–	–
Age range, years	18–33	–	65–95 ^a	–	–	–
Education, years	15.73	1.71	16.27	3.26	–0.72	.47
MHV	17.12	3.39	23.08	3.15	–6.44	< .001
DSST	99.58	14.24	72.38	14.95	6.35	< .001
MMSE	29.46	0.86	28.46	1.02	3.77	< .001
BIS	18.96	4.10	15.79	2.45	3.35	.002
BAS						
Drive	11.85	2.40	9.63	2.14	3.45	.001
Fun-seeking	12.15	2.60	11.29	1.94	1.32	.19
Reward responsiveness	17.35	2.26	16.71	1.85	1.09	.28
PANAS						
Positive affect	31.35	7.44	34.13	5.47	–1.50	.14
Negative affect	13.23	6.13	11.17	1.47	1.67	.11
DASS-21						
Depression	6.62	5.18	4.17	3.95	1.87	.07
Anxiety	4.85	5.34	4.67	4.11	0.13	.90
Stress	10.15	7.52	8.83	5.59	0.70	.49

Bold font indicates a significant age group difference. MHV = Mill Hill Vocabulary Scale; DSST = Digit Symbol Substitution Task; MMSE = Mini Mental State Exam; BIS = Behavioral Inhibition System; BAS = Behavioral Approach System; PANAS = Positive Negative Affective Schedule; DASS-21 = Depression, Anxiety, and Stress Scale.

^a Excluding the 95-year-old individual from the analyses to bring the older-adult age range on par with that of the younger adults (i.e., 15 years), we obtained the same pattern of results.

an additional bonus up to a maximum of \$30 during the experimental task. We obtained approval for all study procedures from the Research Ethics Board of Toronto Metropolitan University.

Background Measures

Before the experiment, participants completed six background measures (see Table 1 for sample descriptives and inferential statistics). All participants completed a measure of cognitive functioning, the Mini Mental State Exam (Folstein, Folstein, & McHugh, 1975), and scored at least 27 out of a possible 30. Participants also completed the Mill Hill Vocabulary Scale (Raven, 1982) to measure crystallized intelligence, the Digit Symbol Substitution Task (Wechsler, 1997) to measure perceptual-motor speed, and the Behavioral Inhibition/Behavioral Activation Scale (BIS/BAS; Carver & White, 1994) to measure dispositional sensitivity to reward and punishment. The

BIS/BAS includes an inhibition scale and an activation scale, the latter of which comprises three subscales: drive, fun-seeking, and reward responsiveness. In addition, participants completed the Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988) and the Depression Anxiety Stress Scales (Lovibond & Lovibond, 1995) to measure current affective state.

Design and Apparatus

A modified version of the ANT was administered using Presentation software (Neurobehavioral Systems), with participants seated approximately 50 cm from the monitor. All stimuli were presented in white against a black background. Spatial and center cues, which are typically used to estimate the efficiency of the orienting network in the ANT, were not included in this task. Furthermore, neutral flankers were not included based on prior evidence that ERPs elicited by congruent and neutral flankers are similar

(Neuhaus et al., 2010). These modifications are analogous to those used in the ANT-G, a version that has previously been used with both healthy older adults and participants with mild cognitive impairment (Van Dam et al., 2013).

A schematic of the trial sequence is presented in Figure 1. The experimental design included the within-subject factors of cue (no cue, double cue), congruency (congruent, incongruent), and block type: gain (G), loss (L), and neutral (N). Within incentive blocks (i.e., gain and loss blocks), incentive availability varied trial-to-trial. On incentive trials (I), participants could win or lose 10 cents, whereas on neutral trials (N), no incentives were present. After taking into account the block-level and trial-level incentive manipulations, this design resulted in five unique trial types: gain–incentive (GI), gain–neutral (GN), loss–incentive (LI), loss–neutral (LN), and neutral–neutral (NN). GN and LN trials were neutral trials presented in incentive blocks. In neutral blocks, only neutral trials were presented (NN). Lastly, the mixed-factorial design of this task also included age group (younger, older) as a between-subjects factor.

Within each of the five trial types, the four combinations of the two ANT cue conditions and two congruency conditions were presented with equal frequency. This resulted in 48 trials of each Trial Type \times ANT Cue \times Flanker combination. As a result of the neutral blocks having only a single trial type, neutral blocks included 48 trials each, whereas incentive blocks included 96 trials each. The total trial count over the course of the six experimental blocks was 480.

Two arrows flanked the target arrow on either side, pointing in either the same (congruent) or opposing

(incongruent) direction as the central arrow. Within each condition, the central arrow pointed left or right, and the row of arrows appeared above or below the central fixation cross on 50% of the trials, respectively. On no-cue trials, no warning cue was presented, whereas on double-cue trials, two asterisks appeared on the screen above and below the central fixation point before the target onset. Lastly, feedback indicating whether the trial was successful (i.e., gain or non-loss) or unsuccessful (i.e., non-gain or loss) was presented after the participant's response.

Before each block, participants were informed whether the current block would be a neutral-only, gain, or loss block. At the start of each trial, an incentive cue appeared in the center of the screen for 200 msec (i.e., “&” on neutral trials, and “\$” on incentive trials). Then, a fixation cross appeared for a variable duration that was randomly drawn from within the 400- to 1700-msec interval. After this, the ANT cue (i.e., no cue or double cue) appeared for 100 msec, followed by another fixation for 400 msec. The target arrows then appeared above or below the fixation cross, and participants had up to 1,700 msec to respond. After a response (or when the time limit had elapsed), the target disappeared and the fixation cross reappeared, followed by a feedback screen.

For GI trials, “+0.10” was presented for successful responses, whereas “+0.00” was presented for unsuccessful responses. For LI trials, “−0.00” and “−0.10” were presented for successful and unsuccessful responses, respectively. Feedback on neutral trials (GN, LN, and NN) was always the same (“#####”). The presentation of feedback was followed by a final fixation cross that stayed onscreen for 600 msec, for a total trial length of

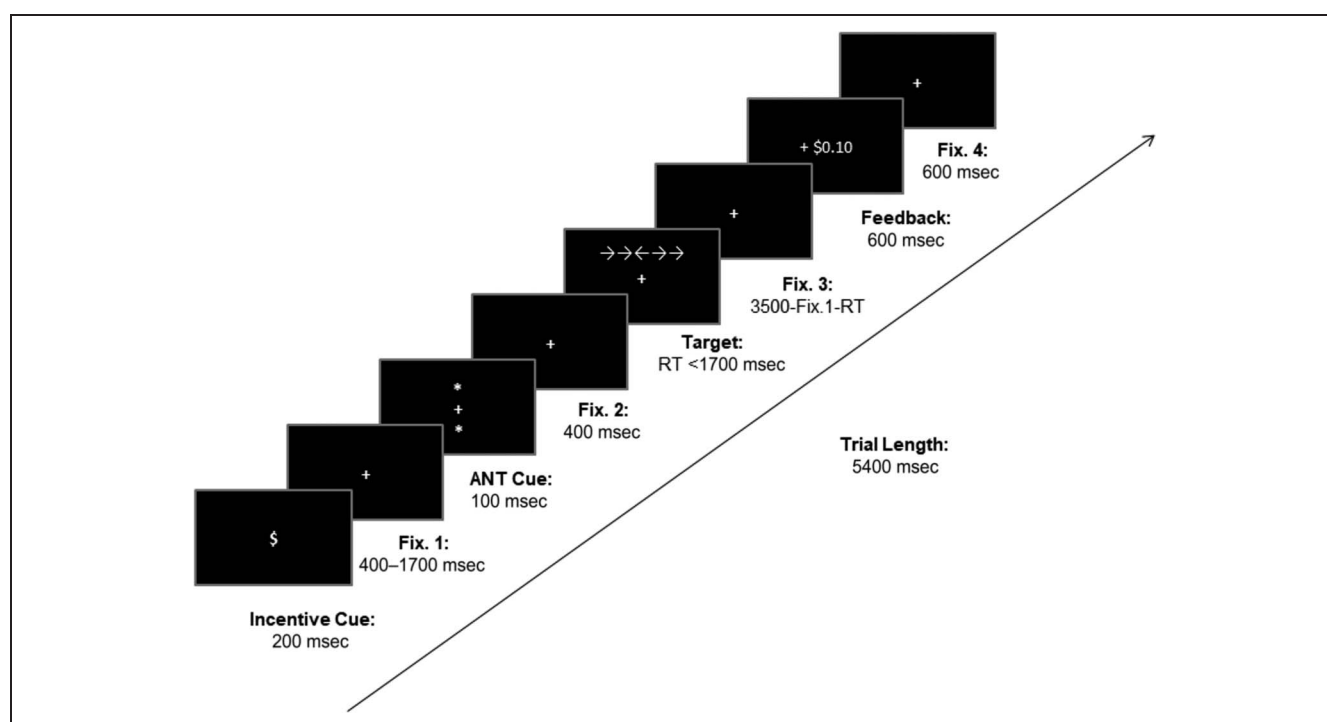


Figure 1. Trial design for the incentivized ANT, showing a single gain–incentive (GI) trial with positive feedback.

5,400 msec. For a trial to be considered successful, participants were told that they had to be both accurate and faster than a time set by the computer. However, in reality, the task used a performance-adaptive response deadline (Williams et al., 2018), which ensured that each participant was successful on roughly 70% of incentivized trials. This was done by adjusting RT limits on a trial-by-trial basis. The RT limit was determined as the sum of cumulative average RT for each correct response (incentive trials only) plus an adjustable value. When the cumulative success rate was 70% or higher, the adjustable value was -10 msec after correct responses and 0 msec after incorrect or too-slow responses. When the cumulative success rate was below 70%, the adjustable value was $+10$ msec after incorrect or too-slow responses and 0 msec after correct responses. End-of-block feedback was also presented, which indicated the participant's winnings (i.e., gains or avoided losses) during that block. No end-of-block feedback was given for neutral blocks. As in Williams and colleagues (2018), the adaptive response deadline determined whether accurate responses were deemed successful (i.e., fast enough). However, the target remained onscreen until a response was made or 1700 msec had elapsed. Therefore, a response logged after the deadline could be accurate even if it was not classified as successful. The analysis of accuracy was conducted on accuracy rather than success rates.

Procedure

After obtaining informed consent, participants completed the questionnaire measures and then moved on to the experimental task. Participants were instructed to respond to the direction (e.g., left or right) of the target arrow as quickly as possible, by pressing the “,” key with their right index finger if the central arrow pointed right, and the “X” key with their left index finger if the central arrow pointed left. Participants were told that they could earn a monetary bonus by giving fast and accurate responses. They completed three practice blocks of 24 trials each (one neutral block, one gain block, one loss block), followed by the six experimental blocks. Between blocks, participants were required to take a break (at least 60 sec after the third block, at least 30 sec after all other blocks). The order of the experimental blocks was counterbalanced across participants within each age group. Following the task, participants were debriefed and received their compensation along with the bonus earned during the task. The bonus amount received was not significantly different for younger adults ($M = 18.51$, $SD = 0.20$) and older adults ($M = 18.49$, $SD = 0.20$), $t(48) = 0.35$, $p = .73$.

ERP Acquisition and Processing

Electrical brain activity was continuously collected for off-line processing using an ActiveTwo system (BioSemi) over an array of 64 electrodes, with a band-pass filter of 208 Hz

and a 512-Hz sampling rate. Recordings were acquired from Ag/AgCl electrodes, which were connected to a cap (Cortech Solutions) at 64 sites, according to the International 10–20 system. Six electrodes were attached externally, with two being placed on the right and left mastoids. Four electrodes were then used to record horizontal and vertical movements for both eyes by placing at the outer canthi and inferior orbits, respectively.

EEGlab (Delorme & Makeig, 2004) and ERPLab (Lopez-Calderon & Luck, 2014) were used to conduct off-line processing. Following the preprocessing procedure outlined by Williams and colleagues (2018), EEG data were referenced to the average of the right and left mastoids and were resampled as 256 Hz. High-pass (0.1 Hz, 12 dB/octave) and low-pass (30 Hz, 24 dB/octave) filters were applied to the continuous data. Then, cues and targets were epoched between 200 msec prestimulus and 1000 msec poststimulus. Independent component analysis was used to correct artifacts (e.g., eye blinks, lateral eye movements). Finally, epochs containing values that exceeded a threshold of $\pm 75 \mu\text{V}$ were automatically rejected. None of the participants had a total trial rejection rate greater than 30%.

Behavioral Data Analysis

Blocks in which a participant failed to respond on more than 10% of trials, or in which accuracy was below 60% for any trial type, were excluded from further analyses. These criteria resulted in one older adult being excluded for having an accuracy rate below 60% for all blocks. To examine correct RT and accuracy effects across age groups and the different experimental conditions at the trial level, we estimated multilevel models using the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2015). Main effects and interactions were tested using the *Anova* function from the car package in R (Fox & Weisberg, 2019) and are reported as Wald chi-square tests using Type III sum of squares. Follow-up comparisons for significant effects and interactions (criterion, $p < .05$) were conducted using the R package emmeans (Lenth, 2020), using the Benjamini–Hochberg (BH) p value adjustment for multiple comparisons.

First, a multilevel linear regression (random intercept only) was estimated, with trials nested within subjects, regressing RT onto age group (younger, older), congruency (congruent, incongruent), ANT cue (no, double), and trial type collapsed across valence into three types (i.e., incentive trials [GI, LI], mixed-block neutral trials [GN, LN], and neutral trials [NN]). The ERP morphology was similar between GI and LI as well as between GN and LN trial types (see Figures 2–5), and preliminary behavioral analyses showed limited valence effects. Therefore, we collapsed across valence to increase statistical power and to focus on the central aim of investigating the interaction of age group and incentive condition. However, we note when the full analysis yielded different effects for gain and losses.

In line with previous work (Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2010; Fan et al., 2002), analyses of RT used correct responses only. The complete model formula for correct RT is specified below.

$$\begin{aligned} & \text{lmer}(RT \sim \text{Age Group} + \text{Congruency} + \text{Cue} \\ & + \text{Trial Type} + \text{Age Group} : \text{Congruency} \\ & + \text{Age Group} : \text{Cue} + \text{Congruency} : \text{Cue} \\ & + \text{Age Group} : \text{Trial Type} + \text{Congruency} \\ & : \text{Trial Type} + \text{Cue} : \text{Trial Type} + (1 | \text{subject})). \end{aligned}$$

Second, a multilevel logistic regression model (random intercept only) was estimated with trials nested within subjects, regressing accuracy (i.e., incorrect = 0, correct = 1) onto age group (younger, older), congruency (congruent, incongruent), ANT cue (no, double), and trial type collapsed across valence (i.e., incentive trials [GI, LI], mixed-block neutral trials [GN, LN], and neutral trials [NN]). The complete model formula for accuracy is specified below.

$$\begin{aligned} & \text{glmer}(\text{Accuracy} \sim \text{Age Group} + \text{Congruency} + \text{Cue} \\ & + \text{Trial Type} + \text{Age Group} : \text{Congruency} \\ & + \text{Age Group} : \text{Cue} + \text{Congruency} : \text{Cue} \\ & + \text{Age Group} : \text{Trial Type} + \text{Congruency} : \text{Trial Type} \\ & + \text{Cue} : \text{Trial Type} + (1 | \text{subject})) \end{aligned}$$

For both models, we specified up to two-way interactions of factors because comparisons with models that included higher-order interactions indicated that the additional parameters did not yield a better fit for the RT model, $X^2(9) = 5.37, p = .80$ ($\text{AIC}_{\text{Full}} = 272116, \text{BIC}_{\text{Full}} = 272324; \text{AIC}_{\text{Reduced}} = 272103, \text{BIC}_{\text{Reduced}} = 272239$), or for the accuracy model, $X^2(9) = 5.74, p = .77$ ($\text{AIC}_{\text{Full}} = 9450.3, \text{BIC}_{\text{Full}} = 9652.5; \text{AIC}_{\text{Reduced}} = 9438.0, \text{BIC}_{\text{Reduced}} = 9567.4$). Follow-up pairwise comparisons of interest for both behavioral and neurophysiological data were the transient (i.e., incentive vs. mixed-block neutral trials) and sustained (i.e., mixed-block neutral vs. neutral trials) effects of incentives.

ERP Data Analysis

ERP analyses were performed in relation to the incentive cue, ANT cue, and target-evoked activity. To coincide with Williams and colleagues (2018), for the incentive cue, mean amplitudes were averaged at frontocentral (FCz and Cz) and centroparietal (CPz and Pz) sites for the P2 and early negative component, and at frontocentral (FCz and Cz) sites for the CNV. Similar to prior work examining P2 amplitude in relation to low- and high-reward cues (Gruber & Otten, 2010), incentive cue-P2 mean amplitude was analyzed during the time window of 200–300 msec. For the incentive cue early negative component analysis, we first extracted peak latencies following the practice of the Williams and colleagues (2018) study, using the time window of 300–500 msec² for younger adults and 350–600 msec for older adults. Mean amplitudes were

defined using a 100-msec window centered on group averaged peak latencies. Mean amplitude of the early negative component was analyzed using a mixed-factorial ANOVA with Age Group (younger, older) as the between-subjects variable and Region (frontocentral, centroparietal) and Trial Type (incentive, mixed-block neutral, neutral) as the within-subject factors. CNV mean amplitude was examined 700–1000 msec following the incentive cue (Williams et al., 2018). The mixed-factorial ANOVA for CNV activity was conducted with Age Group (younger, older) as the between-subjects variable and Trial Type (incentive, mixed-block neutral, neutral) as the single within-subject factor.

Corresponding to the ANT analysis used in Williams and colleagues (2016), posterior N1 was examined 150–250 msec following either (1) the alerting cue or (2) the continuation of the fixation that was on-screen at the time of the alerting cue in the no cue condition. Posterior N1 amplitude was averaged at both parietal (P3, Pz, and P4) and occipital (O1, Oz, and O2) sites (Williams et al., 2016). The mixed-factorial ANOVA for ANT cue-locked N1 mean amplitude was conducted with Age Group (younger, older) as the between-subjects variable and Region (parietal, occipital), ANT Cue Type (no cue, double cue), and Trial Type (incentive, mixed-block neutral, neutral) as the within-subject factors. In addition, posterior N1 was examined 150–250 msec after the presentation of the target. As in the cue-locked analysis, average posterior N1 amplitude was analyzed at parietal (P3, Pz, and P4) and occipital (O1, Oz, and O2) electrodes (Williams et al., 2016). The target-locked posterior N1 analysis was conducted with Age Group (younger, older) as the between-subjects variable and Region (parietal, occipital), Congruency (congruent, incongruent), and Trial Type (incentive, mixed-block neutral, neutral) as the within-subject factors.

For the analysis of target-locked P3 amplitude, we examined both frontocentral (FCz, Cz) and centroparietal (CPz, Pz) sites (Williams et al., 2016, 2018). We first extracted peak latencies, using the time window of 300–800 msec for both age groups following the presentation of the target (Williams et al., 2016). As Williams and colleagues (2016) demonstrated that the P3 component exhibits a wider distribution in older adults, mean amplitudes were calculated over a 200-msec window for older adults, and a 100-msec window for younger adults, centered at group averaged peak latencies. The mixed-factorial ANOVA for target-locked P3 mean amplitude was conducted with Age Group (younger, older) as the between-subjects variable and Region (frontocentral, centroparietal), Congruency (congruent, incongruent), and Trial Type (incentive, mixed-block neutral, neutral) as the within-subject factors. In situations where Mauchly's assumption of sphericity was violated, the Huynh–Feldt correction was used to adjust degrees of freedom. BH adjusted *p* values (Benjamini & Hochberg, 1995) were used to account for multiple comparisons.

RESULTS

Behavioral Results

Correct RT

Means and standard deviations for behavioral measures are presented in Table 2,³ and the results from the ANOVA table calculated on the multilevel linear regression model for RT as well as effect sizes are presented in Table 3. The model revealed participants were faster to respond on congruent versus incongruent trials, and on double cue versus no cue trials. There was also a main effect of Trial Type. Comparisons of interest revealed both transient, $p_{BH} < .001$, $d = .15$, and sustained, $p_{BH} < .001$, $d = .16$, effects of incentives, with faster responses on incentive versus mixed-block neutral trials (i.e., transient) and faster responses on mixed-block neutral trials versus neutral trials (i.e., sustained).

In addition, there was a main effect of Age Group, and Age Group interacted separately with Trial Type, Congruency, and Cue. Younger adults showed transient, $p_{BH} < .001$, $d = .19$, and sustained speed-up effects, $p_{BH} < .001$, $d = .18$, and older adults had transient, $p_{BH} < .001$, $d = .11$, and sustained, $p_{BH} < .001$, $d = .14$, speed-up effects, with both age groups exhibiting faster RT for incentive versus mixed-block neutral trials and faster RT for mixed-block neutral trials versus neutral trials.⁴ When further compared, the transient effect was larger in

younger adults versus older adults, $p_{BH} = .005$, but there was no age difference for the sustained effect, $p_{BH} = .34$. Both younger adults, $p_{BH} < .001$, $d = .83$, and older adults, $p_{BH} < .001$, $d = 1.30$, were faster on congruent versus incongruent trials, with the difference being larger for older adults versus younger adults, $p < .001$. Furthermore, both younger adults, $p_{BH} < .001$, $d = .27$, and older adults, $p_{BH} < .001$, $d = .16$, were faster on double cue versus no cue trials, but this alerting effect was larger for younger adults versus older adults, $p < .001$. Finally, there was a significant interaction of Congruency \times Cue. The presence of the double cue versus no cue resulted in faster responses for both congruent, $p_{BH} < .001$, $d = .27$, and incongruent trials, $p_{BH} < .001$, $d = .15$, with a smaller alerting effect for incongruent versus congruent trials, $p < .001$.

Accuracy

The results from the ANOVA table calculated on the multilevel logistic regression model for accuracy are presented in Table 4. Results of the model indicated a significant main effect of Congruency, which interacted separately with Age Group, Cue, and Trial Type. There was no age group difference in accuracy on congruent trials, $p_{BH} = .61$, $OR = 0.88$, but older adults were more likely to be accurate than younger adults on incongruent trials, $p_{BH} = .004$, $OR = 1.79$. For congruent trials, there was no significant

Table 2. Means (*M*) and Standard Deviations (*SDs*) for Behavioral Data

	Age Group	Cue	Target	GI	GN	LI	LN	NN
				<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)
Accuracy (% correct)	Younger adults	No	Congr.	98.7 (2.0)	99.0 (1.8)	99.0 (2.1)	98.6 (3.3)	98.6 (2.0)
			Incongr.	85.3 (8.0)	90.2 (9.6)	85.3 (11.4)	88.3 (9.8)	90.2 (9.0)
		Double	Congr.	98.4 (2.1)	99.2 (2.0)	99.2 (2.0)	99.2 (2.0)	98.9 (2.5)
			Incongr.	80.0 (13.3)	86.2 (11.4)	80.1 (14.3)	85.9 (14.0)	86.9 (10.3)
	Older adults	No	Congr.	98.4 (3.2)	99.0 (1.8)	98.6 (2.4)	98.4 (3.0)	98.1 (4.1)
			Incongr.	91.8 (5.8)	93.2 (5.6)	92.4 (7.9)	92.9 (6.7)	93.2 (6.0)
		Double	Congr.	99.7 (1.2)	99.3 (2.0)	99.1 (1.7)	99.3 (2.0)	97.7 (3.9)
			Incongr.	88.5 (9.7)	91.0 (6.1)	91.5 (7.5)	91.3 (7.5)	92.2 (10.2)
RT (msec)	Younger adults	No	Congr.	475 (50)	498 (61)	474 (46)	494 (48)	522 (70)
			Incongr.	558 (68)	573 (62)	553 (64)	579 (71)	592 (74)
		Double	Congr.	451 (51)	464 (57)	446 (47)	460 (56)	480 (57)
			Incongr.	528 (64)	553 (59)	539 (58)	559 (68)	569 (71)
	Older adults	No	Congr.	657 (84)	667 (89)	652 (67)	659 (66)	681 (79)
			Incongr.	775 (103)	797 (108)	783 (102)	789 (93)	803 (93)
		Double	Congr.	624 (80)	644 (84)	637 (79)	641 (73)	658 (75)
			Incongr.	767 (107)	779 (102)	775 (111)	785 (92)	795 (103)

GI = gain–incentive trials; GN = gain–neutral trials; LI = loss–incentive trials; LN = loss–neutral trials; NN = neutral–neutral trials; Congr. = congruent targets; Incongr. = incongruent targets.

Table 3. Main Effects and Interactions for Correct RT

Correct RT				
Analysis of Deviance Table (Type III Wald Chi-Square Tests)				
	χ^2	df	p	η_p^2
Intercept	1257.42	1	< .001	
Age group	69.25	1	< .001	.67
Congruency	815.02	1	< .001	.20
Cue	138.62	1	< .001	.01
Trial type	134.11	2	< .001	.01
Age Group × Congruency	313.48	1	< .001	.01
Age Group × Cue	17.46	1	< .001	7.77e-04
Congruency × Cue	19.94	1	< .001	8.88e-04
Age Group × Trial Type	13.53	2	.001	6.02e-04
Congruency × Trial Type	3.53	2	.17	1.57e-04
Cue × Trial Type	1.00	2	.61	4.45e-05

difference in accuracy with respect to the no cue versus double cue condition, $p_{BH} = .08$, $OR = .74$, whereas for incongruent trials, participants were more likely to be accurate in the no cue versus double cue condition, $p_{BH} < .001$, $OR = 1.35$. Accuracy was higher for all three trial types for congruent versus incongruent trials, $p_{BHs} < .001$; however, this congruency effect was larger for mixed-block neutral trials compared with neutral trials (i.e., sustained effect), $p_{BH} = .01$, $OR = 1.83$, with no congruency difference between mixed-block neutral trials and incentive trials (i.e., transient effect), $p_{BH} = .40$, $OR = .84$.

Table 4. Main Effects and Interactions for Accuracy

Accuracy			
Analysis of Deviance Table (Type III Wald Chi-Square Tests)			
	χ^2	df	p
Intercept	413.90	1	< .001
Age group	0.90	1	.34
Congruency	158.03	1	< .001
Cue	2.01	1	.16
Trial type	3.54	2	.17
Age Group × Congruency	15.02	1	< .001
Age Group × Cue	1.12	1	.29
Congruency × Cue	10.92	1	< .001
Age Group × Trial Type	6.32	2	.04
Congruency × Trial Type	12.19	2	.002
Cue × Trial Type	0.23	2	.89

Finally, the presence of an Age Group × Trial Type interaction revealed that older adults were more likely to be accurate than younger adults on incentive trials, $p < .05$; $p_{BH} = .15$, $OR = 1.54$, with no age group difference shown for mixed-block neutral trials, $p_{BH} = .69$, $OR = 1.17$, or neutral trials, $p_{BH} = .71$, $OR = 1.09$. Trial type comparisons revealed a significant transient effect for younger adults, $p_{BH} = .02$, $OR = 1.38$, but not older adults, $p_{BH} = .65$, $OR = 1.06$, with higher accuracy for mixed-block neutral versus incentive trials. Sustained effects were nonsignificant for both younger adults, $p_{BH} = .28$, $OR = 1.20$, and for older adults, $p_{BH} = .24$, $OR = 1.30$.

Summary of Behavioral Results

The presence of incentives was associated with significant transient and sustained speed-up effects for both age groups, but the transient effect was larger for younger adults. Younger adults also exhibited a larger alerting effect for RT compared with older adults. Older adults slowed down more than younger adults on incongruent versus congruent trials. Faster responding by younger adults was associated with reduced accuracy compared with older adults, for both incongruent trials and incentive trials (see Table 5 for a summary of incentive effects).

ERP Results

Incentive Cue-locked Results

P2 amplitude. Average ERP waveforms time-locked to the incentive cue are depicted in Figure 2 for each age group and region. For P2 mean amplitude, there were main effects of Trial Type, $F(1.69, 81.28) = 14.31$, $p < .001$, $\eta_p^2 = .23$, and region, $F(1, 48) = 13.56$, $p < .001$, $\eta_p^2 = .22$. Region

Table 5. Summary of Incentive Effects by Age Group

	Younger Adults		Older Adults	
	Transient	Sustained	Transient	Sustained
Behavioral measures				
RT	x ^a	x	x	x
Accuracy	x ^b	–	–	–
ERP components				
Incentive cue				
P2	x	x	x	x
Early negative	x	–	–	x
CNV	x	–	–	x
ANT cue				
N1	x	x	x	x
Target				
N1	x	x	–	–
P3	x	x	–	–

x = Significant effect.

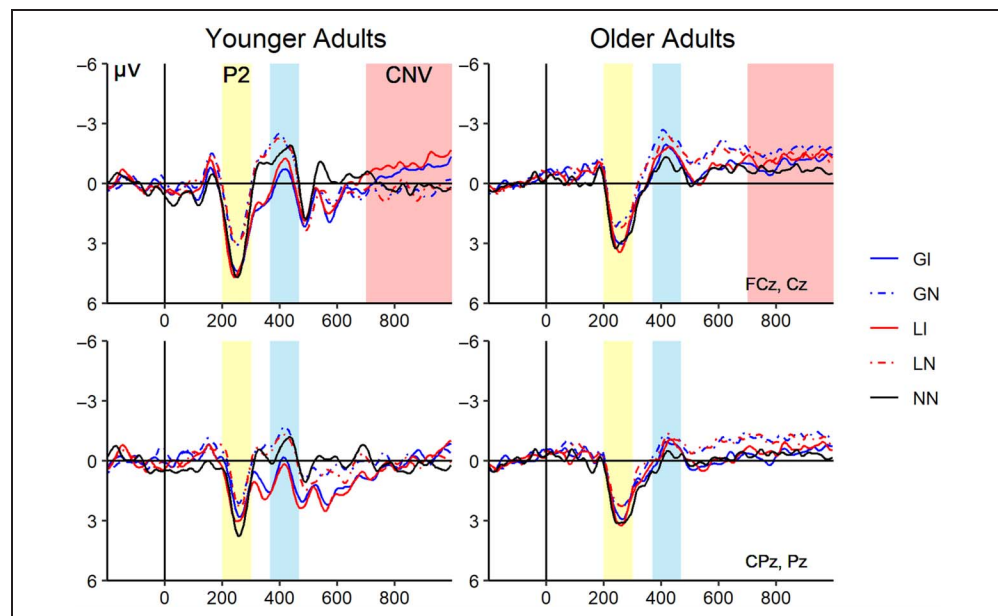
^a Effect is larger in younger adults.

^b Accuracy cost on incentive trials.

interacted with Age Group, $F(1, 48) = 16.22, p < .001, \eta_p^2 = .25$, and Trial Type, $F(1.84, 88.24) = 8.14, p < .001, \eta_p^2 = .15$. Lastly, there was a three-way interaction between Trial Type, Region, and Age Group, $F(1.84, 88.24) = 3.34, p = .04, \eta_p^2 = .07$. As shown in the yellow-shaded regions of Figure 2,

younger adults showed transient and sustained effects of incentives at both frontocentral, $p_{BHS} < .001$, and centroparietal regions, $p_{BHtransient} < .01; p_{BHSustained} < .001$, with larger P2 amplitude shown for incentive versus mixed-block neutral trials, and for neutral versus mixed-block

Figure 2. Incentive cue-locked ERPs by age group, trial type, and region. ERP waveforms are averaged at frontocentral sites (top) and centroparietal sites (bottom). The yellow-shaded region corresponds to the time window for P2 amplitude, the blue-shaded region corresponds to the time window for the early negative component amplitude, and the pink-shaded region corresponds to the time window for CNV amplitude. GI = gain–incentive trials; GN = gain–neutral trials; LI = loss–incentive trials; LN = loss–neutral trials; NN = neutral–neutral trials.



neutral trials. Older adults showed the same P2 amplitude pattern for transient and sustained effects at frontocentral sites, $p_{\text{BHtransient}} < .01$; $p_{\text{BHSustained}} = .01$, but only a sustained effect was significant at centroparietal sites, $p_{\text{BH}} < .05$, whereas the transient effect failed to reach significance, $p_{\text{BH}} = .09$. There were no other significant effects or interactions, $F_s \leq 1.22$.

Early negative component amplitude. For this component, there was a main effect of Region, $F(1, 48) = 42.94$, $p < .001$, $\eta_p^2 = .47$, with more negative amplitude at frontocentral ($M = -1.28$, $SE = 0.35$) versus centroparietal sites ($M = -0.33$, $SE = 0.33$). There was also a main effect of Trial Type, $F(1.62, 77.73) = 6.83$, $p = .004$, $\eta_p^2 = .13$, which interacted with Age Group, $F(1.62, 77.73) = 4.83$, $p = .016$, $\eta_p^2 = .09$. As shown in the blue-shaded regions of Figure 2, younger adults showed a significant transient effect of incentives, $p_{\text{BH}} < .001$, with reduced negative amplitude for incentive versus mixed-block neutral trials, whereas older adults showed a significant sustained effect of incentives, $p_{\text{BH}} < .05$, with more negative amplitude for mixed-block neutral trials versus neutral trials. The sustained effect of incentives was nonsignificant for younger adults, $p_{\text{BH}} = .36$, and the transient effect of incentives was nonsignificant for older adults, $p_{\text{BH}} = .18$. There were no other significant main effects or interactions, $F_s \leq 2.58$.⁵

CNV amplitude. There was a main effect of Age Group, $F(1, 48) = 4.68$, $p = .035$, $\eta_p^2 = .09$, Trial Type, $F(2, 96) = 3.25$, $p = .043$, $\eta_p^2 = .06$, and a significant Age Group \times Trial Type interaction, $F(2, 96) = 3.86$, $p = .024$, $\eta_p^2 = .07$.⁶ As shown in the pink-shaded regions of Figure 2, younger adults displayed a significant transient effect of incentives, $p_{\text{BH}} < .05$, but no sustained effect, $p_{\text{BH}} = .58$, with more negative amplitude for incentive versus mixed-block neutral trials. In contrast, older adults

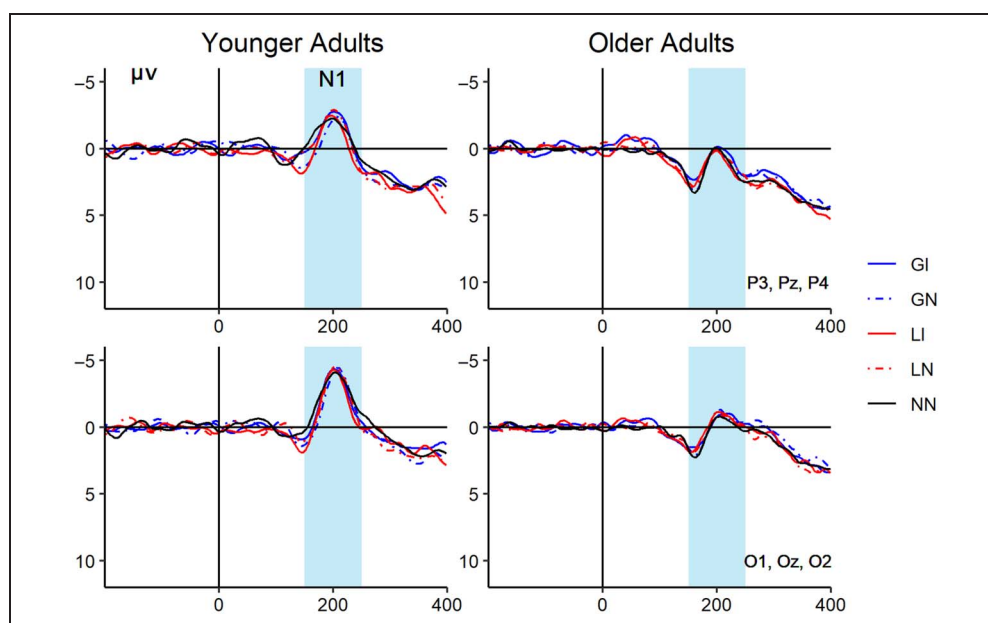
displayed a sustained effect of incentives, $p = .03$; $p_{\text{BH}} = .06$, but not a transient effect, $p_{\text{BH}} = .51$, with more negative amplitude for mixed-block neutral trials versus neutral trials.

ANT Cue-locked Results

ANT cue-N1 amplitude. Difference waves depicting the double cue minus the no cue condition (i.e., alerting effect) are presented in Figure 3. There was a main effect of Age Group, $F(1, 48) = 17.02$, $p < .001$, $\eta_p^2 = .26$; Trial Type, $F(2, 96) = 13.97$, $p < .001$, $\eta_p^2 = .23$; and Region, $F(1, 48) = 19.55$, $p < .001$, $\eta_p^2 = .29$. Age Group interacted with both Cue Type, $F(1, 48) = 16.99$, $p < .001$, $\eta_p^2 = .26$, and Trial Type, $F(2, 96) = 12.92$, $p < .001$, $\eta_p^2 = .21$.⁷ Younger adults ($M = -1.67$, $SE = 0.36$) had more negative amplitude than older adults ($M = 0.57$, $SE = 0.37$) for double cue trials, $p_{\text{BH}} < .001$; however, there was no age difference in N1 amplitude for no cue trials, $p_{\text{BH}} = .84$ ($M_{\text{younger}} = -0.23$, $SE_{\text{younger}} = 0.12$; $M_{\text{older}} = -0.27$, $SE_{\text{older}} = 0.12$). Both younger and older adults showed transient, $p_{\text{BHyounger}} < .001$; $p_{\text{BHolder}} < .05$, and sustained, $p_{\text{BHs}} < .05$, effects of incentives, irrespective of ANT cue type. Younger adults had more negative amplitude for incentive ($M = -1.52$, $SE = 0.20$) versus mixed-block trials ($M = -0.85$, $SE = 0.20$), and for mixed-block trials versus neutral trials ($M = -0.47$, $SE = 0.21$). Older adults showed reduced amplitude for incentive trials ($M = 0.06$, $SE = 0.21$) versus mixed-block trials ($M = 0.37$, $SE = 0.21$), and for neutral trials ($M = 0.02$, $SE = 0.22$) versus mixed-block trials.

There was also a Region \times Trial Type interaction, $F(2, 96) = 6.29$, $p = .003$, $\eta_p^2 = .12$. Transient effects of incentives were present at both parietal ($M_{\text{Incentive}} = -0.58$, $SE_{\text{Incentive}} = 0.16$; $M_{\text{MixedNeutral}} = 0.001$, $SE_{\text{MixedNeutral}} = 0.16$), $p_{\text{BH}} < .001$, and occipital sites ($M_{\text{Incentive}} = -0.88$,

Figure 3. ANT cue-locked difference wave ERPs by age group, trial type, and region. ERP difference waveforms are averaged at parietal sites (top) and occipital sites (bottom). Difference waveforms represent the double cue minus the no cue condition. The blue shaded region corresponds to the time window for posterior N1 amplitude.



$SE_{\text{Incentive}} = 0.15$; $M_{\text{MixedNeutral}} = -0.48$, $SE_{\text{MixedNeutral}} = 0.15$, $p_{\text{BH}} = .001$, whereas there were no sustained effects at parietal ($M_{\text{MixedNeutral}} = 0.001$, $SE_{\text{MixedNeutral}} = 0.16$; $M_{\text{Neutral}} = 0.07$, $SE_{\text{Neutral}} = 0.17$) or occipital sites ($M_{\text{MixedNeutral}} = -0.48$, $SE_{\text{MixedNeutral}} = 0.15$; $M_{\text{Neutral}} = -0.51$, $SE_{\text{Neutral}} = 0.16$), $p_{\text{BHS}} = .79$.

Finally, there was also a Region \times Cue Type interaction, $F(1, 48) = 36.68$, $p < .001$, $\eta_p^2 = .43$. In general, double cue trials ($M = -1.07$, $SE = 0.27$) had more negative amplitude than no cue trials ($M = -0.18$, $SE = 0.08$) at occipital sites, $p_{\text{BH}} < .01$, whereas there was no significant difference in amplitude between double cue ($M = -0.02$, $SE = 0.28$) and no cue ($M = -0.32$, $SE = 0.10$) trials at parietal sites, $p_{\text{BH}} = .33$. There were no other significant main effects or interactions, $F_s \leq 1.23$.⁸

Target-locked Results

Target-N1 amplitude. For posterior N1 amplitude at the level of the target, there was a main effect of Age, $F(1, 48) = 5.85$, $p = .019$, $\eta_p^2 = .11$, and a main effect of Trial Type, $F(1.67, 80.29) = 16.45$, $p < .001$, $\eta_p^2 = .26$. There was also a significant Trial Type \times Age Group interaction, $F(1.67, 80.29) = 9.07$, $p < .001$, $\eta_p^2 = .16$, as well as a significant Trial Type \times Age Group \times Region interaction, $F(1.87, 89.74) = 3.58$, $p = .035$, $\eta_p^2 = .07$. As shown in the blue-shaded region of Figure 4, for younger adults, there were both transient, $p_{\text{BHS}} < .001$, and sustained, $p_{\text{BHS}} < .05$, effects of incentives at parietal and occipital sites, whereas there were no significant incentive effects for older adults at either site, $p_{\text{BHS}} \geq .22$. Younger adults had larger N1 amplitude for incentive versus mixed-block neutral trials and for mixed-block neutral versus neutral trials. There were no other significant main effects or interactions, $F_s \leq 2.97$.

Target-P3 amplitude. Younger adults had larger target-locked P3 amplitude compared with older adults, $F(1, 48) = 7.35$, $p = .009$, $\eta_p^2 = .13$. Larger P3 amplitude was also

present for congruent versus incongruent trials, $F(1, 48) = 5.71$, $p = .021$, $\eta_p^2 = .11$, and for centroparietal sites versus frontocentral sites, $F(1, 48) = 33.58$, $p < .001$, $\eta_p^2 = .41$. There was also a main effect of Trial Type, $F(1.75, 84.11) = 4.69$, $p = .015$, $\eta_p^2 = .09$, and Trial Type interacted with Age Group, $F(1.75, 84.11) = 3.96$, $p = .027$, $\eta_p^2 = .08$. As shown in the blue-shaded regions of Figure 5A and in the bar graph presented in Figure 5B, younger adults showed transient, $p < .05$; $p_{\text{BH}} = .086$, and sustained effects, $p_{\text{BH}} < .05$, of incentives, whereas there were no incentive effects for older adults, $p_{\text{BHS}} = .60$. Younger adult P3 amplitude was larger for incentive versus mixed-block neutral trials, and for mixed-block neutral versus neutral trials.

There was also a significant three-way interaction of Age Group, Congruency, and Region, $F(1, 48) = 8.75$, $p = .005$, $\eta_p^2 = .15$. As shown in Figure 5C, younger adults showed no effect of Congruency at either frontocentral, $p_{\text{BH}} = .71$, or centroparietal sites, $p_{\text{BH}} = .77$. Older adults demonstrated an effect of Congruency, which was larger at centroparietal, $p_{\text{BH}} < .01$, versus frontocentral sites, $p < .05$; $p_{\text{BH}} = .07$. Finally, there was a significant interaction of Trial Type \times Congruency \times Region, $F(1.81, 87.03) = 3.42$, $p = .042$, $\eta_p^2 = .07$. There was a significant congruency effect for incentive trials at frontocentral and centroparietal sites, $p_{\text{BHS}} < .05$, mixed-block neutral trials did not show any congruency effects, $p_{\text{BHS}} \geq .26$, whereas neutral trials only showed a significant congruency effect at centroparietal sites, $p_{\text{BH}} < .05$, but not frontocentral sites, $p_{\text{BH}} = .31$. There were no other significant main effect or interactions, $F_s \leq 3.02$.⁹

Summary of ERP Results

A summary of the incentive effects for each age group, for behavioral and ERP measures, is presented in Table 5. For incentive cue-P2 amplitude, younger and older adults displayed a similar pattern of transient and sustained effects

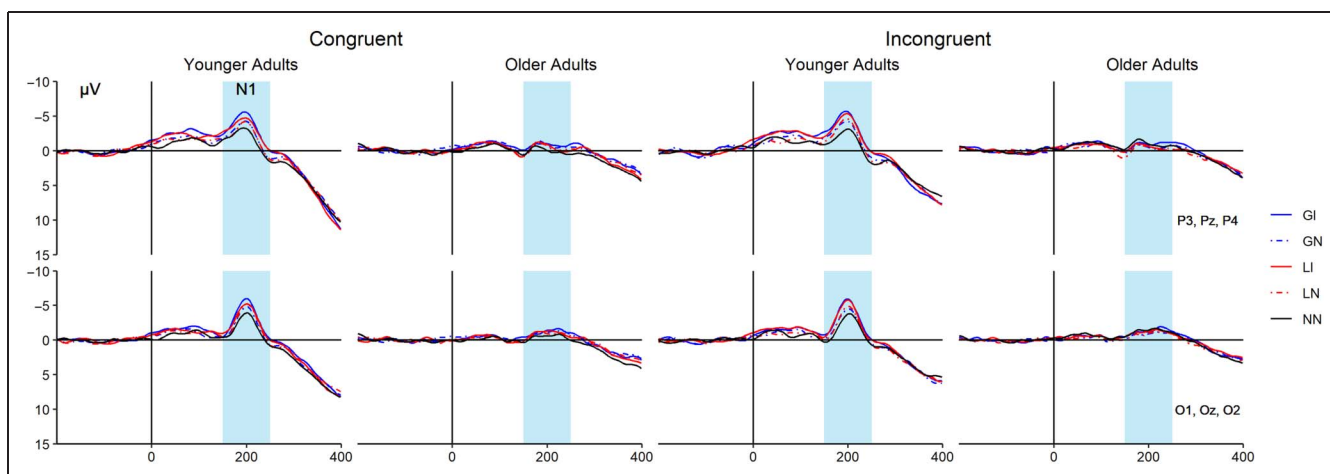


Figure 4. Target-locked ERPs by congruency, age group, trial type, and region for posterior N1 amplitude. ERP waveforms averaged at parietal sites (top) and occipital sites (bottom). The blue shaded region corresponds to the time window for posterior N1 amplitude. GI = gain-incentive trials; GN = gain-neutral trials; LI = loss-incentive trials; LN = loss-neutral trials; NN = neutral-neutral trials.

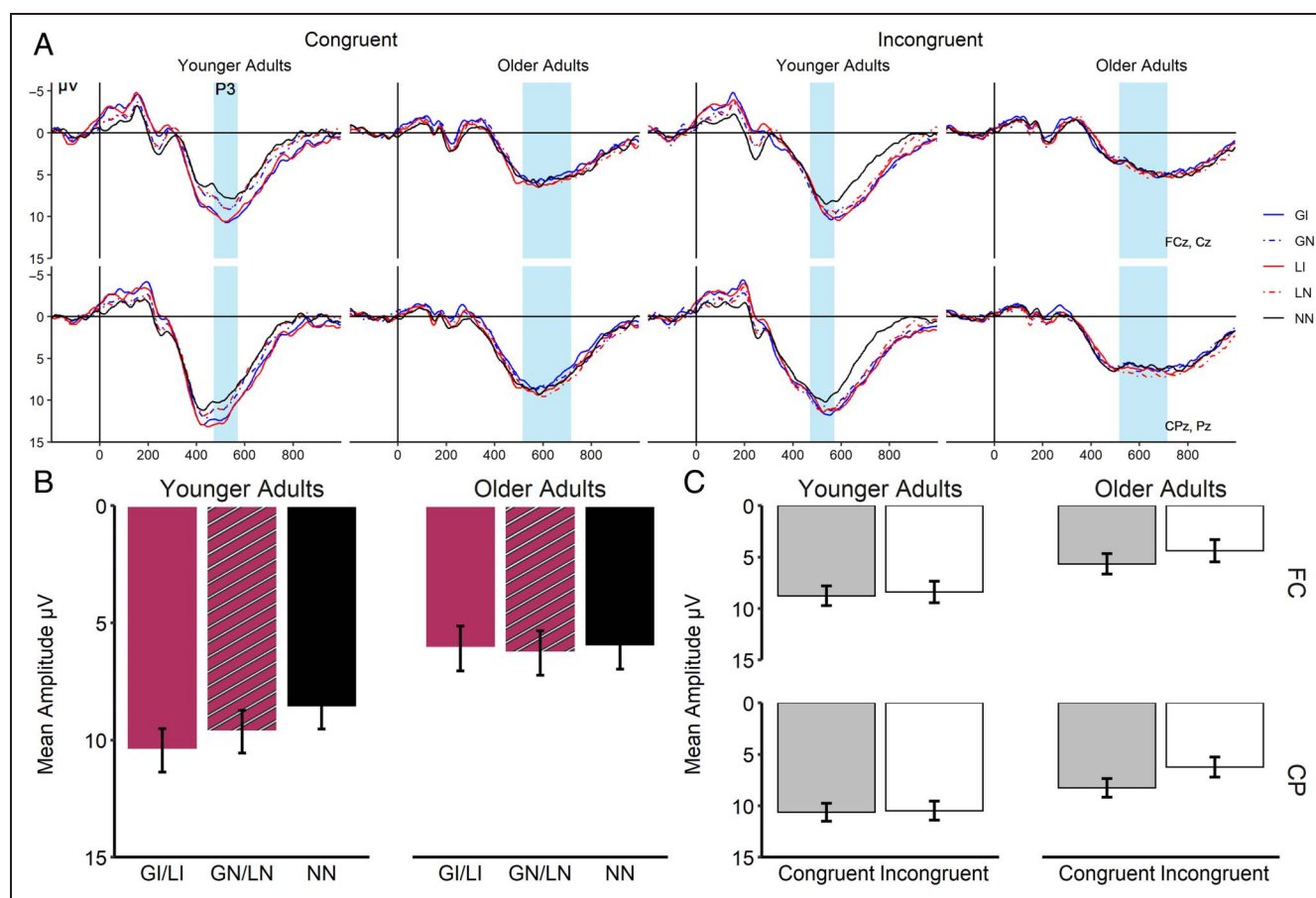


Figure 5. Target-locked ERPs by congruency, age group, trial type, and region for P3 amplitude. Shown in A are ERP waveforms averaged at frontocentral sites (top) and centroparietal sites (bottom). The blue shaded region corresponds to the time window for P3 amplitude. GI = gain-incentive trials; GN = gain-neutral trials; LI = loss-incentive trials; LN = loss-neutral trials; NN = neutral-neutral trials. B represents the estimated marginal means from the Age Group \times Incentive interaction. C represents the estimated marginal means from the Age Group \times Congruency \times Region interaction. FC (frontocentral), CP (centroparietal).

of incentives. Age differences in incentive processing emerged at the time of the early negative component and the subsequent CNV. Here, only transient effects were found for younger adults, whereas only sustained effects were present for older adults. For ANT cue-N1 amplitude, younger adults exhibited a stronger alerting effect than older adults. Both age groups showed transient and sustained effects of incentives, which were not influenced by the presence of the ANT cue. In terms of target-locked N1 amplitude, only younger adults showed transient and sustained effects of incentives at this stage of processing. Similar effects were present for target-locked P3 amplitude, with transient and sustained effects present for younger adults, but not older adults. Finally, only older adults showed a significant congruency effect, with smaller P3 amplitude for incongruent versus congruent trials. This effect was larger at centroparietal versus frontocentral sites.

Exploratory Brain-Behavior Correlations

To assess whether there were potential relationships between behavioral performance and ERP amplitude for

each age group, we explored correlations between (1) behavioral alerting effects and ANT cue-N1 amplitude alerting effects (i.e., double cue – no cue), and (2) behavioral incentive effects and CNV amplitude incentive effects (i.e., transient effect = mixed-block neutral condition – incentive condition; sustained effect = neutral condition – mixed-block neutral condition). Behavioral alerting effects were represented by subtracting average correct RT and accuracy for the no cue condition from the double cue condition across trial types. ERP alerting effects were calculated by subtracting average amplitude from the no cue condition from the double cue condition across trial types and regions. There were no significant correlations between each of the behavioral and electrophysiological measures of alerting for younger adults, $ps \geq .23$, or for older adults, $ps \geq .46$. Younger adults had a significant positive behavioral correlation, $r = .53$, $p = .005$, between the RT and the accuracy alerting effects, such that a larger speed-up effect because of the presence of the double cue versus no cue was associated with a larger detriment to accuracy for the double cue condition. The behavioral correlation between the RT and accuracy

altering effects was nonsignificant for older adults, $r = .23$, $p = .28$.

Behavioral and electrophysiological measures of transient effects were calculated by subtracting average correct RT, accuracy, and average ERP amplitude for the incentive condition from the mixed-block neutral condition, whereas sustained effects were calculated by subtracting average correct RT, accuracy, and average ERP amplitude for the mixed-block neutral condition from the neutral condition. Both younger, $r = .44$, $p = .02$, and older adults, $r = .46$, $p = .02$, had significant positive correlations between the transient RT and transient accuracy effects, which indicated that a larger speed-up in relation to incentives versus mixed-block neutral trials was associated with poorer accuracy on incentive trials. Older adults did not show any significant correlations between transient behavioral effects and transient ERP amplitude, $ps \geq .40$. Younger adults had a significant positive correlation between the transient accuracy effect and the transient ERP effect, $r = .69$, $p < .001$, such that a larger decrease in accuracy in the incentive condition compared with the mixed-block neutral condition (i.e., mixed-block neutral – incentive) was associated with a larger negative amplitude in the incentive versus mixed-block neutral condition (i.e., with mixed-block neutral – incentive resulting in a more positive value, see average waveforms in Figure 2). The correlation between the transient RT effect and the transient ERP effect was marginal, but was in the same direction as the accuracy correlation, $r = .38$, $p = .06$. There were no significant brain–behavior correlations for either age group for the sustained effects, $ps \geq .16$. The behavioral correlation between the sustained RT and accuracy effect was marginal for younger adults, $r = .37$, $p = .06$, and was nonsignificant for older adults, $r = .18$, $p = .39$.

In summary, a finding was that, for younger adults but not older adults, more negative amplitude for the incentive condition versus the mixed-block neutral condition (i.e., transient effect) was associated with a decrease in accuracy for the incentive condition versus the mixed-block neutral condition (i.e., transient behavioral effect). This supports the interpretation that larger incentive-induced CNV amplitude is linked to reduced accuracy for younger adults.

DISCUSSION

The current study sheds new light on the time course of incentive effects on attention and cognitive control in younger and older adults. Behaviorally, incentives led to both transient (trial-level) and sustained (block-level) speed-up effects on RT, with larger transient effects in younger than older adults. However, younger adults were less accurate than older adults on incentive trials and incongruent trials. ERP analyses at the time of the incentive cue showed the same pattern of transient and sustained effects of incentives for P2 amplitude in both age groups. Following the P2, younger adults showed

transient effects, whereas older adults showed sustained effects of incentives for the early negative component and CNV. At the time of the alerting cue, N1 amplitude was larger for younger adults, and showed transient and sustained incentive-related increases in younger adults, but decreases in older adults. At the time of the target, younger adults had larger N1 and P3 amplitudes and continued to show transient and sustained incentive effects, whereas older adults did not show any effects of incentives. We consider each of these results in turn.

Incentive- and Alerting-induced Speed-up Effects Reflect Age Differences in Preparatory Activity and Response Strategies

Consistent with Williams and colleagues (2018), incentives were associated with both transient and sustained speed-up effects. As the transient RT effect was larger for younger adults than for older adults, it appears that incentives were more effective at enhancing trial-level preparatory activity in this age group, albeit at a cost to accuracy. Younger adults also demonstrated greater preparatory activity than older adults by being more sensitive to alerting cues, a finding that aligns with age differences reported in prior literature (e.g., Gamboz et al., 2010; Jennings et al., 2007). Considering that incentive and alerting effects did not interact, this suggests that the different cue types elicit additive rather than interactive effects on preparatory processes in younger adults, promoting faster but less accurate responding.

Compared with younger adults, older adults were slower and more accurate on incongruent and incentive trials. These findings replicate previous reports of age differences in speed-accuracy trade-off settings (e.g., Williams et al., 2018), and they suggest that incentives may cause less interference for older than for younger adults. Incentive cues, either alone or in combination with alerting cues, failed to reduce flanker interference in either age group. This finding suggests that incentive-driven upregulation of cognitive control may be limited to situations in which cues predict target identity or location (e.g., Chiew & Braver, 2016).

Age Differences in Transient versus Sustained Incentive Effects Emerge at Later Stages of Preparatory Control

Replicating previous findings (Schmitt et al., 2015), both age groups showed transient increases in P2 amplitude for incentive versus neutral trials at the time of the incentive cue. The transient effect for older adults was more pronounced at frontocentral relative to centroparietal sites, whereas younger adults had transient effects at both sites, which perhaps reflects greater reliance on frontal attentional resources by older adults. Sustained effects were present for both age groups at both sites. Amplitude was lower for neutral trials embedded in incentive blocks versus

pure blocks, suggesting that in the mixed-block context, greater allocation of attention is directed toward incentive cues versus neutral cues. Importantly, these results indicate that the early, automatic attentional processes associated with incentive cues are preserved with age.

Following the P2, we focused on an early negative component observed during a similar time window as the incentive cue-locked P3 component in Williams and colleagues (2018). It was at this stage of processing that age differences emerged in the form of a dissociation, whereby younger adults showed transient incentive effects and older adults displayed sustained effects. Because of the negative morphology of this component, we suspect this may be an N450 effect. Analogous to the P3, the N450 is involved in cognitive as well as emotional conflict monitoring and detection (Zhu et al., 2018; Ma, Liu, Zhong, Wang, & Chen, 2014). Given that the transient effect in younger adults was represented by attenuated negative amplitude for incentives in relation to mixed-block neutral trials, this may represent more efficient processing and biased detection of incentives by younger adults at this stage in the trial.

For older adults, the presence of sustained but not transient effects suggests that they processed incentives and neutral trials in a similar manner within the mixed-block context. The presence of an N450 component rather than a P3 component during this time window may be because of shorter incentive cue presentation (200 msec vs. 400 msec) than Williams and colleagues (2018) or may be because of participants experiencing a different anticipatory context with the addition of the alerting cue. Consequently, whereas Williams and colleagues (2018) found sustained effects at the time of the incentive cue-P3 for both age groups, there is a lack of a sustained effect for younger adults in the current study at the time of this early negative component. However, we note that in around 600 msec for younger adults in the current study, there is, visually, a graded positive effect that is similar to what was shown for the P3 component for younger adults in the Williams and colleagues (2018) study. Therefore, there may be a shift in the time course because of the addition of the alerting cue.

The age-related dissociation continued late into incentive cue processing during the time window of the CNV component. These results also support greater anticipatory activity by younger adults with larger CNV amplitude for incentive trials, whereas older adults continue to show similar preparatory activity for incentive and neutral trials within the mixed-block context. These results differ from Williams and colleagues (2018), in which both age groups displayed transient effects of incentives for CNV amplitude, but aligns with Schmitt and colleagues (2015) whereby younger adults displayed larger CNV amplitude for loss incentive cues in a design that incorporated a secondary context cue following the incentive cue. Thus, in a dual-cue context, older adults may resort to response strategies that are more likely associated with sustained

preparatory activity to deal with increased processing demands from the combination of incentive and alerting cues.

Following the incentive cue, younger adults had a more prominent alerting effect via N1 amplitude than older adults. Williams and colleagues (2016) found no age differences for ANT cue-locked N1 when incentive information was presented at the block-level, and therefore, the current study's trial-level anticipatory incentive cue context may indirectly exacerbate age differences in the alerting network. Although both age groups showed transient and sustained effects of incentives, younger adults showed a more predictable, graded negative N1 amplitude pattern that scaled with incentives, whereas older adults had a more attenuated effect. Consequently, at the time point of the alerting cue, incentive effects are reduced for older adults compared with younger adults. However, we note that because younger adults showed greater variability than older adults for 4 out of 12 conditions in the ANT cue-locked analysis, these results should be interpreted with caution.

Transient and Sustained Effects of Incentives Are Present during Target Processing for Younger but Not Older Adults and Do Not Enhance Cognitive Control

In support of younger adults showing an enhanced state of preparatory attention throughout the trial, younger adults also had larger N1 amplitude than older adults at the time of the target and showed transient and sustained effects of incentives, whereas at this time point, incentive effects were absent for older adults. Replicating Williams and colleagues (2018), younger adults had larger target-P3 amplitude than older adults. Transient and sustained incentive effects for P3 amplitude were again present only for younger adults. Hence, incentives continued to influence early attentional processes (N1) at the time of the target and later occurring conflict detection processes (P3) for younger adults only. Similar to Williams and colleagues (2016, 2018), older adults showed a typical congruency effect for P3 amplitude, whereas younger adults exhibited similar amplitudes and processing for both trial types. While incentive effects were present for younger adults during target processing, incentives did not improve flanker interference and were instead associated with increased errors. Therefore, the heightened readiness in younger adults associated with incentives and alerting may be hard to counteract when conflict resolution via reactive control is required at the time of the target.

Brain–Behavior Correlations and Implications for Age Differences in Motivated Attention to Incentives

The results of the current study provide greater insight into age differences in the temporal dynamics of incentive

processing. Overall, our results suggests that incentive cues presented at the start of the trial initiate a cascade of heightened motivated preparatory attention in younger adults that interferes with reactive control processing downstream at the time of the target, whereas older adults are less susceptible to these effects. The age difference that emerged at mid-to-late stages of incentive cue processing via CNV amplitude (and the earlier negativity/possible N450 effect), with younger adults showing transient effects and older adults showing sustained effects, was further explored by correlating behavioral incentive effects and CNV amplitude incentive effects. Both age groups exhibited positive correlations between transient RT and transient accuracy effects, indicating that speed-accuracy trade-offs were present in relation to the availability of incentives in mixed blocks. However, only younger adults showed a significant correlation between the transient accuracy effect and the transient CNV effect. This finding provides evidence of a relationship between heightened incentive preparatory processes at the neural level (via the CNV) and lower accuracy in younger adults, and suggests that incentive processing interferes with reactive control in younger but not older adults. In addition, there were no significant brain-behavior correlations for either age group for the sustained effects.

A second modification with respect to age differences in the time course of incentive effects took place at the time of the alerting cue. Younger adults continued to show transient effects of incentives for ANT-cue N1 amplitude, but also showed sustained effects at this point in the time course. Although transient and sustained effects were present for older adults at the time of the alerting cue, they were largely diminished because of a reduced N1 response. We found that there was also a significant speed-accuracy trade-off for younger adults only, represented by a significant correlation of the behavioral alerting effects. There were no significant relationships for either age group between the behavioral alerting effects and the electrophysiological alerting effect represented by ANT-cue N1 amplitude, which may have been because of the more automatic/consistent nature of this response.

Conclusion

Early automatic attentional processes associated with incentives were found to be preserved in older age. Age differences in the temporal dynamics of incentive processing emerged at later stages of the incentive cue, revealing a shift toward transient effects (i.e., trial-level) in younger adults versus sustained effects (block-level) in older adults. Our results support heightened preparatory processing with incentives in younger adults by means of transient effects at the incentive cue, which are followed by a ramping up of sustained effects to accompany transient effects at the time of alerting cue. Incentive effects in older adults began to diminish at the alerting cue and were absent by the time of the target. Transient and sustained

effects of incentives were maintained during target processing for younger adults. Incentives sped up responding in both age groups in both a transient and sustained manner, with a larger transient effect shown in younger adults. Faster responses in younger adults were accompanied by lower accuracy for incentive trials and incongruent trials. In addition, brain-behavior correlations indicated that the larger transient CNV amplitude effect was associated with lower accuracy rates in younger adults only. These results suggest that amplified preparatory processing in younger adults, because of transient effects of incentives, interferes with reactive control processing at the time of the target. Older adults, by contrast, are less vulnerable to the negative effects of incentives on reactive control and engage in strategies that prioritize task performance. Future research should investigate whether the same temporal dynamics persist when predictive task cues are included (e.g., Chiew & Braver, 2016), and if such a context is more conducive to cognitive control benefits across age groups. Importantly, the current study provides novel evidence of when in the time course of incentive processing age difference arise and also the precise nature of these changes.

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Data Statement Availability

Because of institutional restrictions, the raw data cannot be made publicly available. Data may be made available upon request to the corresponding author pending a formal data sharing agreement and ethics approval.

Author Contributions

Margot D. Sullivan: Formal analysis; Visualization; Writing—Original draft; Writing—Review & editing. Farrah Kudus: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Writing—Original draft. Benjamin J. Dyson: Conceptualization; Writing—Review & editing. Julia Spaniol: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were $M(\text{an})/M = .407$, $W(\text{oman})/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows: $M/M = .424$; $W/M = .242$; $M/W = .242$; $W/W = .091$.

Notes

- Upon visual inspection, the ERP component elicited by the incentive cue in the current study, which corresponded to the time window of the incentive cue-P3 component in Williams et al. (2018), was negative rather than positive.
- A slightly earlier window was used for younger adults compared with Williams et al. (2018) because of the morphology of the waveform.
- Levene's Test for Homogeneity of Variance was nonsignificant when comparing younger and older adults' grand means calculated across conditions for both correct RT, $F(1, 48) = 2.77$, $p = .10$, and accuracy, $F(1, 48) = 2.97$, $p = .09$.
- When we conducted this analysis without collapsing across gain and loss trials, the transient effect on RT for losses was significant for younger adults, $p_{\text{BH}} < .001$, but did not reach significance for older adults, $p_{\text{BH}} = .05$.
- For the early negative component, a significant Levene's Test indicated significantly greater variability in younger than older adults, for the centroparietal neutral trial condition only, $F(1, 48) = 6.51$, $p = .014$.
- When we conducted this analysis without collapsing across gain and loss trials, the transient effect of gains on CNV amplitude did not reach significance for younger adults, $p = .09$ (uncorrected), but there was a significant transient effect of losses, $p_{\text{BH}} = .009$. For older adults, before correction, there was a significant sustained effect of gains, $p = .03$; $p_{\text{BH}} = .14$, but the sustained effect of losses did not reach significance, $p = .07$ (uncorrected).
- When we analyzed the ANT cue-N1 analysis without collapsing across gain and loss blocks, younger adults showed significant transient effects for gains and losses, $p_{\text{BH}} = .003$, but for sustained effects only, the effect of gains was significant, $p_{\text{BH}} = .02$, and not losses, $p = .22$ (uncorrected). For older adults, only the transient effect of gains was significant before correction, $p = .03$; $p_{\text{BH}} = .07$, with all other transient and sustained effects not reaching significance, $ps \geq .06$ (uncorrected).
- For ANT cue N1 amplitude, younger adults showed greater variability than older adults for the following conditions, as indicated by significant Levene's Tests: parietal incentive no cue, $F(1, 48) = 7.09$, $p = .011$; occipital incentive no cue, $F(1, 48) = 9.40$, $p = .004$; occipital incentive double cue, $F(1, 48) = 7.49$, $p = .009$; and occipital mixed-block neutral double cue, $F(1, 48) = 6.81$, $p = .012$.
- For target P3 amplitude, older adults showed greater variability than younger adults as indicated by a significant Levene's Test for the centroparietal, mixed-block neutral, incongruent condition only, $F(1, 48) = 6.18$, $p = .016$.

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