The Asymmetric Effects of Aging on Between- and Within-Trial Timescales of Inhibition

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Abstract

Widespread cognitive decline in older adults has been hypothesized to stem from a fundamental deficit in inhibition, or the ability to ignore goal-irrelevant information. The extent to which inhibition operates across different timescales, however, has been under-explored. We introduce a novel cognitive task designed to assess both between- and within-trial inhibition using a common set of stimuli. Behavioral results from younger, middle-aged, and older adults (N=100; age range: 18-73) reveal significant age-related differences in between-trial inhibition, with older adults showing less efficient adaptation to rule changes compared to younger adults. Within-trial inhibition, requiring suppression of distractors within the current visual environment, appears to remain intact alongside normal aging. These findings will support the development of tools for the early detection of age-related cognitive decline, prior to subjective awareness of impaired daily functioning.

Keywords: aging; decision making; learning; memory; computer-based experiment

Introduction

Cognitive abilities such as memory, reasoning, and reaction time are essential in performing everyday tasks from managing finances to maintaining a conversation. Yet, as individuals grow older, research indicates that these cognitive abilities will decline (Craik, 1994; Salthouse, 1996). Contemporary methods for characterizing age-related cognitive decline, such as screening questionnaires and neuropsychological tests, are highly subjective and offer only coarse-grained confirmation of profound deficits. The *clock-drawing test*, for example, is a widely used neuropsychological test of attention and planning in which patients are asked to draw a clock face and hands to depict a specific time (Shulman, 2000). Although clock-drawing failures such as missing numbers or unequal spacing are reliable indicators of acute dementia (Shulman, Shedletsky, & Silver, 1986), they provide little insight into the more subtle cognitive changes that occur in the earlier stages of cognitive decline (Aprahamian, Martinelli, Neri, & Yassuda, 2009).

Several meta-analyses have identified a pervasive inability to distinguish between patients with mild cognitive impairment (MCI) and healthy controls using even the most comprehensive cognitive assessment tools (e.g. Mini-Mental State Examination; Montreal Cognitive Assessment; De Roeck, De Deyn, Dierckx, and Engelborghs, 2019). This distinction is critical, given that early identification of prodromal dementia symptoms offer the most promising window for intervention and for making informed decisions about long term healthcare. There is therefore an urgent need for cognitive assessment tools that tap into the mechanisms that are most foundational to age-related decline. By continuing to rely on tools that require deficits to be severe enough to impact self-report measures or daily functioning, clinicians risk delaying diagnosis and limiting opportunities for preventive strategies, early treatment, and personalized care planning (Weichart et al., 2021).

Dual Timescales of Inhibition

A possible driving factor behind several subjective age-related cognitive complaints may be a reduced capacity for *inhibition*, which broadly refers to the ability to ignore or suppress irrelevant information (Dempster, 1992). The long-standing *inhibitory deficit hypothesis* suggests that a fundamental breakdown of inhibition leaves older adults less-equipped to optimize limited-capacity memory storage, and more susceptible to interference from outdated information when making decisions (Hasher & Zacks, 1988). In the current study, we present a new task that targets and evaluates inhibitory functions. We propose that this may be a promising avenue for cognitive assessment in aging, given evidence that inhibition declines *before* the noticeable memory and attention deficits that dominate self-report measures of impairment (Lustig, Hasher, & Zacks, 2007).

Several cognitive tasks have been developed to examine different aspects of inhibition. One common example is the Wisconsin Card Sorting Task (WCST; Grant and Berg, 1948).

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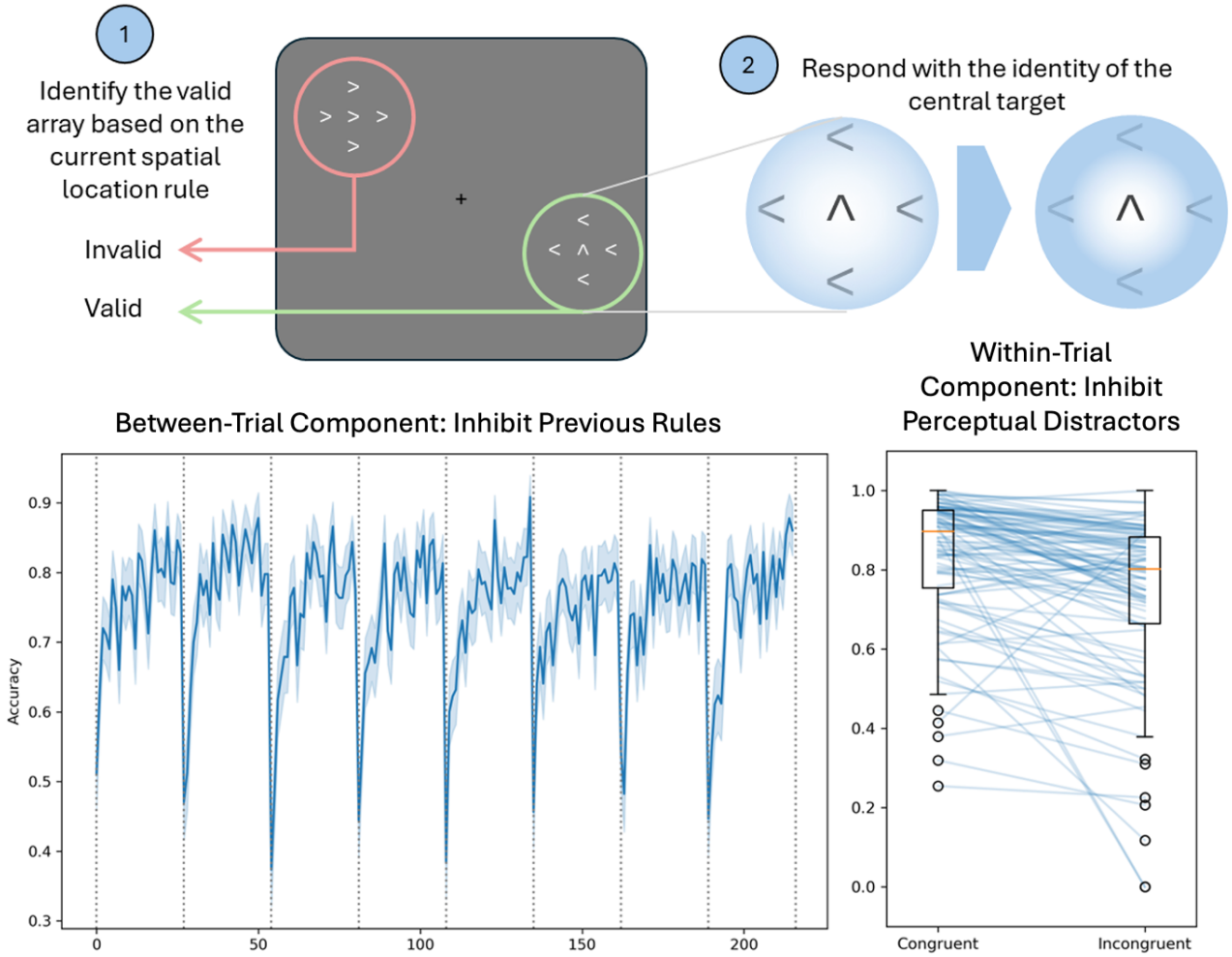

Figure 1: Conceptual overview. Top. Example stimulus. The between-trial component of the task challenges the participant to identify a valid array by learning a spatial location rule. The within-trial component then requires the participant to focus on the central target within the valid array. **Bottom.** Aggregate behavioral results across all participants in the current study (N=100), as measured by each component of the task. The former is evaluated by accuracy after a rule-switch. The latter is evaluated by comparing accuracy when distractors are congruent vs. incongruent to the target.

In this task, participants sort cards based on a certain category rule (e.g., color, number, or shape) that they must infer from evaluator feedback. After the participant has ascertained the rule and correctly sorted a certain number of cards, the rule is changed and the participant must discover the new rule. After a rule switch, the participant may continue to sort based on the former rule; these "perseverative errors" are more common in older adults than in younger adults (Fristoe, Salthouse, & Woodard, 1997). Other tasks, such as Flanker (B. Eriksen & Eriksen, 1974) and Stroop (Stroop, 1935), measure a participant's ability to focus on target stimuli or stimulus attributes and inhibit perceptual distractors. In a standard version of the Flanker task, participants must identify the orientation of a target arrow while ignoring surrounding distractor arrows. These distractors can be either congruent (matching the target) or incongruent (conflicting with the target). Performance is typically worse on incongruent trials due to increased interference. Prior research has shown mixed results when comparing performance between older and younger adults, with some studies suggesting that older adults are able to match younger adult performance only by engaging additional brain regions (Nielson, Langenecker, & Garavan, 2002).

When considered together, the diversity of these tasks reveals that inhibition can occur across different timescales, requiring both the suppression of irrelevant information from prior experiences and the filtering of distractions within the current moment. From the existing literature, however, it remains unclear whether these two forms of inhibition rely on distinct cognitive mechanisms or whether they reflect a shared underlying process that is compromised by age.

The Current Study

We developed a novel task to examine two modes of inhibition (Figure 1). One operates at the between-trial level, where the observer must continuously update their knowl-

edge of relevant task information while suppressing memories of irrelevant details (i.e. WCST). The other operates at the within-trial level, where the observer must ignore distracting information from the current visual environment in order to make accurate decisions (i.e. Flanker). While this distinction is well-aligned with established frameworks in the literature, most cognitive tasks have not been designed to isolate these two modes of inhibition (Weichart, Turner, & Sederberg, 2020; Weichart & Sederberg, 2021). Our task was specifically developed to address this gap, providing a novel approach to examining their independent relationships to cognitive aging. By clarifying how these inhibitory processes change with age, this work may help inform the development of assessment tools that more reliably distinguish between healthy aging and pathological decline (i.e. MCI).

Method

Participants

We first conducted a pilot study to identify an appropriate sample size. Participants in both the pilot study and our main study were recruited online using Prolific (`http://prolific.co`). Following a power analysis of the pilot data, we selected a sample size of 100 to ensure 80% power to detect a moderate flanker congruency effect (Cohen's $d = 0.69$, determined from pilot study) with $\alpha = 0.05$. A sample size of 100 additionally ensured that all age groups (younger, middle-aged, and older adults) could be expected to exceed the minimum requirement of $N = 18$ as determined by power analysis. The main sample consisted of 31 young adults (age 18–29, $M = 23.7$, $SD = 3.09$), 44 middle-aged adults (age 30–49, $M = 37.66$, $SD = 5.67$), and 25 older adults (age 50–73, $M = 59.44$, $SD = 7.13$). Although all analyses are reported with age as a continuous variable, group delineations of ages 30 and 50 were selected *a priori* to probe significant results and visualize behavioral effects.

All participants reported normal or corrected-to-normal vision, English fluency, and residency in the United States. Participants were compensated at a rate of 10 USD per hour (median completion time: 13.67 minutes). All participants completed the full version of the experiment and exceeded chance performance of 33% ($M = 76.8$, $SD = 15.6$). Therefore, no participants were excluded from analysis. All research activities reported here were approved by the Institutional Review Board at Utah State University.

Stimuli and Apparatus

The experiment was coded in JavaScript using the PsychoPy toolbox (Peirce, 2009), and stimulus presentation and response recording were handled online using PsychoPy's integration with the Pavlovia platform (`https://pavlovia.org`). Participants completed the consent procedure and the experiment in their own environments using their personal computers. An example of the progression of a single trial is shown in Figure 3A.

Trial stimuli were two arrays of white arrows presented on a gray background, each consisting of a central target and four distractors arranged in an upright cross formation. Distractor arrows were congruent to the target in one array, and incongruent in the other. Left, right, and up arrows were counterbalanced among three possible roles per trial: 1) congruent array target and distractors, 2) incongruent array target, 3) incongruent array distractors. All possible pairings of congruent and incongruent arrays are shown in Figure 2B. Arrays could occur in 8 locations around the screen, each of which were equidistant from a black fixation cross located at (0,0) in increments of 45°. The task objective was to use the left, right, and up arrow keys to indicate the target of the valid array, where validity was defined by a spatial position rule that changed periodically throughout the task. Feedback was provided on every trial in the form of a green check mark for correct responses, and a red "X" for errors. Example stimulus configurations within a single rule block are illustrated in Figure 2C.

Procedure

Individuals indicated their consent to participate by clicking a checkbox on a digital form. Participants then completed an interactive training module that included three practice sets during which they responded to 1) targets without distractors in the presence of a visual boundary to distinguish valid from invalid locations, 2) full arrays in the presence of a visual boundary, and 3) arrays without a visual boundary. Participants were informed that the position of the boundary would change throughout the main task.

The experiment was divided into 8 blocks, each of which featured a different spatial location rule to distinguish valid and invalid arrays. Within each rule block, an unpresented linear boundary bisected the visual task environment into hemifields. Boundary angles were increments of 45°, resulting in 8 possible rules that all occurred within the experiment in a randomized order. Arrays that occurred in one hemifield were valid, such that responding consistently with the target was coded as correct. Arrays that occurred in the opposing hemifield were invalid. There was one valid and one invalid array per trial, each of which appeared in a semi-randomly selected location within the relevant hemifield. All 8 divisions between valid and invalid locations are shown in Figure 2D.

Transitions between rule blocks were not explicitly announced to participants, and blocks varied in length between 26 and 43 trials ($M = 35$ trials), so that participants could not precisely predict when a transition would occur. Despite variability in block length, the total length of the experiment was held constant across participants at 288 trials with counterbalanced valid array types (congruent or incongruent) and target identity (left, right, up). To maximize performance, participants had to both 1) utilize trial-level feedback to inform their understanding of which spatial locations were currently valid, and 2) inhibit the distractors of the valid array to respond consistently with the target.

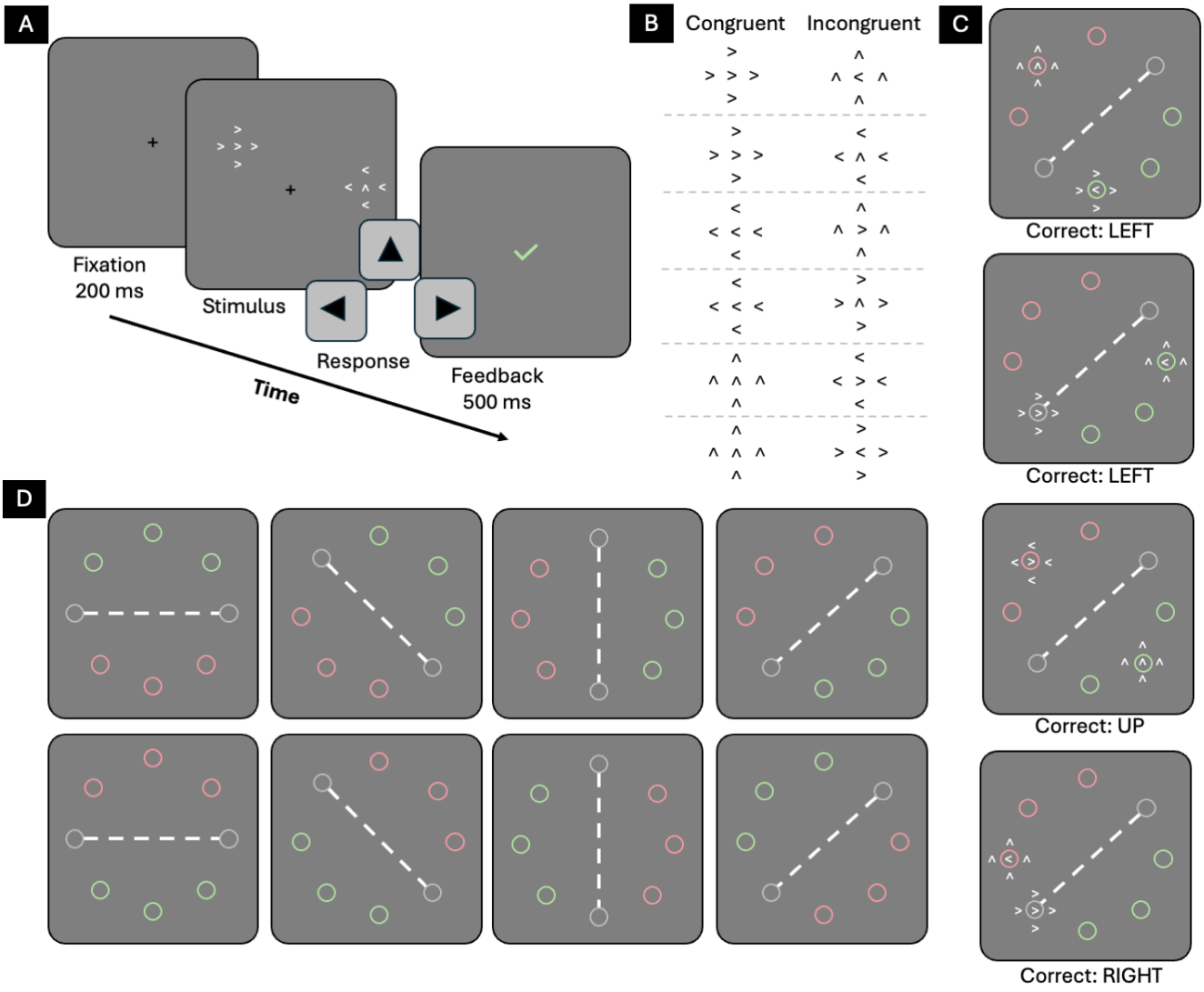

Figure 2: Task design. **(A)** Progression of one trial. **(B)** All possible pairings of congruent and incongruent arrays. **(C)** Example stimulus configurations within a single rule block. The white dashed line indicates the rule for distinguishing between valid (green circles) and invalid (red circles) locations. Lines and circles are shown for illustration only and were not visible to participants during the task. **(D)** All possible rules for distinguishing between valid and invalid locations.

Results

The results are presented in two parts. First, we assess *between-trial inhibition*, investigating how participants adapt their selection strategies in response to error-driven uncertainty about the current spatial rule. Second, we examine *within-trial inhibition*, focusing on participants' ability to selectively filter perceptual distractors in order to identify the orientation of the target.

Between-Trial Inhibition

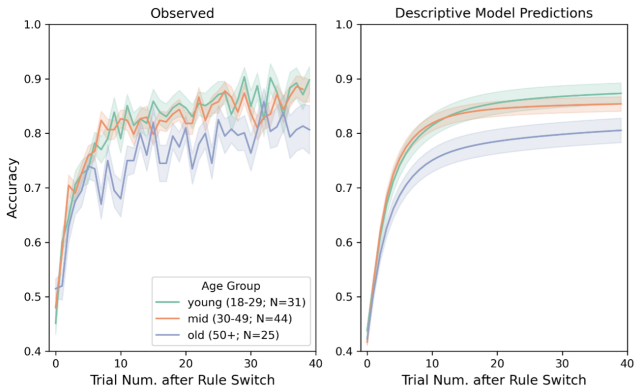

Figure 3: Aggregate learning curves across rule blocks (Left) Observed learning curves, where lines are average trial-level accuracy within-group and error ribbons are standard errors of the mean. **(Right)** Learning curves generated by simulating a logistic function using best-fitting parameter values from each participant.

Our task was designed to naturally produce variability in difficulty via the randomized positions of the arrays. In particular, we expected trials to be more difficult when both arrays were close to the boundary between valid and invalid regions (e.g., the fourth example in Figure 2C), as opposed to perpendicular (e.g., the third example in Figure 2C).

To evaluate the effect of relative array position on performance, we calculated a measure of accuracy that quantified participants' ability to identify the valid array. By this measure, responses were considered "correct" if the participant responded with either the target or distractor arrow of the valid array, and were "incorrect" if they responded with either the target or distractor arrow of the invalid array. We then calculated the total Euclidean distance between the array centers and the boundary line on each trial.

A mixed-effects model examined the effects of age and distance on valid array identification, with Participant ID as a random effect. The model revealed a significant main effect of distance ($Z = 4.62$, $p < 0.001$), such that participants were more accurate at distinguishing between valid and invalid arrays when they were maximally distant from the boundary. There was a marginally significant effect of age on valid array identification ($Z = -1.74$, $p = 0.08$), such that younger adults were marginally more accurate at identifying valid arrays overall (young: $M = 0.81$, $SD = 0.15$; middle: $M = 0.80$, $SD = 0.12$; old: $M = 0.75$, $SD = 0.14$). There was no significant interaction between distance and age ($Z = 0.25$, $p = 0.80$).

We additionally evaluated each participant's ability to learn the currently-valid spatial locations after a rule switch. A mixed-effects model analysis revealed a significant increase in valid array identification across trials following a rule switch ($Z = 11.36$, $p < 0.001$), and a significant interaction between age and trial ($Z = -1.98$, $p < 0.05$; young: first 10 trials: $M = 0.70$, $SD = 0.13$, last 10 trials: $M = 0.87$, $SD = 0.17$; middle: first 10 trials: $M = 0.71$, $SD = 0.10$, last 10 trials: $M = 0.85$, $SD = 0.14$; old: first 10 trials: $M = 0.66$, $SD = 0.11$, last 10 trials: $M = 0.80$, $SD = 0.16$).

For a more nuanced evaluation, we applied a descriptive model of accuracy on each trial following a rule switch in the form of a three-parameter logistic function:

$$y = L_1 + \exp(-k(x - x_0)). \quad (1)$$

In Equation (1), y is the predicted accuracy on trial x since a rule change. The free parameters L, k, and x_0 characterize different shapes that the learning function could take, where L governs the upper asymptote of the curve ($L \in (0,1)$), k governs the steepness of the curve ($k \in (0,1)$), and x_0 governs the inflection point ($x_0 \in (0,5)$). Observed learning curves aggregated across participants within each age group are shown in Figure 3 (left panel). Analogous learning curves, produced by simulating the descriptive model using best-fitting parameter values for each participant, are shown in Figure 3 (right panel) to demonstrate goodness-of-fit via visual inspection.

Nonparametric tests were used to evaluate the impact of age on estimates of key descriptive learning curve parameters, L and k. A Spearman's rank-order correlation identified a significant negative correlation between age and the upper asymptote parameter, L ($\rho = -0.21$, $p < 0.05$), indicating that maximum accuracy within each rule block decreases as age increases (young: $M = 0.94$, $SD = 0.08$; middle: $M = 0.87$, $SD = 0.11$; old: $M = 0.86$, $SD = 0.15$). There was no significant correlation between age and the steepness parameter, k ($\rho = 0.05$, $p = 0.60$).

Within-Trial Inhibition

Several studies have shown that performance is enhanced when targets in a Flanker array are surrounded by congruent compared to neutral distractors, whereas incongruent distractors impair performance (for review, see Egner, 2007). This flanker congruency effect can be explained by the popular conceptualization of attention as a spotlight that centers upon a certain location and is modifiable in size. Objects within the spotlight are selected for decision-relevant processing, while objects outside of the attended field are excluded. When an individual makes more errors on incongruent compared to congruent trials, it is considered to denote a failure of within-trial inhibition; the participant has failed to adjust the attentional spotlight in a manner that aptly excludes the distractors from consideration during the decision (Posner, 1980; C. Eriksen & Yeh, 1985; C. Eriksen & James, 1986).

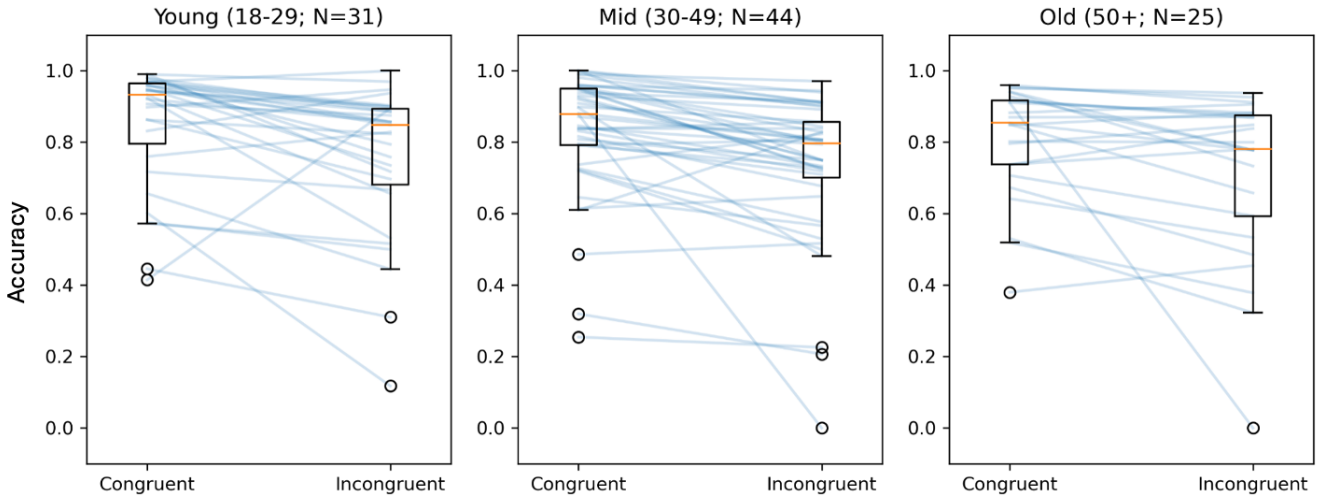

Figure 4: Flanker congruency effects by age group. Boxplots show means and interquartile ranges of accuracy when valid arrays were congruent or incongruent (specifically, left targets flanked by right distractors, or right targets flanked by left distractors). Points indicate subject-level means that fell outside of the overall interquartile range. Lines represent condition-level comparisons within-subject.

An age $\times$ condition (congruent, incongruent) mixed-effects model was used to analyze accuracy data after the first 10 trials of each rule block. Participant ID was included as a random effect. Incongruent trials were defined as valid arrays with "left" targets with "right" distractors or "right" targets with "left" distractors. We observed a significant main effect of condition ($Z = -5.507$, $p < 0.001$), such that participants were more accurate when the valid array was congruent compared to incongruent (congruent: $M = 0.83$, $SD = 0.16$; incongruent: $M = 0.73$, $SD = 0.21$). There was neither a main effect of age ($Z = -1.38$, $p = 0.17$), nor an interaction between age and condition ($Z = 0.89$, $p = 0.38$). Flanker congruency effects within age groups are illustrated in Figure 4.

Discussion

According to the inhibitory deficit hypothesis, aging is accompanied by a weakened ability to inhibit irrelevant information from one's limited-capacity cognitive system, leading to interference in working memory and decision-making (Hasher & Zacks, 1988). Previous efforts to examine age-related inhibitory deficits have been inconsistent, with some supporting the hypothesis and others not (Rey-Mermet & Gade, 2017). We suggested that this inconsistency may be due to an incomplete understanding of the timescales at which inhibition operates and how its component processes interact to support performance. Specifically, while some forms of inhibition function within-trial to filter out perceptual distractors, others operate between-trials to update task-relevant information and suppress outdated rules. We therefore developed a task to examine these dual components of inhibition using a common set of stimuli, with the goal of determining whether they are differentially affected by age-related cognitive decline.

Our results revealed age-related deficits in between-, but not within-trial, inhibition. Older adults were significantly less adept at updating spatial rules after an unannounced switch, consistent with findings from the WCST showing increased perseverative errors among older adults (Fristoe et al., 1997). In contrast, their ability to ignore within-trial distractors remained intact, aligning with studies suggesting that older adults maintain inhibition through compensatory strategies, despite increased response times (Nielson et al., 2002). This dissociation challenges the notion that inhibitory deficits uniformly affect cognition and suggests that between-trial mechanisms may be more vulnerable to age-related decline than within-.

These findings have critical implications for cognitive assessment. Standard screening tools provide only coarse-grained measures of cognitive status and typically detect impairment only after daily functioning is affected (e.g., the clock-drawing test), making them insufficient for early detection. Our results suggest that tasks targeting between-trial inhibition, such as rule-switching paradigms, could offer a more sensitive measure of early cognitive decline. Given the neurodegenerative progression of MCI into Alzheimer's disease, waiting until individuals report subjective awareness of cognitive decline may already be too late for effective intervention. Identifying subtle inhibitory deficits earlier could enable timely detection of pathological aging, allowing for interventions when they are most likely to be effective.

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