

Aging Impairs Reactive Attentional Control but Not Proactive Distractor Inhibition

Andy Jeesu Kim, Joshua Senior, Sonali Chu, and Mara Mather
School of Gerontology, University of Southern California

Older adults tend to be more prone to distraction compared with young adults, and this age-related deficit has been attributed to a deficiency in inhibitory processing. However, recent findings challenge the notion that aging leads to global impairments in inhibition. To reconcile these mixed findings, we investigated how aging modulates multiple mechanisms of attentional control by tracking the timing and direction of eye movements. When engaged in feature-search mode and proactive distractor suppression, older adults made fewer first fixations to the target but inhibited the task-irrelevant salient distractor as effectively as did young adults. However, when engaged in singleton-search mode and required to reactively disengage from the distractor, older adults made significantly more first saccades toward the task-irrelevant salient distractor and showed increased fixation times in orienting to the target, longer dwell times on incorrect saccades, and increased saccadic reaction times compared with young adults. Our findings reveal that aging differently impairs attentional control depending on whether visual search requires proactive distractor suppression or reactive distractor disengagement. Furthermore, our oculomotor measures reveal both age-related deficits and age equivalence in various mechanisms of attention, including goal-directed orienting, selection history, disengagement, and distractor inhibition. These findings help explain why conclusions of age-related declines or age equivalence in mechanisms of attentional control are task specific and reveal that older adults do not exhibit global impairments in mechanisms of inhibition.

Public Significance Statement

It is unclear why some mechanisms of inhibition and attentional control are dysfunctional in aging while others are preserved. By tracking the timing and direction of eye movements in oculomotor visual search tasks, we identified that older adults are more distractible because they are more prone to reflexively orienting to stimuli and less likely to initiate goal-oriented eye movements. Our findings reveal that some mechanisms of attentional control are preserved in aging while others decline which may explain why findings of age-related deficits in the literature are task-specific.

Keywords: aging, inhibition, visual search, distractor suppression, attention capture

Attention is the process that selectively filters incoming sensory information and ultimately determines what is perceived (Desimone & Duncan, 1995). Researchers have categorized mechanisms of attention processing as either goal-directed, in which observers direct their attention in anticipation of a stimulus (Folk et al., 1992; Posner, 1980; Wolfe et al., 1989), or stimulus-driven, in which salient stimuli automatically capture attention even when task-irrelevant (Theeuwes, 1991; Theeuwes et al., 1998). The dorsal and ventral streams of attention are neural networks that not only distinctly coordinate these modes

of attentional control but also interact to reorient attentional resources (Corbetta et al., 2008; Corbetta & Shulman, 2002). More recently, this theoretical dichotomy of attention research was updated to include selection history as a third mechanism of attentional control in which a wide variety of learning experiences could bias attention and thus be experience-driven (Anderson et al., 2021). Interestingly, the neural correlates of experience-driven attention implicate brain structures beyond the traditional dorsal and ventral streams of attention processing (Anderson, 2019; Anderson et al., 2014; Hickey & Peelen,

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Andy Jeesu Kim  <https://orcid.org/0000-0003-1124-0213>

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Correspondence concerning this article should be addressed to Andy Jeesu Kim, School of Gerontology, University of Southern California, 3715 McClintock Avenue, Los Angeles, CA 90089, United States. Email: andyk@usc.edu

2017; Kim & Anderson, 2020a; Serences, 2008; Serences & Saproo, 2010). While the core structures of the frontoparietal attention network are established (Campbell et al., 2012; Grady et al., 2016; Marek & Dosenbach, 2018), the interactions between neural streams of selective attention processing are complex (Vossel et al., 2014) and how these networks are modulated by neurotransmitter activity, including norepinephrine (Corbetta & Shulman, 2002) and dopamine (Anderson et al., 2017), remain unclear.

In neuroimaging studies, older adults show reduced functional connectivity and activation in frontoparietal attention network regions when attempting to downregulate task-irrelevant information (Campbell et al., 2012; Geerligs et al., 2015; Grady et al., 2016; Kennedy & Mather, 2019; Madden, 2007; Nashiro et al., 2017). Consistent with these age differences in the brain networks involved in attentional control, a wide range of behavioral tasks reveal that older adults are indeed more distractible to salient stimuli when required to ignore task-irrelevant information (Kubo-Kawai & Kawai, 2010; Lustig et al., 2007; West & Alain, 2000; Zeef et al., 1996). This age-related increase in distractibility has been attributed to deficiencies in selective attention and theorized to be a function of declines in mechanisms of inhibitory processing (Hasher & Zacks, 1988). In the selective attention literature, older adults are hypothesized to increase prefrontal cortex activity to compensate for age-related declines in inhibitory control, regardless of modality (spatial, feature, object, internal-based; Zanto & Gazzaley, 2016, 2019). When completing tasks modulating spatial selective attention, electroencephalography (EEG) measures reveal increased frontal lobe activity and attenuated sensory processing in older adults compared with younger adults (Curran et al., 2001; Lorenzo-López et al., 2002, 2008; Störmer et al., 2013; Talsma et al., 2006). Furthermore, neuroimaging studies also reveal increased activity in the frontal eye fields (FEFs) and prefrontal cortex in older adults, that extend beyond the activated circuitry of young adults, as a compensatory mechanism to maintain equal performance (Allen & Payne, 2012; Madden, 2007; Piefke et al., 2012; Toepper et al., 2014). In tasks modulating feature selective attention, EEG studies have led to mixed conclusions on whether older adults are able to actively suppress distracting information (Alperin et al., 2013; Gazzaley et al., 2005, 2008; Haring et al., 2013; Zanto et al., 2010), but do demonstrate a consistent poster-to-anterior shift in processing the P300 event-related potential (ERP) component (Alperin et al., 2013; Davis et al., 2008; Haring et al., 2013). Interestingly, steady-state visual-evoked potential studies show that the suppression of the distractor is equal and robust in both young and older adults, indicating that sensory processing of the distractor in the visual cortex is preserved in aging (Quigley et al., 2010; Quigley & Müller, 2014). Lastly, in the attention network test, older adults have demonstrated better efficiency in orienting and inhibitory networks of attention than younger adults while showing impaired efficiency in alerting and executive processing (Gamboz et al., 2010; Mahoney et al., 2010; McDonough et al., 2019; Veríssimo et al., 2022). Although compensatory theories have been proposed to depict how neural networks in older adults adapt to frontal lobe processing deficiencies (Cabeza, 2002; Davis et al., 2008; Kang et al., 2022; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Cappell, 2008), it is still unclear how aging differentially modulates the various mechanisms of selective attention and why age deficits and age equivalence in inhibitory function are task-specific.

Visual search paradigms have been commonly utilized to measure attention capture (Hickey et al., 2009; Kim & Anderson, 2020a, 2020b), and ERP studies have measured covert deployment of attention by the N2pc component (Luck & Hillyard, 1994a, 1994b). Recently, a modified visual search paradigm has been developed to measure active suppression or inhibition of task-irrelevant stimuli (Gaspelin et al., 2015; Jannati et al., 2013; Moher & Egger, 2012). In this paradigm, the target elicits the N2pc component for attention allocation but active suppression of the task-irrelevant distractor elicits a uniquely different P_D component that is separable from mechanisms of attention capture and just ignoring of task-irrelevant nontargets (Hickey et al., 2009; Sawaki & Luck, 2010; Stilwell et al., 2022). This capture-probe paradigm utilizes interspersed memory-probe trials among visual search trials in which participants are asked to recall letters that were overlaid on the shape stimuli in the visual search array (Gaspelin et al., 2015) and requires participants to engage in a feature-specific mode of attentional control (Bacon & Egger, 1994). Interestingly, in this task, participants are less likely to report the probe letter on the task-irrelevant distractor (a unique singleton on that trial) compared to the perceptually matching nontargets, demonstrating an active suppression of attention allocation toward task-irrelevant stimuli even when the stimuli were salient. Furthermore, this mechanism of inhibition has been shown not only to be different from mechanisms of attention capture as indicated by different ERP components but also to override the distractor's attention-capturing properties (Chang & Egger, 2021).

To investigate how aging modulates multiple mechanisms of selective attention, we employed the oculomotor version of the aforementioned visual search paradigm in which participants were required to make eye movements to target stimuli and overtly shift attention (Gaspelin et al., 2017). Visual search requires simultaneous processing of top-down signals from the prefrontal cortex and cortical processing of relevant and task-irrelevant stimuli that is ultimately resolved in the visual cortex (Itti & Koch, 2000; NouNST et al., 2010; Yantis, 1996). With respect to eye movements, goal-directed (top-down) saccades initiated in the pre-frontal cortex and reflexive (bottom-up) saccades are programmed in parallel and the direction of the first saccade measures the outcome of competition (Case & Ferrera, 2007; Nummela & Krauzlis, 2011; Pierrot-Deseilligny et al., 1995; Schall, 1995; Theeuwes et al., 1998). In addition to the absence of memory-probe trials (participants did not have to remember letters overlaid on shapes) and the manual button response that may confound age-dependent comparisons, oculomotor visual search tasks allow the measurement of both top-down and bottom-up processing signals by the timing in which the competition is resolved based on measures of target fixation times, dwell times on incorrect fixations, and saccadic reaction times (sRTs). Furthermore, the direction of the first saccade informs the efficiency of both top-down and bottom-up mechanisms of attentional control. These measures correspond to the initiation, scanning, and verification time for attention processing and the interactions between the dorsal and ventral networks of attention that cannot be distinguished from behavioral response times (Hollingsworth & Bahle, 2020).

In Experiment 1, we investigated how aging modulates mechanisms of inhibition in selective attention, specifically whether older adults maintain the ability to inhibit allocating attentional priority toward salient but task-irrelevant distractors. If older adults are indeed more distractible due to deficiencies in inhibition, the frequency of first-saccade destinations would be greater toward the distractor than toward nontarget stimuli, indicating attention capture. However, if older adults are able to

inhibit attention allocation toward irrelevant information even when it is salient as effectively as do young adults (Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018a, 2018c; Stilwell et al., 2022), the frequency of first saccades toward the distractor would be less than toward a non-target stimuli, demonstrating oculomotor suppression.

Experiment 1

Method

Participants

Twenty-eight young adults (female = 19, male = 9) aged 18–23 inclusive ($M = 20.3$, $SD = 1.5$) were recruited from the University of Southern California (USC) student research participant pool subject pool for course credit. Twenty-eight older adults (female = 18, male = 10) aged 51–79 inclusive ($M = 68.8$, $SD = 7.5$) were recruited from the local Los Angeles communities for monetary compensation. Older adults were screened for cognitive dysfunction using the telescreening protocol and individuals who scored below the cutoff threshold of 16 were excluded from the study (Gatz et al., 1995). All study protocols were approved by the USC Institutional Review Board and all participants provided written, informed consent prior to participation.

Our sample size was based off a power analysis (G*Power 3.1). Our primary question of interest was comparing degree of oculomotor suppression across age groups. To the best of our knowledge, there are no prior findings comparing younger and older adults on this task. We powered our study to be able to detect a large effect size ($d = 0.8$) in a between-subject t -test comparison; this calls for a sample size of 52 total participants (Cohen, 2016). To be conservative in our approach, we recruited 56 total participants.

Apparatus

A custom-built NZXT desktop computer (NZXT, Los Angeles, California, United States) equipped with MATLAB software

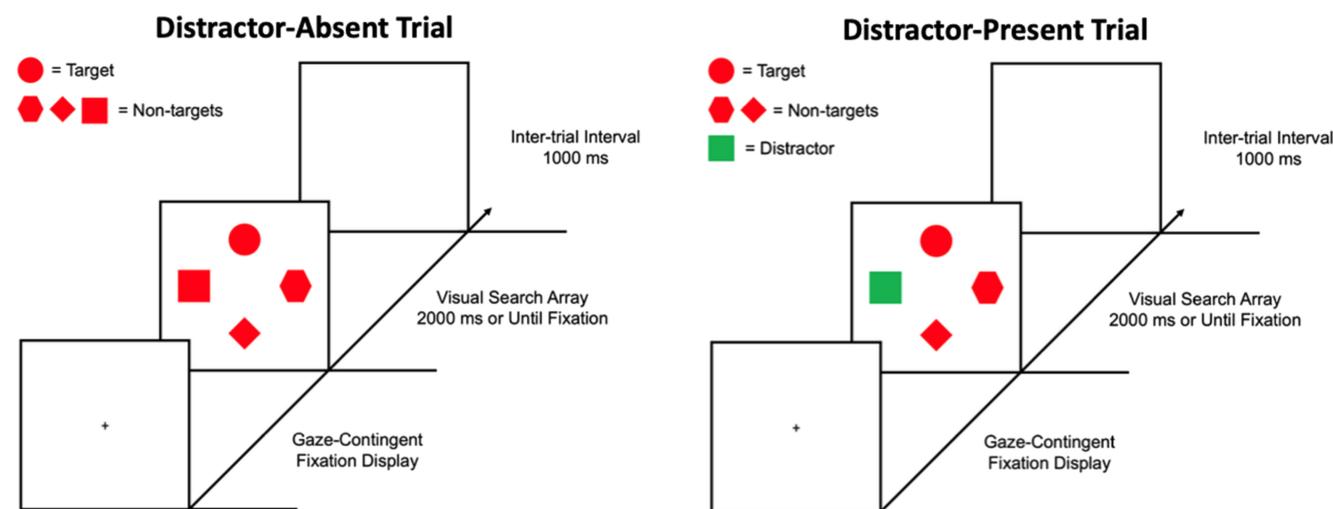
(Mathworks, Natick, Massachusetts, United States) and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Sun Microsystems 4472 (Oracle Corporation, Santa Clara, California, United States) CRT monitor (85 Hz refresh rate). The participants viewed the monitor from 70 cm in a dimly lit, soundproof room. Eye-tracking was conducted using the EyeLink 1000 Plus system (SR Research Ltd., Ottawa, ON, Canada), and head position was maintained using a manufacturer-provided chin rest (SR Research Ltd.).

Stimuli and Task

Each trial consisted of a gaze-contingent fixation display, a visual search array, and an intertrial interval (ITI; see Figure 1). The fixation display consisted of a fixation cross ($0.7^\circ \times 0.7^\circ$ visual angle) at the center of the screen. The fixation display remained on screen until eye position was registered within 1.3° of the center of the fixation cross for a continuous period of 500 ms (Kim & Anderson, 2022). The visual search array was then presented for 2,000 ms or until a fixation on the target was registered. If a target was not fixated within the timeout limit, the words “eye error” would appear in the center of the screen for 500 ms. Lastly, the ITI consisted of a blank screen for 1,000 ms.

The search array consisted of four unique shapes: a circle, diamond, square, and hexagon. In this visual search paradigm, participants were tasked to search for a feature-specific target shape (circle or diamond, counterbalanced across all participants). We utilized a set size of 4 because older adults show age-related declines when visual search is more complex and difficult (Madden et al., 1999; Plude & Doussard-Roosevelt, 1989) and to prevent the floor effect problem (Chang & Egeth, 2021; Stilwell et al., 2022; Wang & Theeuwes, 2020). The length and width of each of the shapes was 4.2° (visual angle), except for the circle with diameter of 4.0° for all shapes to have approximately equal area. Each shape was placed at equal intervals along an imaginary circle with a radius of 9.1° . The color of the

Figure 1
Visual Search Paradigm in Experiment 1



Note. The sequence of events is illustrated in distractor-absent and distractor-present trials. The target shape was counterbalanced across participants to be the diamond or the circle, requiring participants to engage in feature-search mode for this specific shape feature and proactively inhibit the distractor. See the online article for the color version of this figure.

shapes was either red or green. In addition, the color of the distractor on distractor-present trials was counterbalanced across all participants (red distractor among green shapes or green distractor among red shapes).

Design

First, participants completed 20 practice trials to ensure they understood the task instructions. A passing score of 90% accuracy was required to move forward and the practice task would repeat until this threshold was reached. Then, participants completed four runs of 96 trials each for a total of 384 trials. Trials were distractor absent (one target, three nontargets) or distractor present (one target, two nontargets, one distractor) equally often. The target shape (circle or diamond) and the distractor color (red or green) were counterbalanced across participants. On distractor-absent trials, the location of the target was fully counterbalanced. On distractor-present trials, the location of the target and the location of the distractor with respect to the target were fully counterbalanced. Trials were randomized across all participants.

Data Analysis

Eye position was calibrated to each run using five-point calibration and was manually drift corrected online by the experimenter as necessary during the gaze-contingent fixation display (Kim & Anderson, 2022). During the experiment, the *X* and *Y* positions of the eyes were continuously monitored in real time with respect to the four stimulus positions and fixations were recorded during the experiment (fixations to every stimulus on each trial were logged in a variable and output in an excel file at the end of each run; Kim & Anderson, 2020a, 2020b, 2022). The EyeLink 1000 Plus also exported an EDF file after each run that contained both sample information collected at 1,000 Hz and manually encoded event time stamps: presentation of the fixation stimulus, onset of the visual search array, fixation of each stimulus during visual search, and the end of the trial. Fixation of a stimulus was registered if eye position remained within a region extending 1.0° around the stimulus for a continuous period of at least 50 ms for non-targets and distractors and at least 100 ms for the target (Kim & Anderson, 2022). Saccades were defined as a minimum eye velocity threshold of 30° per second and a minimum acceleration threshold of 9,500° per second.

Fixation times are defined as the time measured from the onset of the stimulus array until a valid fixation was registered for the target shape. Fixation times that exceeded three standard deviations of the mean for a given condition for each participant were trimmed (average of 8.6 trials per subject or 0.2% of all trials; Kim & Anderson, 2022). In addition, fixation times less than 50 ms were planned to be excluded as anticipatory saccades, but no trials were actually excluded as anticipatory given the gaze-contingent nature of the paradigm (Gaspelein et al., 2017; Kim & Anderson, 2022; Stilwell et al., 2022). First fixations are defined as the first stimulus that was initially registered as a fixation on each trial. First fixations to the target, nontarget, and distractor stimuli in addition to fixation times were derived from the eye data recorded online during the experiment. Percentage of saccades to the nontarget stimuli were corrected to provide a per-item estimate of fixation; on distractor-absent and distractor-present trials, the percentage of saccades was divided by 3 and 2, respectively. Dwell times were defined as the duration that the eyes remained within the fixation window of the stimulus

and were also recorded online. sRT (also known as saccadic latencies) were computed as the time to initiate a saccade relative to the onset of the visual search array (Kim & Anderson, 2022). sRTs were computed offline from the EyeLink 1000 EDF output using the edfmex MATLAB executable file and the “STARTSACC” code string from the event structure.

All statistical analyses were completed using SPSS (IBM, Armonk, New York, United States). Cohen’s *d* measures of effect sizes were calculated using corrected standard deviations of the mean difference as output by SPSS. Mixed analysis of variance (MANOVA) analyses were conducted with age as a between-subjects factor and all other measures as a within-subjects measure. Post hoc *t*-test analyses were completed using paired sample comparisons for within-subjects measures and independent sample comparisons for between-subjects measures.

Transparency and Openness

Both the oculomotor behavior data from Experiment 1 and the EyeLink EDF outputs collected have been made publicly available at <https://osf.io/g35cs/>. This study was not preregistered.

Results

Accuracy and Fixation Time

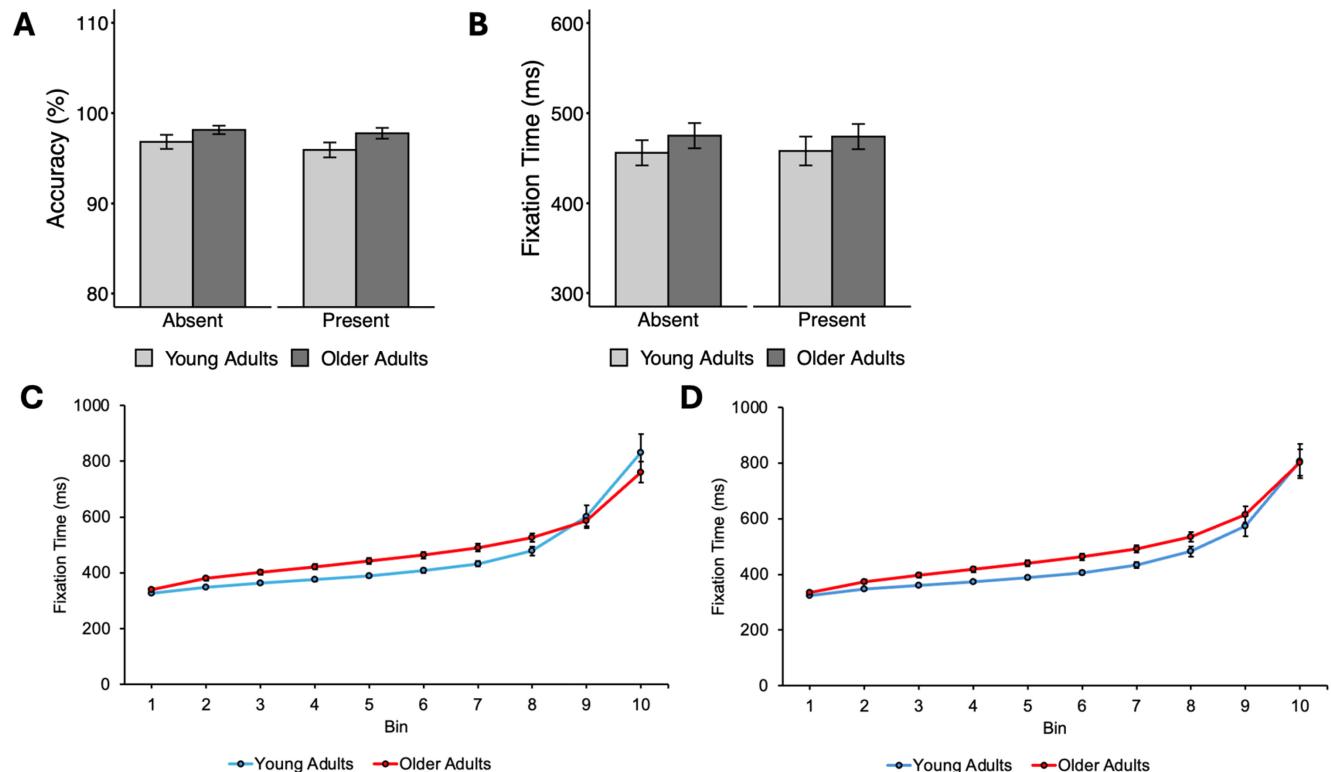
We first investigated whether aging influenced measures of mean accuracy (whether a fixation was made on the target within the time limit) and fixation times to the target. We conducted 2×2 MANOVA analyses over factors age (young vs. older) and distractor presence (absent vs. present). There were no significant effects of age, $F(1, 54) = 3.05, p = .086$; distractor presence, $F(1, 54) = 3.49, p = .067$; nor a significant interaction effect, $F(1, 54) = 0.59, p = .445$ on mean accuracy (see Figure 2A). Likewise, there were no significant effects of age, $F(1, 54) = 0.73, p = .396$; distractor presence, $F(1, 54) = 0.08, p = .777$; nor an interaction effect, $F(1, 54) = 0.23, p = .623$ on fixation times (see Figure 2B). The lack of a distractor presence benefit is consistent with prior findings using a search array set size of 4 (Chang & Eggeth, 2021; Gaspelein et al., 2017; Gaspelein & Luck, 2018a; Stilwell et al., 2022; Wang & Theeuwes, 2020). Given that mean response time is often nonnormally distributed and positively skewed, we examined whether the lack of age differences in fixation time was consistent in the slowest and fastest fixations. We conducted a vincentile analysis by binning fixation times into 10 bins by speed (Kim & Anderson, 2022; Tse et al., 2010), with Bin 1 containing the fastest 10% of saccades and Bin 10 containing the slowest 10% of saccades (see Figure 2C and 2D). As in our results over mean fixation time, we did not find age differences in the fastest (Bin 1) and slowest bin (Bin 10) over distractor-absent trials, $t(54) = 1.80, p = .077$ (Bin 1) and $t(54) = 0.92, p = .360$ (Bin 10), and also over distractor-present trials, $t(54) = 1.32, p = .193$ (Bin 1) and $t(54) = 0.06, p = .950$ (Bin 10).

First-Saccade Destination

The destination of the first saccade measures the outcome of competition between top-down voluntary and bottom-up reflexive saccades programmed in parallel at the onset of the search array. If the first saccade correctly landed on the target item, this indicates a goal-directed saccade and optimal top-down attentional control. We first investigated whether aging modulated goal-directed attentional control on distractor-

Figure 2

No Age Differences in Accuracy and Fixation Time When Searching for a Target Feature



Note. Bar graphs depict age similarities in (A) accuracy and (B) fixation time on distractor-absent and distractor-present trials. Fixation time was also binned by speed in (C) distractor-absent and (D) distractor-present trials (vincentile analyses). Error bars reflect the standard error of the mean. See the online article for the color version of this figure.

absent trials in which there is no competition from the salient task-irrelevant distractor. This measure best evaluates goal-directed attentional control function in the absence of competition from salient bottom-up processing biases. We conducted a 2×2 MANOVA over factors age (young vs. older) and first-saccade destination (target vs. nontargets) and found significant effects of age, $F(1, 54) = 9.09$, $p = .004$, $\eta_p^2 = .144$; first-saccade destination, $F(1, 54) = 1,085.82$, $p < .001$, $\eta_p^2 = .953$; and a significant interaction effect, $F(1, 54) = 9.09$, $p = .004$, $\eta_p^2 = .144$. Post hoc analyses revealed that both young and older adults made significantly more first saccades to the target compared to nontarget stimuli, but that young adults demonstrated more optimal goal-directed attentional control compared with older adults (see Figure 3A and Table 1).

Next, we investigated first-saccade destinations on distractor-present trials. Of particular interest was the frequency of first saccades toward the distractor, demonstrating the initiation of reflexive orienting toward the salient stimuli and overriding goal-oriented top-down biases (Chang & Egeth, 2021). We conducted a 2×3 MANOVA over factors age (young vs. older) and first-saccade destination (target vs. nontargets vs. distractor) and found significant effects of age, $F(1, 54) = 6.47$, $p = .014$, $\eta_p^2 = .107$; first-saccade destination, $F(2, 108) = 920.60$, $p < .001$, $\eta_p^2 = .945$; and a significant interaction effect, $F(2, 108) = 8.28$, $p < .001$, $\eta_p^2 = .133$. Again, post hoc analyses revealed that young adults had more optimal goal-directed attentional control compared with older adults but both young and older adults

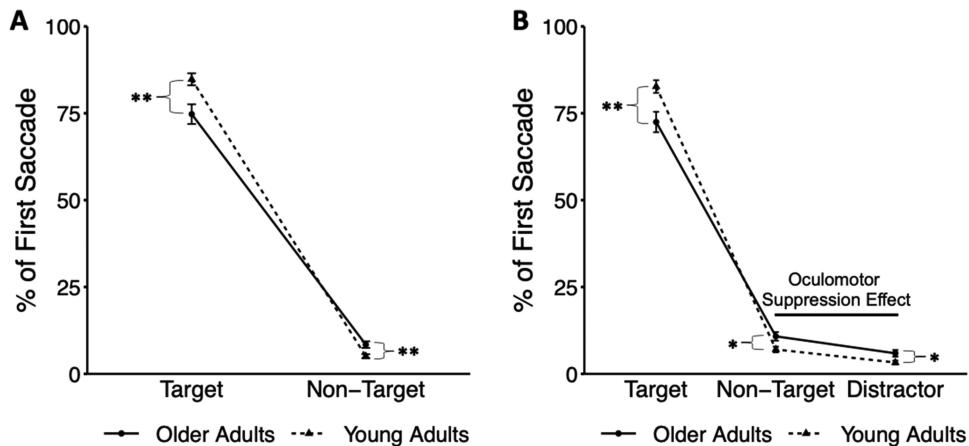
made few first saccades toward the distractor (see Figure 3B and Table 1). To properly evaluate mechanisms of inhibition in selective attention, we calculated the oculomotor suppression effect by subtracting the percentage of first saccades to the distractor from the average nontarget stimuli during distractor-present trials (Gasperlin et al., 2017; Wöstmann et al., 2022). Thus, a positive value would indicate that participants were able to suppress the distractor compared to non-target stimuli (control) while a negative value would indicate attention capture by the distractor. Both young and older adults demonstrated a positive mean oculomotor suppression effect demonstrating preserved mechanisms of inhibition, 3.74% ($SE = 0.90$) and 4.88% ($SE = 1.30$), respectively. Moreover, an independent samples t -test showed that there was no significant difference in the oculomotor suppression effect across age groups, $t(54) = 0.72$, $p = .476$. While there were significant differences between first-saccade destinations to the distractor between age groups, we argue that this general increase in saccades toward non-target and distractor stimuli in older adults is due to reduced first saccades toward the target in this visual search paradigm and the correct assessment of inhibitory control and distractor suppression requires computing the oculomotor suppression effect (Wöstmann et al., 2022).

Dwell Time and Saccadic Reaction Times

Next, we investigated how long participants fixated on an incorrect initial saccade (when the first-saccade destination is not the target), or

Figure 3

While in Feature-Search Mode, Mechanisms of Goal-Directed Attentional Control Decline but Proactive Distractor Suppression Is Preserved in Aging



Note. Line graphs depict age differences in goal-directed attentional control and the oculomotor suppression effect while in feature-search mode and proactive distractor suppression. The plots show percentage of first saccades made to each stimulus on (A) distractor-absent and (B) distractor-present trials. Error bars reflect the standard error of the mean. Asterisks illustrate statistically significant differences between the two age groups. While there were age differences for first saccades to each type of item, there was no significant age difference in the oculomotor suppression effect.

* $p < .05$. ** $p < .01$.

dwell time, as a measure of reactive disengagement and reorienting following an incorrect fixation. Longer dwell times would indicate a prolonged processing requirement of a stimulus until the next saccade is initiated and demonstrates deficiencies in rejecting a stimulus as a non-target stimulus. A 2×2 MANOVA over factors age (young vs. older) and stimuli (nontargets vs. distractors) over dwell time revealed a significant effect of age, $F(1, 50) = 5.34, p = .025, \eta_p^2 = .096$, but no significant effect of stimuli, $F(1, 50) = 0.10, p = .755$, nor an interaction effect, $F(1, 50) = 0.63, p = .430$ (see Figure 4A).

In addition, we investigated mean sRTs or the time to initiate the first saccade from the onset of the visual search array. Mean sRTs measure the time required to resolve competition and determine how long it takes to initiate a reflexive saccade or make a goal-directed saccade after rejecting the reflexive saccade. We analyzed mean sRTs separately by the direction of the initial saccade and evaluated whether the time to initiate a goal-directed or reflexive saccade was modulated by age. Over distractor-absent trials, we conducted a 2×2 MANOVA over factors age (young vs. older) and stimuli (target vs. nontarget) and did not find a significant effect of age, $F(1, 54) = 1.78, p = .188$, but found a significant effect of stimuli, $F(1, 54) = 97.02, p < .001, \eta_p^2 = .642$, and a significant interaction effect, $F(1, 54) = 11.67, p < .001, \eta_p^2 = .178$. Post hoc analyses revealed that both young and older adults had delayed mean sRTs toward the target compared to nontarget stimuli, demonstrating the natural time requirement of processing top-down signals compared with when just initiating reflexive saccades (see Figure 4B and Table 1). However, this processing time was further extended for older adults when the direction of the saccade was toward the target, indicating age-related delays in top-down processing with a longer time requirement to resolve competing neural signals (see Figure 4B and Table 1). Over distractor-present trials, we conducted a 2×3 MANOVA over factors age (young vs. older) and stimuli (target vs. nontarget vs. distractor). Again, we did

not find a significant effect of age, $F(1, 49) = 0.40, p = .530$, but found a significant effect of stimuli, $F(2, 98) = 17.21, p < .001, \eta_p^2 = .260$, and a marginal interaction effect, $F(2, 98) = 2.72, p = .071$. Post hoc analyses mirrored findings in distractor-absent trials (see Figure 4C and Table 1).

Effects of Practice and Learning on Attentional Control

Lastly, we investigated whether mechanisms of goal-directed attentional control and distractor suppression were improved over repeated practice and learning. In distractor-present trials, we calculated the percentage of first saccades to the target and the oculomotor suppression effect for each run among young and older adults. We first conducted a 2×4 ANOVA over age (young vs. older) and run (1, 2, 3, 4) to determine if there were age differences in learning and practice over time. When evaluating goal-directed attentional control by first saccades to the target, there was a significant main effect of age, $F(1, 54) = 8.75, p = .005, \eta_p^2 = .139$, significant main effect of run, $F(3, 162) = 5.29, p = .002, \eta_p^2 = .089$, but no interaction effect, $F(3, 162) = 0.64, p = .591$. Post hoc analyses revealed that, for young adults, first saccades to the target improved from Run 1 to Run 2, $t(27) = 2.13, p = .042, d = .298$, and did not show additional significant improvements over the next runs, $t(27) < 1.61, ps > .120$ (see Figure 5A). In contrast, for older adults, first saccades to the target did not significantly improve from Run 1 in any of the following runs, $t(27) < 1.48, ps > .151$. When evaluating first saccades to the distractor, there was a significant main effect of age, $F(1, 54) = 5.73, p = .020, \eta_p^2 = .096$, but no significant effect of run, $F(3, 162) = 0.46, p = .713$, nor an interaction effect, $F(3, 162) = 0.39, p = .762$ (see Figure 5B). Lastly, when evaluating the oculomotor suppression effect, there were no significant main effects of age, $F(1, 54) = 0.53, p = .472$; run, $F(3, 162) =$

Table 1*Descriptive Statistics and Post Hoc t-Test Analyses for Experiment 1*

| Descriptive statistics | Post hoc t-test analyses | <i>t</i> | <i>p</i> | <i>d</i> |
|--|-------------------------------|----------|----------|----------|
| Accuracy (%) | | | | |
| Young, Abs: $M = 96.8$, $SE = 0.8$ | Interaction not significant | | | |
| Young, Pres: $M = 95.9$, $SE = 0.8$ | | | | |
| Older, Abs: $M = 98.1$, $SE = 0.5$ | | | | |
| Older, Pres: $M = 97.8$, $SE = 0.6$ | | | | |
| Fixation times (ms) | | | | |
| Young, Abs: $M = 456$, $SE = 14$ | Interaction not significant | | | |
| Young, Pres: $M = 458$, $SE = 16$ | | | | |
| Older, Abs: $M = 475$, $SE = 14$ | | | | |
| Older, Pres: $M = 474$, $SE = 14$ | | | | |
| First-saccade destination on distractor-absent trials (%) | | | | |
| Young, Tar: $M = 84.8$, $SE = 1.7$ | Young: Tar versus NonTar*** | 34.64 | <.001 | 13.093 |
| Young, NonTar: $M = 5.1$, $SE = 0.6$ | Older: Tar versus NonTar*** | 17.51 | <.001 | 6.619 |
| Older, Tar: $M = 74.8$, $SE = 2.8$ | Tar: young versus older** | 3.02 | .004 | 0.806 |
| Older, NonTar: $M = 8.4$, $SE = 0.9$ | NonTar: young versus older** | 3.02 | .004 | 0.806 |
| First-saccade destination on distractor-present trials (%) | | | | |
| Young, Tar: $M = 82.7$, $SE = 1.8$ | Young: Tar versus NonTar*** | 29.06 | <.001 | 10.864 |
| Young, NonTar: $M = 7.0$, $SE = 0.8$ | Young: Tar versus Dist*** | 37.65 | <.001 | 12.130 |
| Young, Dist: $M = 3.3$, $SE = 0.5$ | Young: NonTar versus Dist*** | 4.17 | <.001 | 1.014 |
| Older, Tar: $M = 72.5$, $SE = 2.9$ | Older: Tar versus NonTar*** | 14.92 | <.001 | 5.571 |
| Older, NonTar: $M = 10.8$, $SE = 1.2$ | Older: Tar versus Dist*** | 18.53 | <.001 | 6.262 |
| Older, Dist: $M = 5.9$, $SE = 1.0$ | Older: NonTar. versus Dist*** | 3.75 | <.001 | 0.826 |
| Dwell time (ms) | Young: Tar versus older** | 2.96 | .005 | 0.791 |
| Young, NonTar: $M = 144.6$, $SE = 5.7$ | NonTar: young versus older* | 2.54 | .014 | 0.680 |
| Young, Dist: $M = 143.3$, $SE = 9.6$ | Dist: young versus older* | 2.41 | .020 | 0.643 |
| Older, NonTar: $M = 163.3$, $SE = 5.7$ | Interaction not significant | | | |
| Older, Dist: $M = 168.2$, $SE = 8.1$ | | | | |
| Mean saccadic reaction times on distractor-absent trials (ms) | | | | |
| Young, Tar: $M = 247.2$, $SE = 4.0$ | Young: Tar versus NonTar*** | 4.39 | <.001 | 0.634 |
| Young, NonTar: $M = 231.1$, $SE = 5.2$ | Older: Tar versus NonTar*** | 9.76 | <.001 | 0.751 |
| Older, Tar: $M = 268.0$, $SE = 8.6$ | Tar: young versus older* | 2.19 | .033 | 0.584 |
| Older, NonTar: $M = 234.6$, $SE = 7.9$ | NonTar: young versus older | 0.38 | .708 | |
| Mean saccadic reaction times on distractor-present trials (ms) | | | | |
| Young, Tar: $M = 242.9$, $SE = 4.4$ | Young: Tar versus NonTar | 1.48 | .150 | |
| Young, NonTar: $M = 236.0$, $SE = 6.7$ | Young: Tar versus Dist* | 2.72 | .012 | 0.615 |
| Young, Dist: $M = 218.7$, $SE = 8.6$ | Young: NonTar versus Dist | 1.46 | .157 | |
| Older, Tar: $M = 262.2$, $SE = 9.0$ | Older: Tar versus NonTar*** | 8.53 | <.001 | 0.578 |
| Older, NonTar: $M = 234.1$, $SE = 8.1$ | Older: Tar versus Dist*** | 4.53 | <.001 | 0.902 |
| Older, Dist: $M = 216.0$, $SE = 10.4$ | Older: NonTar. versus Dist | 1.99 | .057 | |
| | Tar: young versus older | 1.92 | .060 | |
| | NonTar: young versus older | 0.178 | .860 | |
| | Dist: young versus older | 0.195 | .846 | |

Note. Young = young adults; Abs = distractor-absent trials; Pres = distractor-present trials; older = older adults; Tar = target; NonTar = nontarget; Dist = distractor.

* $p < .05$. ** $p < .01$. *** $p < .001$.

1.09, $p = .356$; nor an interaction effect, $F(3, 162) = 0.10$, $p = .959$ (see Figure 5C).

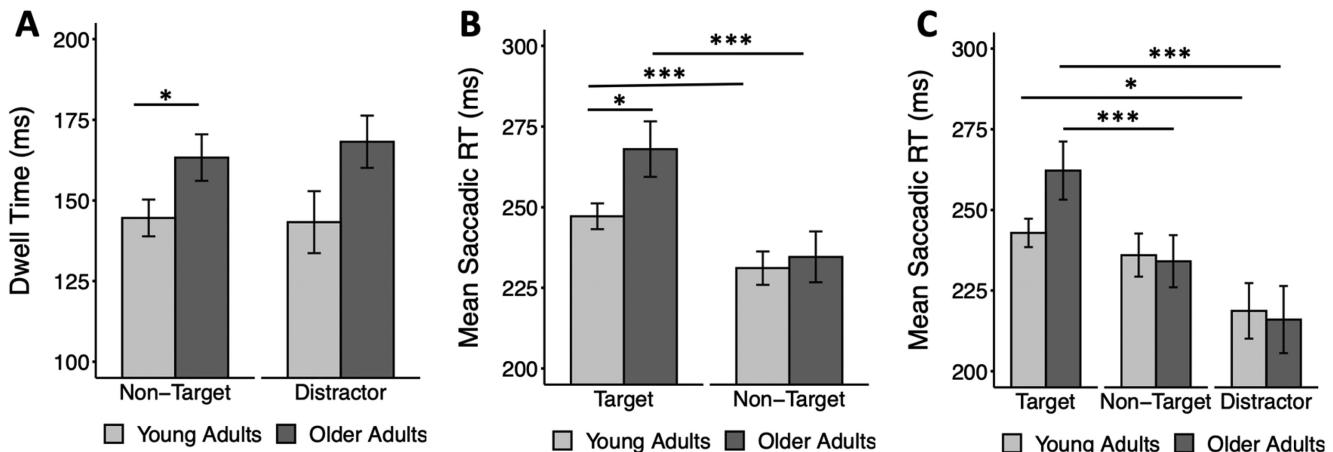
Discussion

In Experiment 1, we investigated whether aging modulated multiple mechanisms of attentional control when engaged in target feature visual search, with particular interest in whether older adults exhibited preserved mechanisms of distractor suppression compared with young adults. First, older adults' goal-directed attentional control was significantly impaired, even on distractor-absent trials in which competing biases from a salient distractor is absent. The mean sRT findings further reveal that older adults had particularly longer processing times

when the direction of the initial saccade was the target, suggesting that delayed processing of top-down information led to competition favoring reflexive orienting to nontarget and distractor stimuli and may also explain why older adults made significantly more first saccades toward nontarget stimuli on distractor-absent trials. Second, we found that older adults had preserved mechanisms of inhibition as measured by the oculomotor suppression effect. Third, we identified that older adults had impaired mechanisms of disengagement as measured by dwell time compared with young adults, indicating a prolonged processing requirement until the next eye movement is initiated. Lastly, repeated practice and learning over time improved goal-directed attentional control in young adults compared with older adults but not for mechanisms of distractor suppression.

Figure 4

While in Feature-Search Mode, Older Adults Were Slower to Disengage From Incorrect Fixations and to Initiate Saccades When Directed Toward the Target



Note. We investigated age differences in (A) dwell time and mean saccadic reaction in (B) distractor-absent trials and (C) distractor-present trials. Error bars reflect standard error of the mean. RT = reaction time.

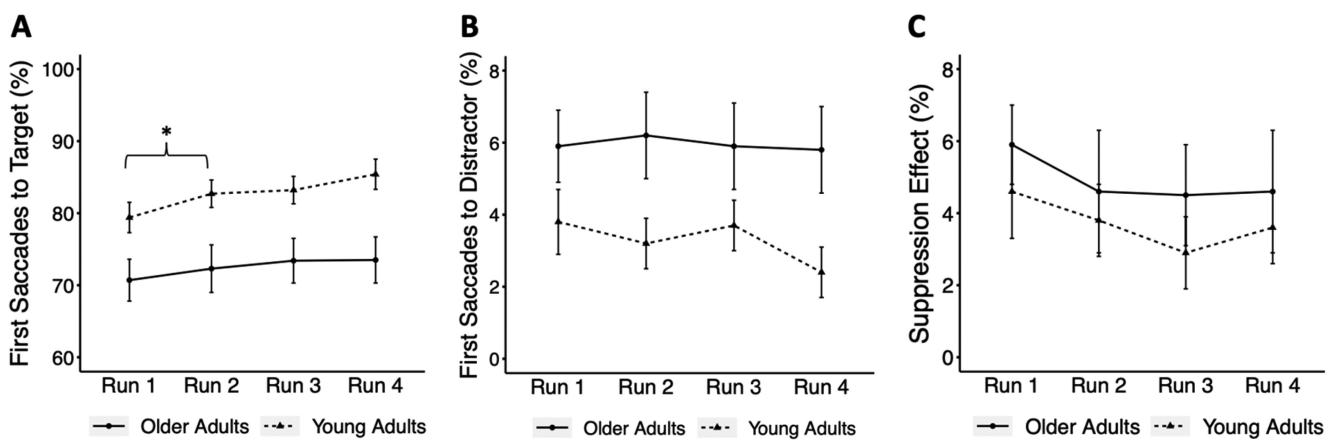
* $p < .05$. *** $p < .001$.

Given the multitude of studies supporting the global inhibitory processing theory in aging (Hasher & Zacks, 1988), we were surprised to find that older adults were able to inhibit attention allocation and suppress reflexive saccades toward a salient task-irrelevant distractor, exhibiting similar levels of oculomotor suppression as young adults. However, one unique component of this visual search paradigm is that the distractor is proactively inhibited prior to stimulus onset. Previous studies have demonstrated that a salient distractor can be proactively inhibited to prevent capture (Cosman et al., 2018; Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018c; Stilwell et al., 2022) by suppressing the saliency signal created from the specific feature (Arita et al., 2012; Sawaki & Luck, 2010; Vatterott et al., 2018). Specifically, this visual search paradigm requires

knowledge of the first-order feature to be suppressed in order for the salient distractor to be proactively inhibited (Vatterott & Vecera, 2012; Won & Geng, 2018), and control experiments further validated that the oculomotor suppression effect only appeared when participants learned the color feature to be suppressed over multiple trials (Gaspelin et al., 2019; Gaspelin & Luck, 2018b). Mechanisms of suppression when proactively inhibiting distractors requires top-down input, but is not dominantly modulated by other mechanisms of attentional control including mismatch detection, disengagement, and bottom-up attentional capture (Geng, 2014). Furthermore, from our findings in Experiment 1, it is unclear whether older adults experience equal bottom-up capture by salient, task-irrelevant distractors compared to young adults. Thus, in Experiment 2, we modified our visual

Figure 5

Both Age Groups Did Not Improve Performance Across Runs



Note. Line graphs depict age differences in the benefits of practice and learning over runs while in feature-search mode. Graphs depict (A) percentage of first saccade destinations to the target, (B) percentage of first saccade destinations to the distractor, and the (C) oculomotor suppression effect in each run of the experiment. Error bars reflect standard error of the mean.

* $p < .05$.

search paradigm to the additional singleton task (Theeuwes, 1991, 1992; Theeuwes et al., 1998) which requires participants to engage in singleton-detection mode and reactively reject salient, task-irrelevant distractors. Importantly, we investigated age differences in oculomotor capture by the salient distractor. If older adults exhibit equal or greater oculomotor capture by the distractor compared to young adults, we would be able to rule out the possibility that older adults' successful suppression in Experiment 1 was due to them experiencing less bottom-up attentional capture by the distractor (saliency signal) and therefore having less need to suppress it.

Experiment 2

In prior studies, visual attention tasks requiring reactive disengagement from a distractor show mixed findings in terms of age differences. In the antisaccade task in which participants are required to suppress a reflexive saccade and initiate an eye movement in the opposite direction, older adults have shown equivalent attention capture compared to young adults but also declines in performance measured by saccade direction accuracy (Butler et al., 1999; Fischer et al., 1997; Munoz et al., 1998; Nieuwenhuis et al., 2000). Interestingly, in abrupt-onset oculomotor visual search tasks, older adults demonstrate age equivalence in capture by the distractor in addition to no differences in dwell times (Cassavaugh et al., 2003; Colcombe et al., 2003; Kramer et al., 1999). However, older adults showed increased distractibility by the distractor in this visual search paradigm when awareness was increased (Kramer et al., 2000) and this age decline in inhibition has been attributed to a decreased ability to disengage rather than from increased attentional priority allocation (Cashdollar et al., 2013). Both antisaccade and prior versions of these oculomotor visual search paradigms utilized abrupt onset of the distractor which shifts competition toward bottom-up processing and does not measure timing between parallel initiation of goal-directed and reflexive saccades (Vecera & Behrman, 2001; Yantis, 1996, 1998). Thus, in Experiment 2, we modified our visual search paradigm to the additional singleton task (Theeuwes, 1991) while keeping the exact visual search design elements as in Experiment 1. The additional singleton task requires reactive disengagement of the distractor in singleton-search mode and presents the target and distractor simultaneously in the visual search array which allows for competition of top-down and bottom-up initiated saccades simultaneously. If deficiencies in inhibitory processing among older adults are due to deficits in mechanisms of reactive inhibition of distractors, our findings should reveal longer fixation times when the distractor is present and increased attention capture by the distractor among older adults than among younger adults. Alternatively, if older adults are not equally captured by the distractor compared with young adults, we predict fewer reflexively oriented saccades to the distractor and an absence of the oculomotor capture effect among older adults. Finally, it is also plausible that we observe equal magnitude of attention capture between age groups indicating that older adults are just as distractible as young adults when engaged in reactive distractor inhibition.

Method

Participants

To match the sample size in Experiment 1, 28 young adults (female = 19, male = 8, prefer not to say = 1) aged 19–30 inclusive ($M = 21.8$, $SD = 2.9$) and 28 older adults (female = 11, male = 6) aged 57–80 inclusive ($M = 70.5$, $SD = 6.4$) were recruited to complete

Experiment 2. We reinvited all older adults who completed Experiment 1 and 15 of the 28 older adults returned. Thirteen older adults were newly recruited and all young adults were newly recruited. All participants provided written, informed consent prior to participation even if they had already completed Experiment 1.

Apparatus

The equipment used in Experiment 2 is identical to that of Experiment 1.

Stimuli and Task

As in Experiment 1, each trial consisted of a gaze-contingent fixation display, a visual search array, and an ITI. The fixation display and ITI are identical to Experiment 1. The visual search array was slightly modified from Kim and Anderson (2022). In brief, participants were tasked to search for the unique shape among the four possible stimuli (one circle among diamonds, or vice versa) and engage in singleton-search mode (see Figure 6). The key difference in Experiment 2 from Experiment 1 is that the nontarget shapes and the distractor are now the same feature shape. Thus, participants cannot simply utilize a specific feature as an attentional template as in Experiment 1, but rather must assess the entire search array to find the target singleton shape and then subsequently reject the distractor if present. In this design, the task-irrelevant salient distractor captures attention due to bottom-up processing and participants cannot proactively suppress the distractor. The size of the circle and diamond in addition to their locations on the screen were identical to Experiment 1. The color of shapes was either red or green.

Design

Participants completed practice trials likewise to Experiment 1. Then, participants completed four runs of 96 trials for a total of 384 trials. Trials were distractor absent (no salient color distractor) or distractor present (one salient color distractor) equally often. The target shape was the circle or diamond equally often and the distractor color (red or green) was counterbalanced across participants. On distractor-absent trials, the location of the target was fully counterbalanced. On distractor-present trials, the location of the target and the location of the distractor with respect to the target were fully counterbalanced. Trials were randomized across all participants.

Data Analysis

Data analysis methods were identical to Experiment 1.

Transparency and Openness

Both the oculomotor behavior data from Experiment 2 and the EyeLink EDF outputs collected have been made publicly available at <https://osf.io/g35cs/>. This study was not preregistered.

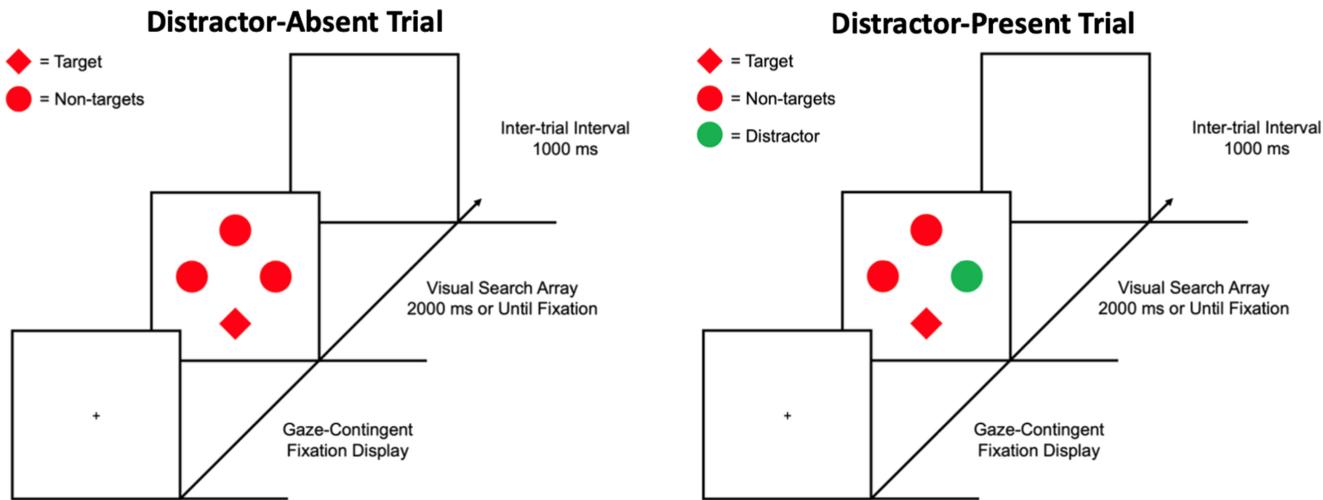
Results

Accuracy and Fixation Time

We conducted a 2×2 MANOVA analysis over factors age (young vs. older) and distractor presence (absent vs. present) on mean accuracy and did not observe a significant effect of age,

Figure 6

Visual Search Paradigm in Experiment 2



Note. The sequence of events is illustrated in distractor-absent and distractor-present trials. The target shape was either the circle or diamond equally often for every participant. See the online article for the color version of this figure.

$F(1, 54) = 1.65, p = .205$, observed a significant effect of distractor presence, $F(1, 54) = 5.12, p = .028, \eta_p^2 = .087$, but did not observe a significant interaction effect, $F(1, 54) = 0.16, p = .688$ (see Figure 7A and Table 2). Using the same MANOVA model with fixation times as the dependent variable revealed a significant effect of age, $F(1, 54) = 27.61, p < .001, \eta_p^2 = .338$; a significant effect of distractor presence, $F(1, 54) = 162.92, p < .001, \eta_p^2 = .751$; and a significant interaction effect, $F(1, 54) = 22.54, p < .001, \eta_p^2 = .294$ (see Figure 7B). Post hoc *t*-test analyses revealed that the presence of the distractor delayed fixation times in both age groups but that the distractor presence deficit was significantly worse in older adults (see Figure 7B and Table 2). Given that slower fixation times are commonly observed to have greater variability, we investigated whether the interaction effect holds when normalizing speeded performance between age groups. When removing the slowest 15% of fixation times in older adults to match the slowest fixation times between young and older adults (see Figure 7D for reference), a MANOVA analysis still revealed a significant distractor presence by age interaction, $F(1, 54) = 17.54, p < .001, \eta_p^2 = .294$. However, this comparison still revealed significant age differences in fixation time over distractor-absent trials. Therefore, we further verified if the distractor presence deficit was worse in older adults by matching mean fixation times in distractor-absent trials and then examined whether older adults had significantly slower fixation times in distractor-present trials. For this aim, we removed the slowest 35% of fixation times in older adults in both distractor-absent and distractor-present trials to match mean fixation times in distractor-absent trials across both age groups (see Figure 7C). The identical MANOVA analyses revealed a significant main effect of distractor presence, $F(1, 54) = 145.29, p < .001, \eta_p^2 = .729$, no main effect of age, $F(1, 54) = 3.46, p = .068$, but again identified a significant interaction, $F(1, 54) = 8.55, p = .005, \eta_p^2 = .137$. Independent samples *t*-test analyses showed no age group differences over distractor-absent trials, $t(54) = 1.30, p = .198$, but revealed a significant age difference over distractor-present trials, $t(54) = 2.27, p = .027$,

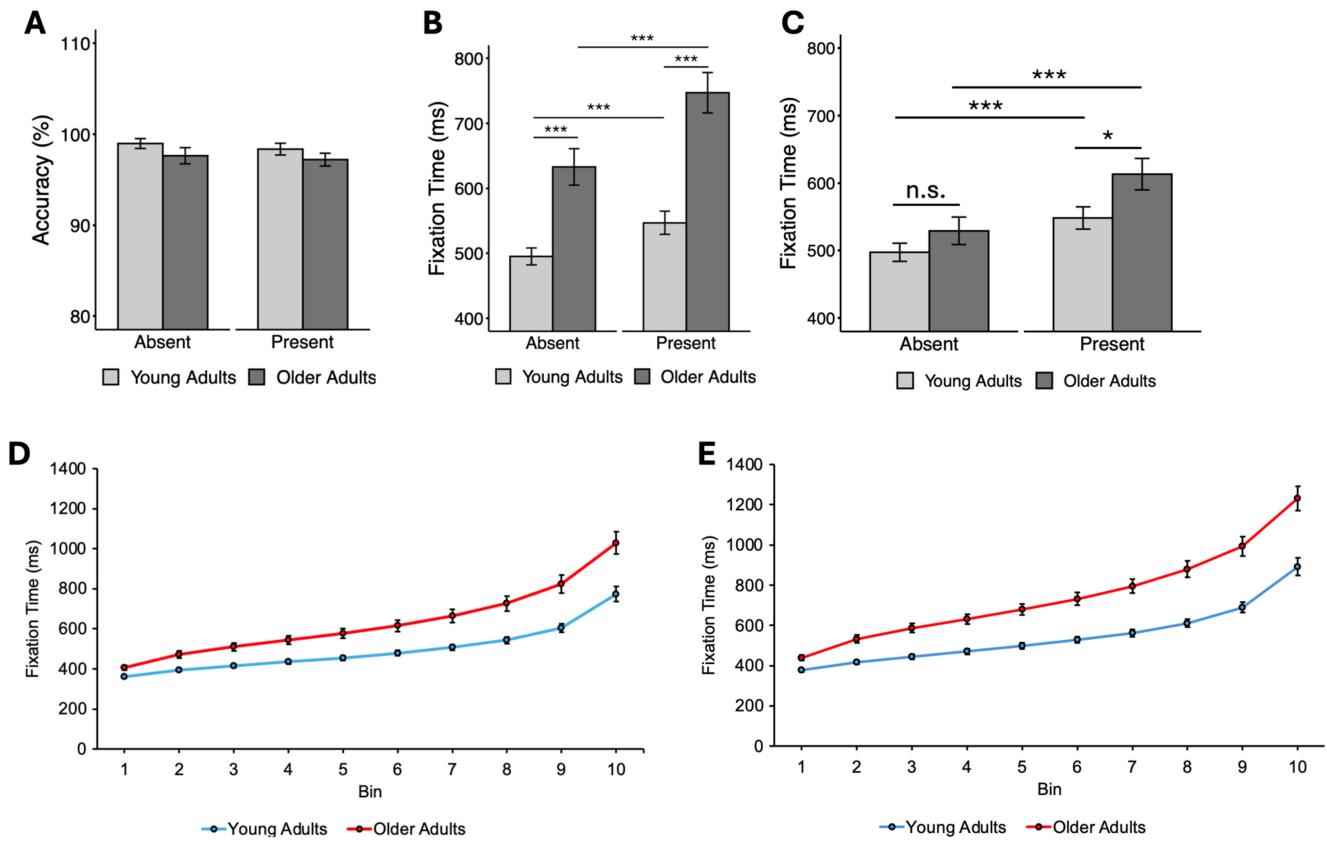
$d = 0.608$. Lastly, as in Experiment 1, we examined whether the lack of age differences in fixation time was consistent in the slowest and fastest fixations by conducting a vincentile analysis. In our visual search paradigms, the fastest bins contain reflexive saccades and the slowest bins are comprised of mainly goal-oriented saccades. As in our results over mean fixation time, we identified significant age differences in the fastest (Bin 1) and slowest bin (Bin 10) over distractor-absent trials, $t(54) = 3.34, p = .002, d = 1.004$ (Bin 1) and $t(54) = 3.81, p < .001, d = 1.109$ (Bin 10), and also over distractor-present trials, $t(54) = 4.15, p < .001, d = 0.893$ (Bin 1) and $t(54) = 4.53, p < .001, d = 1.193$ (Bin 10).

First-Saccade Destination

Like in Experiment 1, we investigated first-saccade destinations in distractor-absent trials to investigate whether aging modulated goal-directed control in contexts without competing bottom-up biases from the salient distractor. We conducted a 2×2 MANOVA over factors age (young vs. older) and first-saccade destination (target vs. nontargets) and found a significant effect of age, $F(1, 54) = 8.56, p = .005, \eta_p^2 = .137$; first-saccade destination, $F(1, 54) = 1,263.79, p < .001, \eta_p^2 = .959$; and interaction effect, $F(1, 54) = 8.56, p = .005, \eta_p^2 = .137$ (see Figure 8A and Table 2). Our findings mirrored those in Experiment 1 in which young adults made significantly more first saccades to the target compared to older adults (see Table 2). For distractor-present trials, we conducted a 2×3 MANOVA with factors age (young vs. older) and first-saccade destination (target vs. nontargets vs. distractor) and found a significant effect of age, $F(1, 54) = 6.01, p = .018, \eta_p^2 = .100$; first-saccade destination, $F(2, 108) = 203.21, p < .001, \eta_p^2 = .790$; and an interaction effect, $F(2, 108) = 12.39, p < .001, \eta_p^2 = .187$ (see Figure 8B). Post hoc analyses revealed that older adults made significantly fewer first saccades toward the target and initiated more reflexive saccades toward the distractor rather than nontarget stimuli (see Figure 8B and Table 2).

Figure 7

Older Adults Exhibited Slower Fixation Times When Engaged in Singleton Search and the Distractor Presence Deficit Was Significantly Worse



Note. Bar graphs depict age differences in (A) accuracy and (B) fixation time on distractor-absent and distractor-present trials while in singleton-search mode. (C) When removing the slowest 35% of fixation times in older adults to match mean fixation times over distractor-absent trials, the Age \times Distractor Presence interaction still holds. Fixation times were also binned by speed in (D) distractor-absent and (E) distractor-present trials (vincentile analyses). Error bars reflect the standard error of the mean. n.s. = not significant. See the online article for the color version of this figure.

* $p < .05$. *** $p < .001$.

Furthermore, we identified an oculomotor capture effect in both young and older adults when required to reactively disengage from the salient distractor. The oculomotor capture effect was computed by subtracting the percentage of first saccades to the distractor from the average nontarget stimuli in distractor-present trials. Again, a negative value would indicate attention capture by the salient distractor. The mean oculomotor capture effect was -14.0% ($SE = 1.9$) for young adults and -22.1% ($SE = 2.9$) for older adults. An independent samples t -test revealed a significant difference between age groups, $t(54) = 2.34$, $p = .023$, $d = 0.625$, demonstrating that older adults were significantly worse in inhibiting attention capture by the salient, task-irrelevant distractor when reactively disengaging.

Dwell Time and Saccadic Reaction Times

To further investigate whether delayed fixation times in both young and older adults are due to deficiencies in disengagement, we investigated how long initial incorrect fixations were made until a subsequent saccade was initiated. A 2×2 MANOVA over factors age (young vs. older) and stimuli (nontargets vs. distractor) over dwell time revealed a

significant effect of age, $F(1, 54) = 10.38$, $p = .002$, $\eta_p^2 = .161$; stimuli, $F(1, 54) = 20.33$, $p < .001$, $\eta_p^2 = .273$; and interaction effect, $F(1, 54) = 7.35$, $p = .009$, $\eta_p^2 = .120$ (see Figure 9A). Post hoc analyses revealed that older adults had longer dwell times in general compared with young adults over all stimuli, but this deficiency was exacerbated when the initial saccade was toward the distractor indicating that older adults were significantly worse at reactively disengaging when the stimulus was salient (see Figure 9A and Table 2).

We also investigated whether aging modulated mean sRTs when required to reactively reject the distractor, or the time to resolve competition and initiate a saccade. Over distractor-absent trials, we conducted a 2×2 MANOVA over factors age (young vs. older) and stimuli (target vs. nontarget) and found a significant effect of age, $F(1, 54) = 4.28$, $p = .043$, $\eta_p^2 = .073$, stimuli, $F(1, 54) = 16.56$, $p < .001$, $\eta_p^2 = .235$, but no interaction effect, $F(1, 54) = 0.19$, $p = .668$ (see Figure 9B). Post hoc analyses revealed that mean sRTs were again delayed in both young and older adults as in Experiment 1, and that older adults had significantly more delayed sRTs when the initial saccade was toward the target (see Figure 9B and Table 2). Over distractor-present trials, we conducted a 2×3

Table 2*Descriptive Statistics and Post Hoc t-Test Analyses for Experiment 2*

| Descriptive statistics | Post hoc t-test analyses | t | p | d |
|--|---------------------------------|-------|-------|-------|
| Accuracy (%) | Interaction not significant | | | |
| Young, Abs: $M = 99.0$, $SE = 0.5$ | | | | |
| Young, Pres: $M = 98.4$, $SE = 0.7$ | | | | |
| Older, Abs: $M = 97.6$, $SE = 0.9$ | | | | |
| Older, Pres: $M = 97.2$, $SE = 0.7$ | | | | |
| Fixation times (ms) | | | | |
| Young, Abs: $M = 495$, $SE = 13$ | Young: absent versus present*** | 7.85 | <.001 | 0.564 |
| Young, Pres: $M = 547$, $SE = 16$ | Older: absent versus present*** | 10.18 | <.001 | 0.716 |
| Older, Abs: $M = 633$, $SE = 27$ | Absent: young versus older*** | 4.52 | <.001 | 1.208 |
| Older, Pres: $M = 747$, $SE = 30$ | Present: young versus older*** | 5.72 | <.001 | 1.529 |
| First-saccade destination on distractor-absent trials (%) | | | | |
| Young, Tar: $M = 83.6$, $SE = 1.9$ | Young: Tar versus NonTar*** | 30.69 | <.001 | 11.60 |
| Young, NonTar: $M = 5.5$, $SE = 0.6$ | Older: Tar versus NonTar*** | 20.94 | <.001 | 7.91 |
| Older, Tar: $M = 74.7$, $SE = 2.4$ | Tar: young versus older** | 2.93 | .005 | 0.782 |
| Older, NonTar: $M = 8.4$, $SE = 0.8$ | NonTar: young versus older** | 2.93 | .005 | 0.782 |
| First-saccade destination on distractor-present trials (%) | | | | |
| Young, Tar: $M = 68.7$, $SE = 2.3$ | Young: Tar versus NonTar*** | 22.93 | <.001 | 7.73 |
| Young, NonTar: $M = 5.8$, $SE = 0.6$ | Young: Tar versus Dist*** | 12.10 | <.001 | 4.39 |
| Young, Dist: $M = 19.8$, $SE = 1.9$ | Young: NonTar versus Dist*** | 7.23 | <.001 | 1.86 |
| Older, Tar: $M = 53.0$, $SE = 3.4$ | Older: Tar versus NonTar*** | 11.32 | <.001 | 3.78 |
| Older, NonTar: $M = 8.3$, $SE = 0.8$ | Older: Tar versus Dist*** | 3.70 | <.001 | 1.36 |
| Older, Dist: $M = 30.4$, $SE = 2.9$ | Older: NonTar. versus Dist*** | 7.66 | <.001 | 1.95 |
| Dwell time (ms) | Tar: young versus older*** | 3.80 | <.001 | 1.016 |
| Young, NonTar: $M = 183$, $SE = 5.2$ | NonTar: young versus older* | 2.45 | .018 | 0.655 |
| Young, Dist: $M = 191$, $SE = 7.1$ | Dist: young versus older** | 3.13 | .003 | 0.835 |
| Older, NonTar: $M = 203$, $SE = 7.5$ | | | | |
| Older, Dist: $M = 234$, $SE = 9.6$ | Young: Nontar versus Dist | 1.63 | .115 | |
| Mean saccadic reaction times on distractor-absent trials (ms) | Older: Nontar versus Dist*** | 4.33 | <.001 | 0.657 |
| Young, Tar: $M = 309.2$, $SE = 9.8$ | Nontar: young versus older* | 2.17 | .035 | 0.580 |
| Young, NonTar: $M = 276.1$, $SE = 9.1$ | Dist: young versus older*** | 3.59 | <.001 | 0.960 |
| Older, Tar: $M = 349.3$, $SE = 16.5$ | | | | |
| Older, NonTar: $M = 322.6$, $SE = 23.1$ | Young: Tar versus NonTar*** | 4.66 | <.001 | 0.659 |
| Mean saccadic reaction times on distractor-present trials (ms) | Older: Tar versus NonTar* | 2.08 | .047 | 0.223 |
| Young, Tar: $M = 321.0$, $SE = 12.7$ | Tar: young versus older* | 2.09 | .041 | 0.559 |
| Young, NonTar: $M = 312.1$, $SE = 17.0$ | NonTar: young versus older | 1.87 | .066 | |
| Young, Dist: $M = 270.0$, $SE = 7.7$ | | | | |
| Older, Tar: $M = 367.3$, $SE = 20.3$ | Young: Tar versus NonTar | 1.05 | .302 | |
| Older, NonTar: $M = 331.1$, $SE = 18.4$ | Young: Tar versus Dist*** | 6.28 | <.001 | 0.770 |
| Older, Dist: $M = 325.2$, $SE = 18.5$ | Young: NonTar versus Dist** | 3.29 | .003 | 0.485 |
| | Older: Tar versus NonTar*** | 3.67 | .001 | 0.348 |
| | Older: Tar versus Dist*** | 6.03 | <.001 | 0.397 |
| | Older: NonTar. versus Dist | 0.53 | .600 | |
| | Tar: young versus older | 1.93 | .059 | |
| | NonTar: young versus older | 0.76 | .452 | |
| | Dist: young versus older** | 2.78 | .007 | 0.743 |

Note. Young = young adults; Abs = distractor-absent trials; Pres = distractor-present trials; older = older adults; Tar = target; NonTar = nontarget; Dist = distractor.

* $p < .05$. ** $p < .01$. *** $p < .001$.

MANOVA over factors age (young vs. older) and stimuli (target vs. nontarget vs. distractor) and found a marginal effect of age, $F(1, 54) = 3.45$, $p = .069$; a significant effect of stimuli, $F(2, 108) = 22.81$, $p < .001$, $\eta^2_p = .297$; and an interaction effect, $F(2, 108) = 3.84$, $p = .026$, $\eta^2_p = .065$ (see Figure 9C). Contrary to findings in distractor-absent trials, mean sRTs were significantly delayed in older adults when the saccade was toward the distractor (see Figure 9C and Table 2).

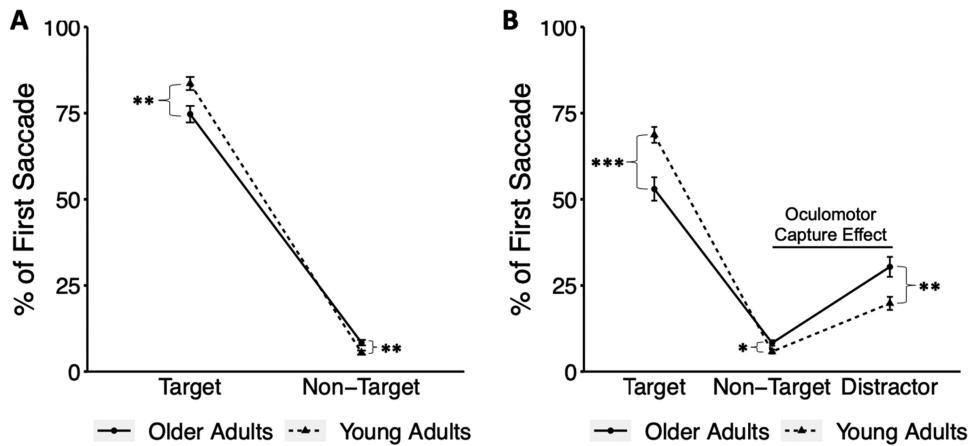
Longitudinal Changes in Attention Capture

Next, we investigated whether attention capture by the distractor was modulated over repeated learning in both age groups. In

distractor-present trials, we calculated the percentage of first saccades to the distractor for each run among young and older adults. We conducted a 2×4 ANOVA over age (young vs. older) and run (1, 2, 3, 4) over first-saccade destinations to the distractor and found a significant effect of age, $F(1, 54) = 9.77$, $p = .003$, $\eta^2_p = .153$, and run, $F(3, 162) = 3.82$, $p = .011$, $\eta^2_p = .066$, but no interaction effect, $F(3, 162) = 0.72$, $p = .540$ (see Figure 9D). Young adults became more distracted in Run 2 compared with Run 1, $t(27) = 2.63$, $p = .014$, $d = 0.357$, but Runs 3 and 4 were not significantly different than Run 1, $t_{s}(27) < 1.83$, $ps > .078$ (see Figure 9D). In contrast, older adults had no significant changes in attention capture by the distractor in Runs 1–3, $t_{s}(27) < 1.32$, $ps > .199$, but were significantly less captured by the distractor

Figure 8

While in Singleton-Search Mode, Mechanisms of Goal-Directed Attentional Control Decline and Distractibility Are Increased Among Older Adults



Note. Line graphs depict age differences in goal-directed attentional control and attention capture by the salient, task-irrelevant distractor when engaging in reactive distractor rejection. Line graphs depict the percentage of first saccades made to each stimulus on (A) distractor-absent and (B) distractor-present trials. Error bars reflect the standard error of the mean. Asterisks illustrate significant differences between the two age groups.

* $p < .05$. ** $p < .01$. *** $p < .001$.

in Run 4 compared with Run 3, $t(27) = 2.38$, $p = .025$, $d = 0.235$ (see Figure 9D).

Selection History (Intertrial Priming)

Given that older adults performed more poorly in Experiment 2 compared to Experiment 1, we investigated the plausibility for experience-driven effects (selection history) to be more negatively impacting older adults and thus a potential source for age-related deficits seen in fixation time. Since the target shape can switch trial-to-trial in Experiment 2, we evaluated whether intertrial priming effects were equally modulating young and older adults by examining repeat (identical target shape) and switch (different target shape) trials (1-back). Over our primary oculomotor measures (fixation time and first saccade direction) in both distractor absent and present trials, we found significant main effects of trial type (repeat vs. switch), $F_s > 40.52$, $ps < .001$, but no interaction between trial type and age, $F_s < 0.85$, $ps > .362$ (see Figure 10). These findings indicate that experience-driven attention (switch cost) did not differ between young and older adults and that differences in intertrial priming is not contributing to the age-related slowing observed in Experiment 2.

Age-Related Trends Within Older Adult Cohorts in Both Experiments 1 and 2

The older adult participants we recruited for this study incorporated a wide age range (51–79 years old in Experiment 1 and 57–80 years old in Experiment 2). Thus, we investigated whether trends in age-related decline were observable even within our older adult samples. When correlating acquired oculomotor measures with age, we found that first saccade to target (%) showed a marginal negative correlation with age indicating that goal-directed attentional control steadily decreases with increasing age (see Figure 11C, 11D, 11H, and 11I).

Furthermore, we found that fixation time in Experiment 2 demonstrated a significant positive correlation with age (see Figure 11F and 11G). However, we did not observe significant relationships between fixation time in Experiment 1 (Figure 11A and 11B) nor the oculomotor suppression and capture effects (Figure 11E and 11J) with age.

Older Adults Who Completed Both Studies

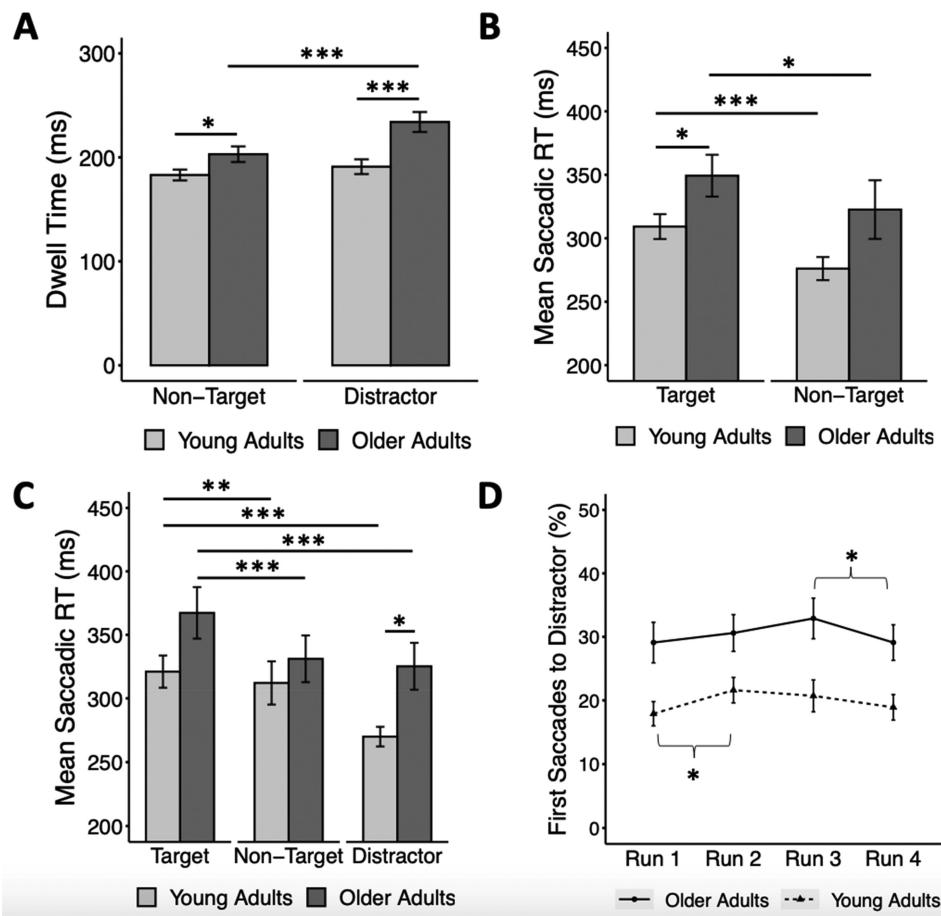
Since we had 15 older adults who completed both Experiments 1 and 2, we specifically measured whether these participants exhibited an oculomotor capture effect by the salient distractor in Experiment 2, in addition to an oculomotor suppression effect in Experiment 1. This would demonstrate that the observed oculomotor suppression effect can occur in older adults even in the presence of a bottom-up saliency signal within this group. These older adults demonstrated a significant oculomotor capture effect in Experiment 2, $t(14) = 5.75$, $p < .001$, $d = 1.484$, and a significant oculomotor suppression effect in Experiment 1, $t(14) = 3.49$, $p = .004$, $d = 0.900$. Furthermore, we compared measures between the two groups of older adults (completed both experiments vs. newly recruited for Experiment 2) to ensure that there were no differences between subset of older adults. Between older adult groups, there was no difference over the critical measures including the oculomotor capture effect, goal-directed attentional control measured by first fixations to the target, and distractor presence deficit measured by fixation times, $ts < 0.80$, $ps > .441$.

Discussion

In Experiment 2, we investigated how aging modulated multiple mechanisms of attentional control when participants were required to reactively disengage from a salient, task-irrelevant distractor. Our findings reveal that older adults demonstrated significantly more attention capture by the salient distractor compared with young adults as assessed by first-saccade destinations to the distractor. Furthermore,

Figure 9

While in Singleton-Search Mode, Older Adults Were Slower to Disengage From Incorrect Fixations and to Initiate Saccades



Note. These effects were exacerbated when the stimulus was the distractor. We investigated age differences in (A) dwell time, mean saccadic reaction times in (B) distractor-absent and (C) distractor-present trials, and attention capture by the salient, task-irrelevant distractor over each run. Error bars reflect the standard error of the mean. RT = reaction time.

* $p < .05$. ** $p < .01$. *** $p < .001$.

the presence of the distractor increased fixation times more in older adults than in young adults. This prolonged delay can be attributed to slower processing speeds among older adults as seen in the following measures. First, older adults had significantly increased dwell times compared with young adults demonstrating deficiencies in disengagement, and this difference was more evident when the stimulus was a distractor. Furthermore, contrary to Experiment 1, older adults had significantly longer sRTs when the direction of the saccade was the distractor. Even initiating a reflexive saccade toward the distractor required processing of competition between top-down and bottom-up attentional control mechanisms and this delay in older adults may be due to increased attention priority allocation toward the distractor or longer processing of suppressive feedback mechanisms toward the visual cortex. Interestingly, the longer processing time does not seem to benefit initiation of goal-oriented saccades instead of reflexive saccades in older adults. Lastly, as in Experiment 1, we identified deficiencies in goal-directed attentional control in older adults with

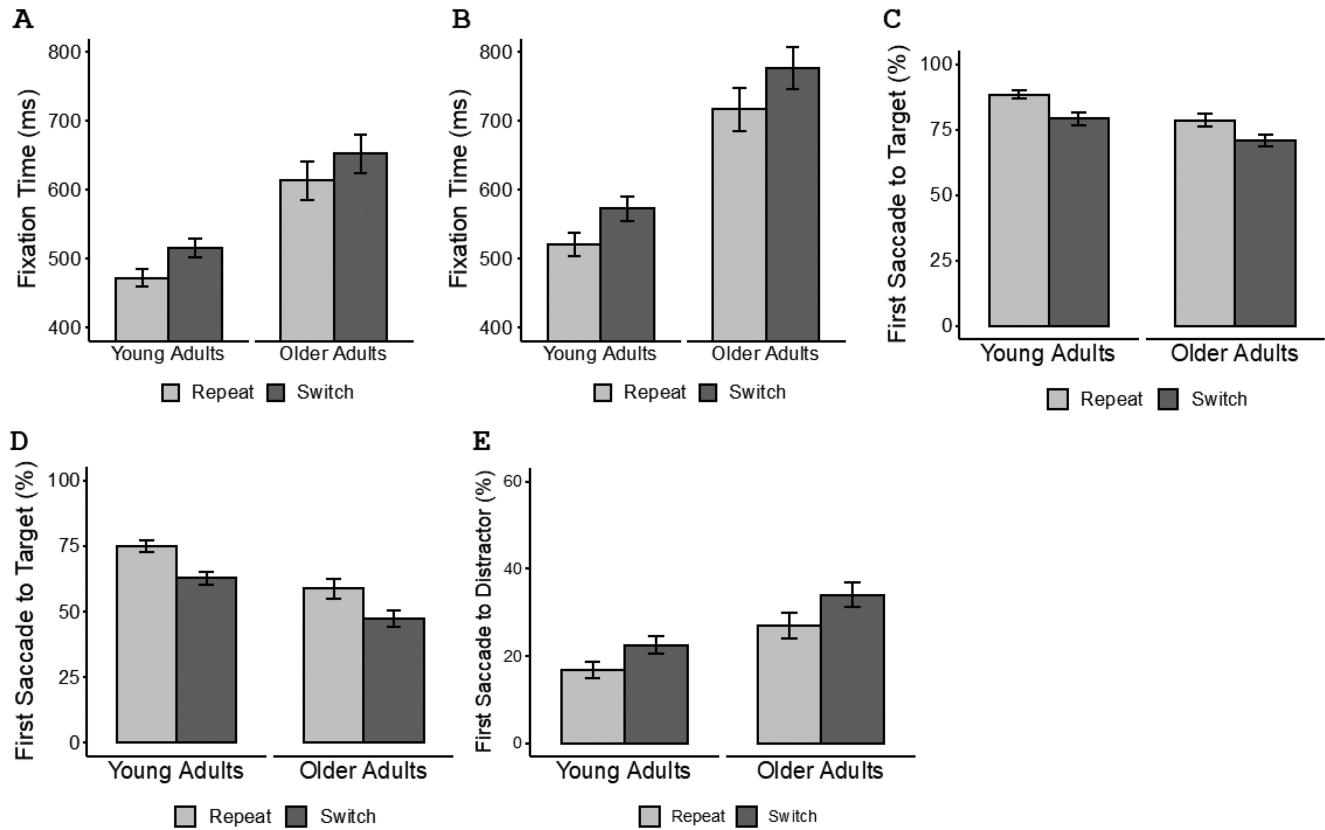
decreased first-saccade destinations to the target, even on distractor-absent trials.

General Discussion

Given the similarity in design and stimuli, the combined findings from both experiments reveal that effects of aging on attentional control depend on the specific mechanisms involved (see Table 3). These divergent findings give insight into why age-related deficits or age equivalence are often found to be task-specific and offer the possibility for accurate hypothesis in future research depending on which mechanisms is incorporated in each task. However, a common finding in both experiments was that older adults showed deficiencies in goal-directed attentional control on distractor-absent trials. Even in the absence of bottom-up competing biases (as in distractor-present trials), older adults made significantly fewer goal-oriented saccades to the target. These findings suggest that the deficiencies in goal-directed attentional

Figure 10

Effects of Selection History (Intertrial Priming) Are Not Contributing to the Age-Related Slowing Observed in Experiment 2

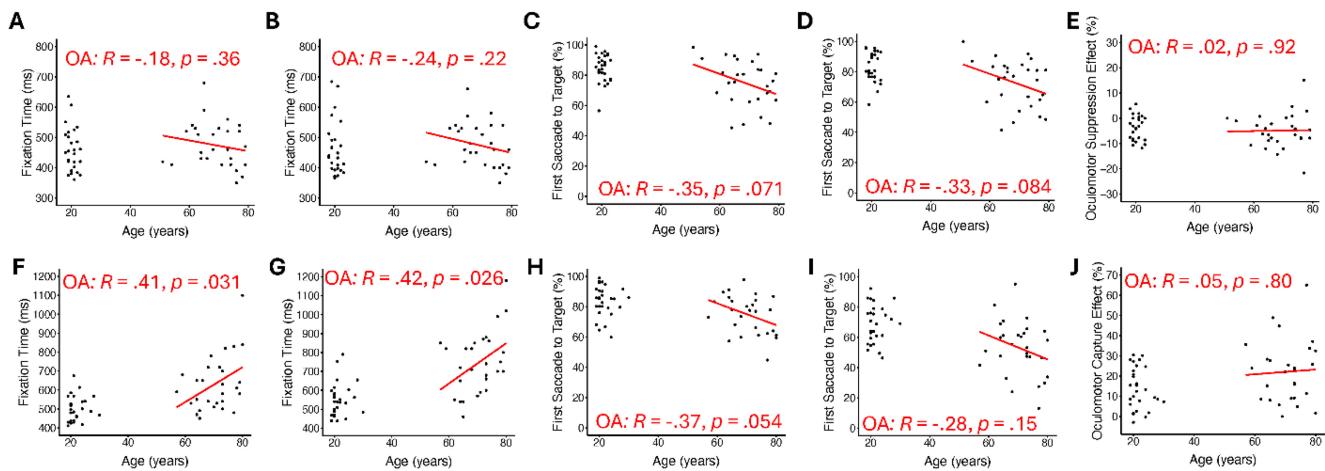


Note. The performance cost on switch trials (the target shape switched from the previous trial) compared with repeat trials (identical target shape from the previous trial) was not exacerbated in older adults over fixation time on (A) distractor-absent trials and (B) distractor-present trials, in addition to first-saccade destinations on (C) distractor-absent trials and (D-E) distractor-present trials. Error bars reflect the standard error of the mean.

control from this measure are not due to deficits in integrating inputs from top-down and bottom-up signals in regions like the FEFs, but may rather be from deficits in neural regions in where goal-directed eye movements are initiated such as the dorsolateral prefrontal cortex (Pierrot-Deseilligny et al., 1995; Schall, 1995; Schall & Hanes, 1993), which is also involved in suppressing unwanted reflex-like oculomotor activity (Guitton et al., 1985). Despite this evident deficiency in top-down attentional control, we identified that older adults were still able to suppress orienting to the distractor when engaged in proactive inhibition. Proactive inhibition is a learned attentional control setting in which the brain repeatedly downregulates the attentional priority for a specific feature (Gaspar & McDonald, 2014; Gaspelin et al., 2019; Stilwell & Vecera, 2022; Vecera et al., 2014). Thus, proactive inhibition requires top-down processing from working memory and task contexts to ultimately suppress this feature in visual cortex (Geng, 2014; Won & Geng, 2018). However, older adults demonstrated the ability to maintain this attentional template once established, potentially suggesting that the visual cortex does not need constant refreshing of this top-down bias once the feature is suppressed in the visual cortex (Won et al., 2020) and that older adults maintain functional bottom-up processing with respect to distractor suppression (Quigley et al., 2010; Quigley & Müller, 2014). An alternative explanation could be that deficiencies in top-down attentional control leads to

slower neural processing but that this deficit is minimally evident when competition is predominantly completed proactively. Our dwell time findings demonstrate that older adults take longer to process stimuli and disengage, a proxy of verification time. Furthermore, our mean sRT results reveal that older adults take longer to initiate saccades when the direction of the saccade is toward the target when proactively inhibiting distractors, and longer when the direction of the saccade is toward the distractor when reactively disengaging. This finding is further corroborated in the vincentile analysis which shows that both reflexive saccades (seen in the fastest bins) and goal-oriented saccades (more commonly observed in the slowest bins) are slower in older adults in Experiment 2 and is in concordance with the saccadic RT results. Both measures signify that processing speeds become slower in aging, although in Experiment 1, overall fixation times in older adults were not significantly different from that of young adults potentially due to the benefits of proactive inhibition. We hypothesize that this longer processing requirement would be more evident in larger search array sizes and suggest that older adults' performance in other tasks may not be impaired due to increased task difficulty per se but due to delays in processing that are compounded with more stimuli to disengage from and increased competition.

Our findings in Experiment 2 demonstrate that older adults exhibit numerous deficiencies in mechanisms of reactive attentional

Figure 11*Age-Related Performance Decline Within Older Adult Samples*

Note. We evaluated whether measures of oculomotor performance including fixation time in distractor-absent trials (A, F), and distractor-present trials (B, G), percentage of first saccades to the target on distractor-absent trials (C, H), on distractor-present trials (D, I), and the oculomotor suppression (E) and capture effects (J) were correlated with age in Experiment 1 (A–E) and Experiment 2 (F–J). Young adult data points were included in plots for reference. The linear-fitted line and Pearson's correlation coefficient only characterize the relationship within the OA sample. OA = older adult. See the online article for the color version of this figure.

control. In contrast to Experiment 1, older adults in Experiment 2 demonstrated significantly more delayed fixation times by the presence of the distractor and this interaction persisted even when matching fixation time speeds across age groups. This age deficit is a function of deficiencies in multiple mechanisms. First, older adults demonstrate longer dwell times, signifying deficiencies in disengagement. While older adults have shown to be able to disengage from processing irrelevant information in passage completion tasks or directed forgetting paradigms (Hamm & Hasher, 1992; Zacks et al., 1996), older adults have consistently shown to show delays in disengagement during visual search and tasks requiring shifting attention from one stimulus to another (Cashdollar et al., 2013; Clapp et al., 2011; Cona et al., 2013; Polden et al., 2020). Second, mean sRT findings in Experiment 2 again demonstrate that older adults require increased processing times before saccade

initiation. Both of these findings suggest that older adults have deficiencies in resolving top-down versus bottom-up competition, particularly with mismatch detection or verifying the stimulus with the top-down attentional template (Itti & Koch, 2000, 2001). Thus, we argue that the increased oculomotor capture effect in older adults is a consequence of slowed processing of top-down attentional signals, and thus, reflexive saccades toward the distractor are initiated following competition. However, in Experiment 2, we also find evidence that older adults are particularly more influenced by the distractor compared to nontarget stimuli, suggesting that older adults not only exhibit top-down deficiencies but also allocate increased attentional priority to salient stimuli. Specifically, dwell time is particularly longer in older adults when the stimulus is a distractor and mean sRTs are significantly longer when the initiated saccade is toward the distractor. These data also suggest a shift in

Table 3
Aging Differentially Modulates Unique Mechanisms of Attentional Control

| Brain function | Oculomotor measure | Change in older adults | |
|--|---|---------------------------|---|
| | | Experiment 1 | Experiment 2 |
| Nonmotor cognitive processing | Fixation time (ms) | No change | Slower |
| Goal-directed attentional control | First saccade to target (%) | Reduced | Reduced |
| Selection history (intertrial priming of target shape) | Target shape switch cost (ms) | Not applicable | No change |
| Disengagement | Dwell Time (ms) | Slower | Slower |
| Time to initiate saccade | Saccadic reaction time or saccadic latency (ms) | Slower when goal-oriented | Slower when goal-oriented and reflexive |
| Distractibility (inhibition of salient distractor) | First saccade to distractor (%) | No change in suppression | Increased distractibility |

Note. This table summarizes the age-related changes in both experiments in which evaluating eye movements allows investigation into individual mechanisms of attention processing. Age-related differences were identified over each mechanism of attentional control depending on whether the task required proactive distractor suppression (Experiment 1) or reactive distractor disengagement (Experiment 2) and provided insight into why age-related deficits in attention and aging research are task-specific.

attentional priority maps within the visual cortex and cortical processing that favors salient stimuli (Won et al., 2020) and the allocation of more attentional priority. Of particular interest for future studies would be whether shifts in attentional priority maps within the visual cortex can also be applied for emotional stimuli, as seen in older adults who demonstrate the positivity effect (Mather & Carstensen, 2005). Finally, we identified that deficiencies in selection history, specifically intertrial priming, do not explain why older adults show slowing in performance. This finding is consistent with the aging literature that selection history effects are preserved in older adults over different attention tasks (Howard et al., 2004; Lega et al., 2023; Lyon et al., 2014; Smyth & Shanks, 2011).

It is important to recognize that our findings in Experiment 2 do not specifically reflect age-related deficits in reactive suppression and more likely a product of impairments in mechanisms of disengagement and/or distractor rejection that fall under the larger umbrella of cognitive control. Indeed, the measure of fixation time likely is a proxy of the accumulation of all of the aforementioned nonmotor cognitive mechanisms that are slowed during aging (e.g., saccade initiation, disengagement, reorienting) and the observed age-related deficit may be considered to be a part of a more domain-general function (e.g., executive control). Nevertheless, our oculomotor measures allow differentiating between individual mechanisms of cognitive control and provide nuance into which cognitive processes are negatively impacted in aging. Furthermore, the preservation of some mechanisms in older adults provides additional insight into which neural networks or brain regions may be affected during aging. Unfortunately, the neural correlates underlying proactive and reactive mechanisms of visual suppression are still undetermined with some networks thought to be independent, the dorsolateral prefrontal and parietal regions shared, and perhaps some common regions are activated at different times (Geng, 2014; Hickey et al., 2009; Marini et al., 2016; Perri, 2020; van Belle et al., 2014; Vissers et al., 2016). However, the findings from this set of experiments lay the foundation for researchers in both the experimental psychology and aging fields to help solve unanswered questions in each field such as which neural networks are impacted during aging or what are the neural networks surrounding proactive distractor inhibition as the latter function is unaffected in aging.

A potential explanation of the preservation of mechanisms controlling proactive distractor suppression in aging is due to differences in the temporal processing speeds poststimulus presentation. The dual-mechanisms framework embodies the idea that common regions are shared but activated at different times and proactive control has been conceptualized as an early selection process while reactive control as a late correction process (Braver, 2012). In an ERP study, older adults have indeed demonstrated no deficiencies in early selective attention processing at ~150–350 ms, but an age deficit is evident in late selection at ~500–650 ms (Alperin et al., 2013). Our findings that top-down processing is delayed, and that early proactive inhibition is preserved in older adults would also support this notion. However, there are some studies that conclude that proactive distractor suppression is impaired in older adults (Ashinoff et al., 2019, 2020; Lega et al., 2023; Lustig & Jantz, 2015). Furthermore, Ashinoff et al. (2020) suggest that older adults shift from proactive inhibitory processing to reactive control in a global/local task. However, the plausibility that proactive inhibition is preserved in aging due to faster processing and learned adaptation is challenged by our sRT data. Older adults are even slower to initiate saccades and this specific processing occurs between ~250 and 350 ms. Our findings suggest that age-related deficits in

mechanisms of reactive attentional control are due to a sum of deficiencies in multiple mechanisms including cognitive functions driven by the frontal cortex (goal-directed orienting, disengagement, saccade initiation), the integration or conflict resolution between top-down control and bottom-up saliency signals (older adults show greater distractor presence deficit and slower saccade initiation even when the direction of the saccade is toward the distractor), and potentially a shift in saliency in the visual cortex (attention capture; increased distractibility by the salient distractor). Future neuroimaging studies may help validate these hypotheses such as examining age differences in the functional connectivity of the visual cortex, frontal lobe, and the FEFs. Furthermore, the hypothesis that changes in the saliency signal in older adults is leading to increased distractibility by task-irrelevant salient distractors can be examined by comparing hypothesized population-level tuning functions within the visual cortex using inverted encoding models (Sprague et al., 2018).

There are two important limitations in our study that call for more investigation. First, we observed that older adults have equal oculomotor suppression compared to young adults and we interpreted this as preserved mechanisms of proactive distractor suppression. However, due to the design of our task, increases in the magnitude of oculomotor suppression compared with young adults may not be observable as first saccades to nontargets were already very low with a set size of four stimuli. It is plausible that utilizing larger set sizes to elicit greater effects of proactive distractor suppression would lead to findings of older adults having greater suppression effects, potentially leading to interpretations that aging leads to a compensatory shift in proactive processing due to delays in other reactive mechanisms (Ashinoff et al., 2020). An additional alternative would be to measure ERPs on the distractor suppression effect (P_D —distractor positivity component) and investigate whether older adults show increased P_D amplitudes (Gasparin et al., 2023) to demonstrate greater inhibitory control compared with young adults. In addition, another limitation of our studies is the wide range of older adults that were recruited. From our scatterplots, we observed significant trends in age-related performance decline even within our older adult samples. To appropriately characterize how aging impacts mechanisms of attentional control, we emphasize the need for longitudinal studies or even cross-sectional studies with subjects represented in age groups across the lifespan. It is plausible that performance even increases with age that peaks around 40 years old (Douaud et al., 2014) and would be of interest to see if age-related changes across the lifespan over these measures are correlated with gray/white matter concentrations or with specific regions of the brain such as the prefrontal cortex.

In Alzheimer's disease (AD) research, the eye has been investigated as a potential biomarker (Lim et al., 2016) and pupillary responses has shown to predict AD risk (Granholm et al., 2017; Kremen et al., 2019). In addition, eye movements have shown to be sensitive in distinguishing between neurodegenerative diseases (Garbutt et al., 2008; Lage et al., 2021; Liu et al., 2021) and also between patients with AD and prodromal stages such as mild cognitive impairment (MCI) using the antisaccade task (Chehrehnegar et al., 2019, 2022; Opwonya et al., 2022; Peitsch et al., 2014; Wilcockson et al., 2019). However, some measures of eye movements have shown to be indistinguishable between healthy controls and patients with MCI (Chehrehnegar et al., 2022), demonstrating the limitations in measuring eye movements in antisaccade tasks to detect early deficits in aging, prior to the onset of clinical

symptoms. In this study, we demonstrate that healthy older adults have significant deficiencies in attentional control as measured by eye movements when completing a visual search paradigm. While pro- and antisaccade tasks measure basic horizontal eye movements when a target and distractor are in competition, visual search embodies more complex search patterns, orienting and reorienting, and the constant engagement and rejection of stimuli that resemble more real-world scenarios. Measuring eye movements in visual search paradigms may prove to be a more sensitive marker of early cognitive deficiencies prior to the onset of irreversible neurodegeneration and clinical pathology.

Overall, our findings reveal differences in how aging differentially modulates specific mechanisms of attentional control depending on the required attentional set, offering an explanation to why many age-related deficits in studies of attention are found to be task-specific. While most of our interpretations were focused on the aging literature, the findings in this set of experiments provide the foundation for understanding differences in neural networks of proactive and reactive distractor suppression and disengagement, with proactive inhibitory mechanisms to be potentially unique and outside of prefrontal cortex control. Further inspections into the precise neural networks modulated by aging can inform attention researchers in uncovering previously unknown networks underlying these processes. In addition, these experiments lay the framework to investigate how different attention processing disorders (e.g., attention-deficit/hyperactivity disorder, schizophrenia) or neurodegeneration (e.g., Alzheimer's or Parkinson's disease) may differentially modulate specific cognitive control mechanisms and giving insight into where and when certain neural networks are impacted. This further emphasizes the need for longitudinal studies to better characterize the progression of such disorders and neurodegenerative diseases and offer potential for measuring eye movements as a biomarker to predict the progression and incidence of early pathology. In addition, numerous studies have reached mixed conclusions that are often found to be task-specific including perception, cognition, general reasoning, and memory (Kelly & Martin, 1994; Logie, 2018; Thompson, 2000). These experiments convey the importance of differentiating within multiple mechanisms over a broad cognitive construct (e.g., attention) and call for experimental psychologists to develop specific methodologies and tasks to test individual mechanisms beyond the visual domain using eye tracking. Lastly, the field of experimental psychology has questioned the applicability of small mean differences in response time measures. As seen in Experiment 2, significant mean differences of 100–200 ms (or even smaller mean changes in some comparisons) may not be particularly significant in real-world scenarios of visual search. However, our findings across the aging spectrum (ages 18–30 and 50–80 years old) indicate the reliability of observing trends in brain function, posing the plausibility for oculomotor measures to be effective biomarkers of aging or cognitive decline. That is, although mean differences may be relatively insignificant in real-world scenarios, the changes in cognitive processing that is portrayed in these measures is informative in understanding changes in neural function.

Constraints on Generality

Although our findings are primarily interpreted in the context of aging, the generalizability of our cross-sectional findings is constrained to older adults aged 50–80 years old. While our data reveal patterns of age-related deterioration among some of our oculomotor measures

even within our older age sample, our conclusions may not apply to middle-aged adults between 30 and 50 years old and patterns of performance may differ. Additional research across the entire age spectrum or longitudinal designs may inform whether age-related changes identified in this show a linear decline or perhaps may be curvilinear as seen in age-related changes in white matter (Douaud et al., 2014). Furthermore, our results reflect age-related changes to specific mechanisms of attention processing in the visual domain and may not be generalizable to cognitive process that require higher-order integration. However, our findings in Experiment 2 reveal a general slowing in older adults across numerous types of cognitive processing that may explain the broad decline in cognitive control seen in higher-order brain processing.

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