

Title: Does global slowing explain age effects in inhibitory control?

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Abstract

A long-standing debate in the study of cognitive aging concerns whether aging results in a selective deficit in inhibitory control beyond a general slowing of cognitive processing. Previous studies have obtained mixed findings, in part because the typical free response time paradigm lacks the specificity required to disentangle component processes underlying inhibitory control. Here, we apply a novel forced-response paradigm and a computational model to disentangle these processes to test if aging results in overall speed differences or a selective deficit in inhibitory control. 50 older adults and 57 younger adults completed a “forced-response” arrow flanker task. We find strong evidence that older adults demonstrate a global slowing of processing, without any selective deficit in inhibitory control. Furthermore, we demonstrate global slowing is sufficient to explain the mixed findings in previous free RT studies. Overall, these results highlight the utility of using a theory-informed, fine-grained approach to study inhibitory control.

Keywords: cognitive aging, inhibitory control, computational modeling, cognitive control, executive functions

Research Transparency Statement

General Disclosures

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Study Disclosures

Preregistration: No aspects of this study were preregistered. Materials: All task code is publicly available on GitHub (<https://github.com/jacobsellers/fr-aging>). Data: All primary data and model fits to data are publicly available on Open Science framework (<https://osf.io/dhkve/>). Analysis scripts: All code to reproduce the analyses is publicly available on GitHub (<https://github.com/jacobsellers/fr-aging>).

Introduction

Aging brings about profound changes to one's physical and cognitive life. Older adults have been shown to perform worse than younger adults on a wide variety of cognitive tasks, including recalling past events (Nyberg et al., 2012), abstract reasoning (Salthouse, 2004), and learning complex motor skills (Voelcker-Rehage, 2008). Characterizing these age-related changes in cognition aids our understanding of the nature of basic cognitive processes, which ultimately helps us gain greater knowledge about healthy aging.

What cognitive substrates are impaired as a person ages? It is well-known that older adults demonstrate slower processing speeds than younger adults, and this global slowdown is known to explain impaired performance on many tasks (Salthouse, 1996). In contrast, some have proposed that aging brings about a selective cognitive deficit in *inhibitory control* (Hasher & Zacks, 1979, 1988) beyond general slowing. This theory holds that what deteriorates as a person ages is the ability to actively suppress and control automatic impulses and distracting information when they conflict with goal-directed behavior.

Perhaps the most popular class of paradigms to assess inhibitory control are “response conflict” tasks. Tasks of this type induce competing responses, and successful performance hinges on suppressing habitual (automatic) responses to produce goal-directed responses. In one example, the arrow flanker task (Eriksen & Eriksen, 1974; Stoffels & Van Der Molen, 1988), participants are shown a line of arrows and are asked to report whether the center arrow points to the left or the right. On congruent trials, the flanking arrows point in the same direction as the center arrow. On incongruent trials, the flanking arrows point in the direction opposite the center arrow, thus creating a response conflict. The congruency effect, or the difference in free response

time (RT) between incongruent and congruent trials, is commonly used to index the efficacy of inhibitory control with a larger difference denoting worse control.

Despite decades of research, testing younger and older adults on response conflict tasks has produced mixed findings; some studies report worse inhibitory control in older adults while others fail to find a significant difference (Rey-Mermet & Gade, 2018). Some studies using conflict tasks have even reported findings suggesting that inhibitory control may even *improve* with age (Rey-Mermet et al., 2018; Veríssimo et al., 2021).

A persistent issue when using response conflict tasks to study age-related deficits is that the slowing of overall processing speed in older individuals presents a confound in these experiments: Slower overall RT in older adults makes it difficult to interpret RT difference scores because differences tend to exaggerate with increasing overall RT. Past studies have employed various methods to mitigate this issue, but there is no universally accepted approach to account for this problem. For example, recent studies using graphical meta-analytic techniques (i.e., Brinley and State-Trace plots) have failed to find clear support for an age-related deficit in inhibitory control (Rey-Mermet & Gade, 2018; Verhaeghen, 2011; Verhaeghen & Cerella, 2002). However, these techniques have been criticized for lacking sensitivity to detect age-related effects (Nicosia et al., 2021; Perfect, 1994). To date, it remains unclear whether older adults truly exhibit an inhibitory control deficit in conflict tasks or whether any apparent deficits can be simply attributed to slower overall processing speed.

More fundamentally, RT difference scores between congruent and incongruent conditions lack specificity about different component processes underlying inhibitory control. Human decision-making in these tasks is often conceptualized as a time-dependent interplay between

habitual processes and goal-directed processes (Evans, 2008). Dual process models of this sort have collectively been a cornerstone in understanding inhibitory control (Cohen et al., 1992; Hübner et al., 2010; Kornblum et al., 1990; Logan, 1980; Luck et al., 2020; Ridderinkhof, 2002; Ridderinkhof et al., 2004, 2011; Ulrich et al., 2015). Control takes time to develop as habitual and goal-directed processes unfold asynchronously over time (Ridderinkhof et al., 2011; Ulrich et al., 2015). As a result, habitual responses are usually prepared much more quickly than goal-directed responses. Furthermore, recent evidence suggests that response preparation and the actual expression of that response are separable (Haith et al., 2016; Hardwick et al., 2022; Wong et al., 2017; Zhang et al., 2024). A response could be prepared as certain cognitive processes complete, but it can still be inhibited from being overtly expressed. Overall, RT difference scores do not capture the precise timing of habitual and goal-directed processes nor how these processes may eventually lead to an overt response. Understanding age-related changes in inhibitory control thus requires a theory-informed, fine-grained measurement to capture both the latencies of habitual and goal-directed processes as well as their overt expression probabilities.

Lee et al. (2024) recently described a behavioral paradigm that is suitable to study the dynamics of inhibitory control: the “forced-response” paradigm (Lee et al., 2024). The method forces participants to respond at a prespecified time while systematically varying the duration between stimulus onset and the required response. This allows us to measure task performance during all stages between stimulus and response, as opposed to measuring performance at one point in time.

Importantly, the forced-response paradigm allows us to disentangle the contribution of habitual processing and goal-directed processing to behavioral performance using a computational model of response preparation. This model assumes that habitual and goal-

directed responses are prepared separately and asynchronously in time. When examining age-related differences in behavior in a forced-response conflict task, the model thus allows us to distinguish between changes in overall processing speed versus one or more of three separate inhibitory control processes: 1) slowing the latency of habitual processing, (2) accelerating the latency of goal-directed processing, and (3) inhibiting the expression of habitual responses.

We had older and younger adults complete a forced-response version of a flanker task and we employed our computational approach to examine age-related differences in inhibitory control. Our computational modeling rules out that performance of older adults in response conflict tasks is driven by an impairment in inhibitory control processes. Instead, we find strong evidence that aging is associated with a global slowing of both habitual and goal-directed processing. Finally, we show that this global slowing could nonetheless produce results that seemingly support an inhibitory control-deficit account in free RT paradigms. These results help explain the mixed findings seen in the literature and highlight the utility of using a theory-informed approach to study age differences in inhibitory control.

Method

Sample

We aimed to collect usable data from 50 younger adults (YAs) and 50 older adults (OAs). We collected data from 153 total participants (61 YA, 92 OA). After excluding participants from further analysis based on poor task performance, we were left with 107 total participants: 50 younger adults (23 female) and 57 older adults (32 female). See preprocessing section for participant exclusion criteria. Data were collected online using Prolific.co. Adults aged 18-30

years were recruited for the younger adult group, and adults older than 65 years were recruited for the older adult group. The final sample had a mean age of 25.5 years ($SD=3.12$) for younger adults and mean of 68.8 years ($SD=3.63$) for older adults.

Justification of Sample Size

Sample size was determined by evaluating statistical power to detect strong evidence for a change in parameter values of the computational model described below when fit to simulated data. Briefly, we pooled data across multiple pilot experiments in a similar conflict resolution task with a mix of younger ($N=105$) and older ($N=38$) adults. We arbitrarily chose a target sample size of 50 older and 50 younger adults and generated 100 simulated data sets by sampling with replacement from our larger pool of pilot data. We fit the model to each new dataset to obtain an estimate of power. In older adults, we observed strong evidence for our hypothesized effects over 93% of the time and thus targeted a final sample size of 50 per group.

Experimental Design and Task

The experiment was programmed in Psychopy and run online using Pavlovia (Peirce et al., 2019). A demo of the experiment is available online: <https://pavlovia.org/hanzh/forced-response-flanker-demo>

Participants performed the arrow flanker task (Fig. 1a). Participants were instructed to respond to the direction of a central arrow that could be pointing to the left or the right. Participants were instructed to press the “W” key on a standard keyboard if the central arrow was pointing to the left and the “P” key if the central arrow was pointing to the right. The central arrow could be flanked by two arrows on the left and the right that were pointing in a direction

congruent to the central arrow (e.g., <<<<< or >>>>>) or pointing in a direction incongruent to the central arrow (e.g., <<><< or >>>>>).

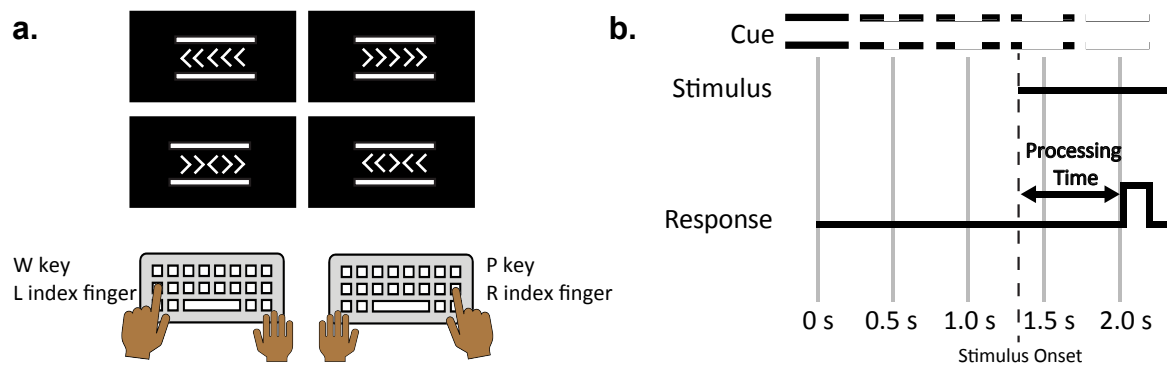


Fig. 1. The arrow flanker task and the forced-response method. (a) In the arrow flanker task, participants are instructed to respond to the direction of the central arrow while ignoring the flanking arrows. The flanking arrows can be pointing in the same direction as the central arrow (congruent, top row) or in the opposite direction to the central arrow (incongruent, bottom row). The example shows the moment when a response is cued, as indicated by the white bars above and below (b) The forced-response method. Response time is fixed at 2 seconds on every trial. Participants are instructed to respond exactly when the bars (the cues) turn white. Stimulus onset is varied from trial to trial, allowing for processing time to be varied.

The experiment began with practice on a free RT variant of this flanker task. Participants could respond at any time following stimulus onset and were given feedback about whether they were correct or incorrect following each trial. Participants first completed 40 trials as a warm-up). Then, as participants completed additional trials, accuracy for the most recent 20 trials was computed on a rolling basis. Once a participant reached 85% accuracy, they moved onto the next practice phase. If a participant could not reach 85% accuracy after a total of 80 trials, they were excluded from the experiment.

The second practice phase had participants perform the timing component of the forced-response task. Participants were instructed to respond exactly when two outlined rectangles

turned white (see Fig. 1b for the timing cues). These rectangles were positioned to appear above and below where the flanker task stimuli appeared during the test phase. The rectangles gradually turned white in 25% increments every 500 ms, resulting in a fully white rectangle at 2000 ms. Thus, participants were required to respond at 2000 ms on each trial. Participants responded by using the same keys they used to respond in the flanker task (“W” and “P”), and they were encouraged to alternate between these keys during this practice. A response was considered on time if it was made within ± 100 ms of 2000 ms. Participants were given feedback on their timing accuracy after each trial. Participants first completed 30 trials of the timing practice as a warm-up. Then, as participants complete more trials, timing accuracy for the last 20 trials was computed on a rolling basis. Once a participant reached 70% timing accuracy, they moved onto the next practice phase. If a participant could not reach 70% timing accuracy after a total of 60 trials, they were excluded from the experiment.

Participants then moved on to the test phase of the experiment, in which they completed the forced-response flanker task. The test phase consisted of 10 blocks of 52 trials (26 congruent and 26 incongruent trials per block). On each trial, participants were instructed to respond when the two outlined rectangles turned white at 2000 ms, just as during the timing practice. Following each trial, participants were given feedback about whether they were too fast (more than 100 ms early), too slow (more than 100 ms late), or on time. Stimulus onset time on each trial was uniformly distributed from 500-2000 ms, meaning the temporal distance between stimulus onset and the response signal ranged from 0-1500 ms.

Following completion of the task, participants completed a questionnaire that assessed their experience while completing the task and their dispositional attention deficits. The details and results of this questionnaire are reported in the supplement.

Preprocessing

We analyzed data collected during the flanker task with forced responding. We define processing time (PT) as the difference between actual response time and stimulus onset. For example, if a participant responded at 2050 ms and the stimulus appeared at 1500 ms on a given trial, $PT = 550$ ms for that trial.

For participant-level exclusions, we excluded participants based on two criteria. First, participants were required to have response accuracy over 70% for PTs greater than 750 ms collapsed across both trial types. We chose this PT cutoff as pilot data suggested that response accuracy typically reaches above 70% after 750 ms in forced-response conflict tasks. Second, participants were required to have timing accuracy greater than 40% in 8 or more task blocks. We computed timing accuracy per block using a widened timing window. A response was considered on time for analysis if that response was made within ± 150 ms of the response signal. If a participant did not meet the accuracy or timing criteria, they were excluded from further analysis. This ensured that inferences made from our final analyses could be attributed to cognitive processing during task performance rather than a failure to adhere to directions or complete the task. We excluded a total of 35 older adults and 11 younger adults, resulting in a final sample size of 57 older adults and 50 younger adults.

For trial level exclusions, we excluded trials on which participants did not respond on time (i.e., out of ± 150 ms of the response signal). We excluded trials that had a PT less than 0 ms, as these are trials in which the stimulus appeared after the participant responded. Our results do not substantially differ when including all participants and all trials (see supplementary material).

Behavioral Analysis

We visualized the trajectories of response accuracy over PT using a sliding window procedure in which accuracy was iteratively computed in a 100 ms window sliding from 0 to 1500 ms with a step size of 1 ms. Error bands denote the standard error at each time step. We display the 0-1000 ms PT range as accuracy was asymptotic by 800 ms.

To examine congruency effects over time, we fit a rolling logistic regression over the 0 ms to 1000 ms PT range using the Python library Bambi (Capretto et al., 2022). This allowed us to examine age-related differences in the congruency effect, as defined by an accuracy difference score, at each time point in the PT range. We report the probability of direction (pd). The pd is the proportion of the obtained posterior distribution that is the same direction as the median of the posterior. The pd can range from 0.5 to 1. A pd of 0.5 indicates no evidence for the existence of an effect (i.e., a posterior completely centered on 0). A pd close to 1 indicates very strong evidence for the existence of an effect (i.e., a posterior that is almost all negative or all positive). We highlight periods of time during which $pd \geq 0.975$ and interpret this as strong evidence for an effect. We also highlight times during which $0.9 \leq pd < 0.975$ and interpret this as some evidence for an effect.

Computational Model of Response Preparation

We conducted a model-based analysis in which we treat response accuracy arising from competitive preparation of habitual and goal-directed response mappings (see Fig. 2a for a schematic of the model). According to this model, habitual responses to the entire array of arrows and goal-directed responses to the identity of the central arrow are prepared independently and in parallel with normally distributed latencies (response preparation

distributions in Fig. 2a). Response accuracy is assumed to be a Bernoulli variable with probability θ . This probability is assumed to be a function of time t and denotes the probability of expressing the correct response at t . It is defined as the product of a matrix specifying the preparatory state at t (ϕ) and a matrix of the conditional mappings of preparatory states to responses (ψ). Note the subscript c and i refer to the predictions for congruent and incongruent trials respectively:

$$\begin{aligned}\theta_c(t) &= \psi_c \cdot \phi(t) \\ \theta_i(t) &= \psi_i \cdot \phi(t)\end{aligned}\tag{1}$$

The matrix $\phi(t)$ in Eq. 1 gives the probabilities of all combinations of habitual and goal-directed responses being prepared and unprepared at t (response preparation state probabilities in Fig. 2a). These probabilities depend on t and the preparation parameters (μ and σ):

$$\phi(t) = \begin{bmatrix} \text{P(not habit and not goal)} \\ \text{P(habit and not goal)} \\ \text{P(goal and not habit)} \\ \text{P(habit and goal)} \end{bmatrix} = \begin{bmatrix} (1 - \Phi(t, \mu_h, \sigma_h))(1 - \Phi(t, \mu_g, \sigma_g)) \\ \Phi(t, \mu_h, \sigma_h)(1 - \Phi(t, \mu_g, \sigma_g)) \\ (1 - \Phi(t, \mu_h, \sigma_h))\Phi(t, \mu_g, \sigma_g) \\ \Phi(t, \mu_h, \sigma_h)\Phi(t, \mu_g, \sigma_g) \end{bmatrix}\tag{2}$$

Where Φ denotes the cumulative distribution function for the normal distribution. Then, for example, $\Phi(t, \mu_h, \sigma_h)$ is the probability of the habitual response being prepared at t , and $1 - \Phi(t, \mu_h, \sigma_h)$ is the probability of the habitual response not being prepared at t . As we assume each response is prepared independently, Eq. 2 contains the joint probabilities of all combinations of habitual and goal-directed responses being prepared and unprepared.

The matrix ψ in Eq. 1 specifies the probabilities of expressing a habit or goal depending on the preparatory state (weights in Fig. 2a):

$$\psi_c = [\alpha \quad \beta_h \quad \beta_g \quad \beta_g]$$

(3)

$$\psi_i = [\alpha \quad 1 - \beta_h \quad \beta_g \quad \beta_g]$$

In Eq. 3, α is the probability of expressing the correct response (the goal) if neither the goal nor the habit is prepared. This probability can be thought to capture ‘chance’ performance in a task. β_h is the probability of expressing the habitual response given only the habitual response is prepared. Since the habitual response is incorrect on incongruent trials and we are modeling accuracy, we use $1 - \beta_h$ for incongruent trials. β_h can be thought of as an inhibitory control parameter, as a decrease in β_h would capture an increased ability to suppress habitual response expression. β_g governs the probability of correctly expressing the goal-directed response any time the goal-directed response is prepared. This includes time periods when the goal is prepared but the habit is not prepared, and time periods when both the habit and the goal are prepared. β_g captures ceiling level accuracy in forced-response tasks.

In summary, the model yields 7 group level parameters. These are the means and standard deviations of the habit and goal preparation distributions ($\mu_h, \mu_g, \sigma_h, \sigma_g$), the probability of emitting the correct response if nothing is prepared α , the probability of emitting the habitual response if only the habit is prepared β_h , and the probability of emitting the goal-directed response if the goal is prepared β_g .

We allowed all parameters except for α (the chance-level guess rate) to vary with age group. We examined the 95% credible interval (95CI) to test for an effect of age group on parameters. If the credible interval does not contain 0, we interpret this as strong evidence for the

existence of an effect. We also again report the probability of direction (pd), which was calculated the same way as described in the behavioral analysis section.

The model described above was programmed with the Python library PyMC (Abril-Pla et al., 2023). Weakly informative priors were assigned for each parameter to increase identifiability. The prior for the effect of age group was zero-centered to reflect ambiguity about this effect. The model was fit hierarchically to the data, meaning a group level set of parameters constrained parameter estimation at the participant level.

Figure 2b shows the possible effects of age on model parameters, and how changes in these parameters would affect behavioral performance. Specifically, an inhibitory control deficit in older adults could be the result of three unique deficits in control compared to younger adults: 1) facilitated habitual processing (decrease in μ_h), 2) slowed goal-directed processing (increase in μ_g), or 3) disinhibited habitual output (increase in β_h). Alternatively, older adults could demonstrate global slowing relative to younger adults, which would result in a slowing of both habitual and goal-directed response preparation (increase in μ_h and μ_g).

Free RT Simulation

Upon observing the modeling results from our experiment, we sought to determine whether these results could be used to explain variability across free RT aging studies using conflict tasks. We conducted a simulation analysis based on the model fit to the behavioral data. We simulated free RT data by choosing accuracy rates for each age group using β_g estimates. We found a suitable accuracy rate below β_g for each age group that would correspond to a strategy that balances speed and accuracy. For older adults, we simulated two additional conservative strategies, in which the chosen accuracy rate was closer to β_g . RT was computed as

the amount of processing time necessary to reach the chosen accuracy rate for congruent and incongruent conditions.

Results

A sliding-window smoothing of response accuracy over PT illustrates the time-dependent control of response conflicts in each age group (Fig. 3a). The difference in accuracy for congruent and incongruent trials was much larger at 300 ms than at 800 ms. Accuracy for incongruent trials initially dropped below chance level and then began to rise at approximately 350 ms, suggesting that participants were incorrectly responding to the flanking arrows during this time. To pinpoint when congruency effects emerged in each age group, we performed a rolling logistic regression analysis. We observe strong evidence for a main effect of congruency from 280 ms onward. For the interaction term, we observe strong evidence for a larger congruency effect in younger adults than older adults from 240 ms to 460 ms. This result is primarily due to the delayed deviation from chance-level performance in response accuracy for older adults compared to younger adults. We observe strong evidence for a larger congruency effect in older adults than younger adults from 610 ms to 670 ms. This result can be attributed to the delayed rise in accuracy to asymptote on incongruent trials for older adults compared to younger adults. Overall, these results illustrate that condition contrasts could lead to seemingly opposite conclusions about age-differences in inhibitory control depending on *when* a response is emitted.

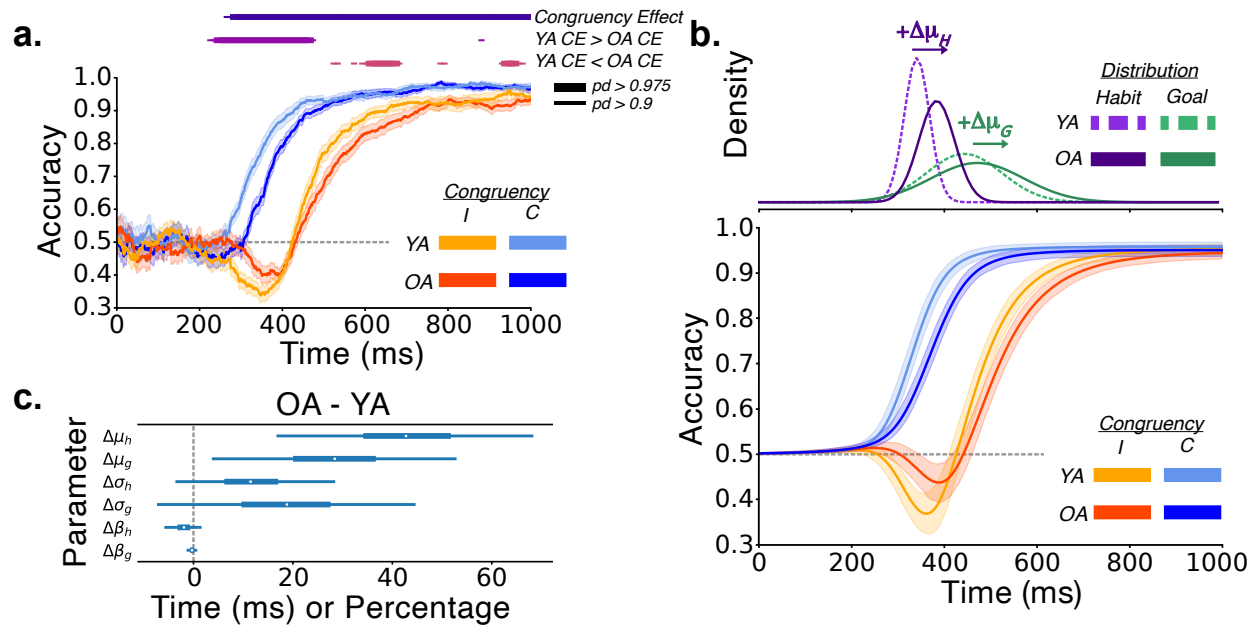


Fig. 3. Behavioral and modeling results for performance in the forced-response arrow flanker task. (a) Behavioral accuracy as a function of processing time split by congruency and age group. Error bars denote standard error. The bars above the plot show the results of the rolling logistic regression analysis and display time periods when there is a robust congruency effect (black), age effect on congruent trials (blue), or age effect on incongruent trials (orange). (b) Predicted response preparation distributions (top) and predicted behavior (bottom) obtained from fitting the response preparation model (RPM) to the data shown in (a). Note that the mean of both distributions is shifted later in time in older adults. (c) Contrasts showing the difference in parameter estimates between older and younger adults. The units for changes in μ and σ parameters are milliseconds. The units for changes in β parameters are percentages. The mean difference and the 95% credible interval are displayed. The dashed line denotes no difference. There is strong evidence that older adults show a delay in mean preparation time for both habitual and goal-directed responses.

Predicted response preparation distributions (top panel) and predicted behavior from fitting the response preparation model to the behavioral data (bottom panel) are shown in figure 3b. The predicted behavior from fitting the model to the data demonstrates that this modeling approach can capture the key differences between age groups present in the observed data. Notably, the model can capture the initial delayed rise in accuracy for congruent trials and the

delayed dip in accuracy for incongruent trials in older adults compared to younger adults.

Additionally, the model captures the delayed recovery in accuracy for incongruent trials in older adults compared to younger adults.

The difference in parameter estimates for older and younger adults is shown in figure 3C. We find strong evidence that habitual processing and goal-directed processing are both slower in older adults compared to younger adults ($\Delta\mu_h = 43.2$ ms, 95CI = [19.3, 67.9], $pd = 0.999$; $\Delta\mu_g = 24.3$ ms, 95CI = [0.690, 49.3], $pd = 0.978$). We find some evidence that habitual and goal-directed processing are also more variable in older adults compared to younger adults ($\Delta\sigma_h = 9.88$ ms, 95CI = [-4.62, 25.9], $pd = 0.900$; $\Delta\sigma_g = 21.1$ ms, 95CI = [-10.6, 52.3], $pd = 0.901$). Furthermore, we find only weak evidence for any difference in the tendency to express habitual and goal-directed responses in older adults compared to younger adults ($\Delta\beta_h = -1.87\%$, 95CI = [-5.64, 1.74], $pd = 0.845$; $\Delta\beta_g = -0.303\%$, 95CI = [-1.35, 0.689], $pd = 0.731$).

We additionally examined whether the age-related slowdown in goal-directed response preparation was more severe compared to the slowdown in habitual response preparation. We computed the difference between posterior samples from $\Delta\mu_g$ and $\Delta\mu_h$. If the slowdown in goal-directed response preparation was more severe, we would expect this difference posterior to not contain 0. However, we found only weak evidence for a difference in $\Delta\mu_g$ and $\Delta\mu_h$ ($\Delta\mu_g - \Delta\mu_h = -18.9$ ms, 95CI = [-53.5, 15.8], $pd = 0.856$). If anything, the slowdown in habitual response is numerically more pronounced compared to the slowdown in goal-directed response. This runs counter to the idea that aging leads to a selective slowdown in goal-directed processing.

Overall, these results suggest that aging leads to a global slowing in response preparation rather than a change in the ability to exert inhibitory control. Older adults show a slowing of both

habitual and goal-directed processing. This can be seen in the behavioral data (Fig. 3a), where it seems that age leads to a shift in the speed-accuracy tradeoff function for older adults compared to younger adults. The computational modeling analysis reproduced this shift, which is driven by both delayed latency in habitual response preparation, μ_h , and goal-directed response preparation, μ_g . Furthermore, this slowing did not appear more pronounced for either habitual or goal-directed responses.

Finally, we sought to account for how these group differences in performance on the forced-response flanker task could explain the documented variation in effects from free-response paradigms. The essence of the forced-response method is to explicitly map out the speed-accuracy tradeoff function by forcing participants to respond at specific times. However, in free RT paradigms, participants have the freedom to choose their own speed-accuracy criterion. We therefore used our model predictions as the true speed-accuracy tradeoff function for each group, and simulated situations in which participants can choose any point on these curves. We chose points for congruent and incongruent trial types on modeled younger adult speed-accuracy tradeoff functions (Fig. 4a). We reasoned that these points would represent a decision criterion that balances speed and accuracy. For older adults, we choose sets of points for congruent and incongruent trial types that represent three different decision criteria: 1) balanced speed and accuracy (OA1), 2) a conservative strategy to maximize accuracy (OA2), and 3) an overly conservative accuracy maximization strategy. We used these points to generate predicted mean RT for congruent and incongruent trial types by taking the amount of processing time necessary to reach a given point (Fig. 4b). We also used these predicted reaction times to calculate predicted congruency effects (Fig. 4c). This simulation demonstrates how a combination of processing speed and strategy differences between age groups is enough to

obtain: 1) larger congruency effects for older adults than younger adults (YA vs OA1), 2) no difference in older and younger adult congruency effects (YA vs OA2), and 3) smaller congruency effects for older adults than younger adults (YA vs OA3). Importantly, all three simulated free RT results can be explained by the a single underlying deficit, a global slowing of processing speed, combined with a shift in decision criteria that is possible in free RT paradigms.

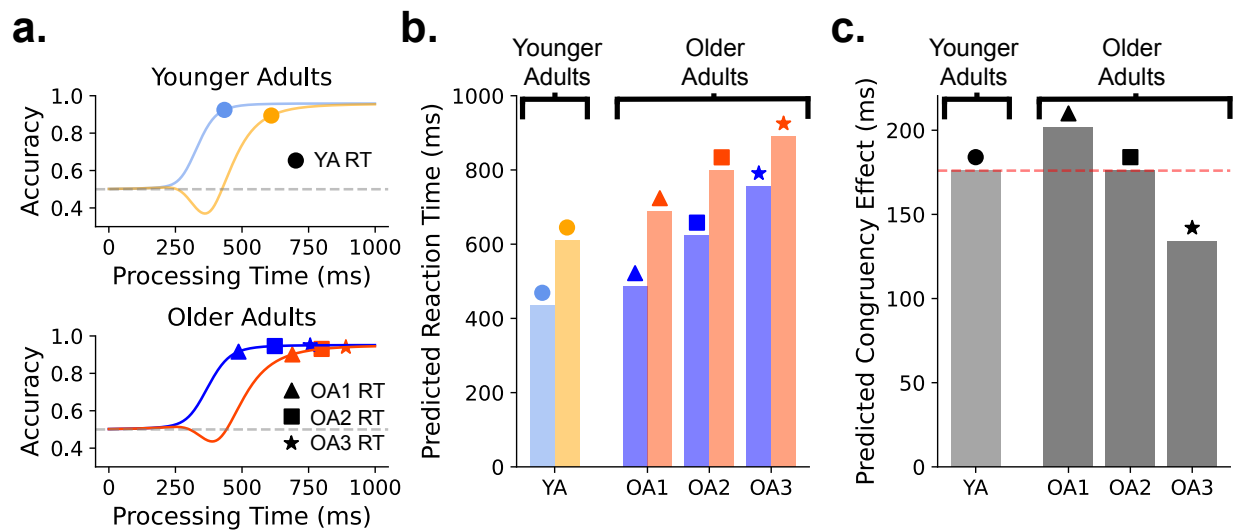


Fig 4. Simulation of free RT data from modeled forced-response data demonstrating how forced-response aging effects can explain variation in free RT aging-study effects. *(a)* We chose points for congruent and incongruent trial types on the group speed-accuracy tradeoff function for younger adults (upper panel). These points represent a decision criterion that balances speed and accuracy (YA, circles). For older adults, we chose three sets of points for congruent and incongruent trial types to compare to younger adults (lower panel). The first also represents a balanced speed-accuracy criterion (OA1, triangles). The second represents a conservative accuracy maximization strategy (OA2, squares). The third represents an overly conservative accuracy maximization strategy (OA3, stars). *(b)* We obtained predicted reaction times from our chosen decision criteria by computing how much processing time would be necessary to reach a given point on the speed-accuracy tradeoff function. Predicted reaction times are displayed for younger and older adults in both congruent and incongruent conditions. Note that the predicted reaction time is always higher for older adults than younger adults within congruency conditions, and the overall predicted reaction time increases with how conservative the older adult strategy is. *(c)* Using the predicted reaction times in *(b)*, we computed predicted congruency effects by taking the difference between predicted incongruent and predicted congruent reaction times. The dashed red line denotes the predicted younger adult congruency effect.

Discussion

A long-standing debate in the study of cognitive aging concerns whether aging results in a selective deficit in inhibitory control (Hasher & Zacks, 1988) in addition to a general slowing

of processing speed (Salthouse, 1996). The inhibitory control deficit hypothesis proposes that this process deteriorates with age, meaning older adults are more susceptible to task irrelevant distractions (Hasher & Zacks, 1988). However, the results of many experiments to test this hypothesis reveal great inconsistency in whether the congruency effect thought to index the efficacy of inhibitory control is smaller, larger, or the same comparing younger and older adults. We argue that traditional methods based on RT contrasts in classic interference resolution tasks using free-response paradigms lack the specificity needed to answer this question. To overcome this limitation, we applied the forced-response method in conjunction with a computational model to disentangle the contributions of habitual and goal-directed processing to overall behavior. The computational model specifies inhibitory control in terms of the latencies in the preparation of habitual and goal-directed responses as well as their overt expression probabilities. We found that the preparation of both habitual and goal-directed responses is slowed in older adults compared to younger adults. This shift in habitual and goal-directed response preparation is relatively constant, suggesting a global slowing of response preparation in older adults compared to younger adults. Furthermore, we found little evidence for any change in the probability to inhibit a prepared habitual response between age groups. These results strongly suggest that aging leads to a global slowing of processing rather than a selective deficit in inhibitory control processes.

We go beyond this by providing an additional analysis showing how a combination of processing speed differences and idiosyncratic choices about acceptable speed-accuracy criteria between age groups can result in different effects: 1) larger RT congruency effects for older compared to younger adults, 2) no difference in RT congruency effects for older and younger adults, and 3) smaller RT congruency effects for older compared to younger adults. How does

one make sense of these results? First, if both older and younger adults aim to balance speed and accuracy, their criterion for responding would result in a point on the speed-accuracy tradeoff function just before accuracy levels asymptote. This criterion would lead to larger congruency effects for older compared to younger adults, largely due to the processing speed differences between groups. Second, if older adults adopted a strategy that sought to maximize accuracy rates rather than balance speed and accuracy, their criterion for responding would result in a time after accuracy levels asymptote for congruent and incongruent trial types. This strategy difference between age groups could result in no difference between the overall congruency effect for older and younger adults. This strategy difference would also lead to larger overall RT differences and higher accuracy rates for older adults compared to younger adults, which has been observed in several free RT tasks (Ratcliff et al., 2001; Servant & Evans, 2020). Third, if older adults adopted a more extreme accuracy maximization strategy, their criterion for responding would result in an even later time after accuracy levels asymptote for congruent and incongruent trials. This strategy could result in smaller overall RT congruency effects for older adults compared to younger adults. Note that none of these alternatives is indicative of an inhibitory control deficit in older adults.

The forced-response method constrains participants' idiosyncratic speed-accuracy preference by cueing participants to respond at specific times. Because of this, we could directly model the component processes of inhibitory control. This approach makes it clear that processing speed differences are at the core of cognitive aging, and differences in conflict task performance observed in prior work could merely reflect age differences in speed-accuracy preference.

A recent study also used the forced-response method to investigate the effect of age on processing speed (Hardwick et al., 2022). Hardwick et al. used a planar reaching task with a forced-response and free RT condition. They found that processing time in the forced-response condition and RTs in the free RT condition both increased with age. However, they found that the difference between processing time and RT had no relationship with age. They interpreted this finding as evidence for processing speed differences primarily driving aging effects in this reaching task, since a shift in speed-accuracy preference would suggest that older adults have a larger difference in RT and processing time (i.e., an increased hesitancy to respond). As such, this work provides independent evidence of slower processing speed in older adults and demonstrates that slowed processing speed is not specific to a conflict task.

One shortcoming of the response preparation model is that the response preparation distributions that govern the latency of responding are agnostic as to the cognitive processes that underlie a response. For a response to be executed, the stimulus must be processed perceptually, the appropriate response must be selected based on this perceptual information, and then the motoric processes must unfold to move the hand. Our model does not afford inferences about which of these processes underlying the preparation of a response is slowed in older adults. Instead, the model simply quantifies the aggregated time needed to prepare a habitual or a goal-directed response. Indeed, prior work has suggested deficits in both perceptual processing speed and movement speed in older individuals (Ebaid et al., 2017; Ketcham et al., 2001; Salthouse, 1996).

The present work provides evidence that cognitive aging results in a global slowing of habitual and goal-directed processing rather than a specific deficit in inhibitory control. We further demonstrate that a global slowing is sufficient to explain the mixed results seen in

previous studies using free RT paradigms. These results highlight the utility of using a theory-informed, fine-grained approach to understand inhibitory control.

References

- Abril-Pla, O., Andreani, V., Carroll, C., Dong, L., Fonnesbeck, C. J., Kochurov, M., Kumar, R., Lao, J., Luhmann, C. C., Martin, O. A., Osthege, M., Vieira, R., Wiecki, T., & Zinkov, R. (2023). PyMC: A modern, and comprehensive probabilistic programming framework in Python. *PeerJ Computer Science*, 9, e1516. <https://doi.org/10.7717/peerj-cs.1516>
- Capretto, T., Piho, C., Kumar, R., Westfall, J., Yarkoni, T., & Martin, O. A. (2022). **Bambi**: A Simple Interface for Fitting Bayesian Linear Models in *Python*. *Journal of Statistical Software*, 103(15). <https://doi.org/10.18637/jss.v103.i15>
- Cohen, J. D., Servan-Schreiber, D., & McClelland, J. L. (1992). A Parallel Distributed Processing Approach to Automaticity. *The American Journal of Psychology*, 105(2), 239–269. <https://doi.org/10.2307/1423029>
- Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive Processing Speed across the Lifespan: Beyond the Influence of Motor Speed. *Frontiers in Aging Neuroscience*, 9. <https://doi.org/10.3389/fnagi.2017.00062>
- Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16(1), 143–149. <https://doi.org/10.3758/BF03203267>
- Evans, J. St. B. T. (2008). Dual-Processing Accounts of Reasoning, Judgment, and Social Cognition. *Annual Review of Psychology*, 59(1), 255–278. <https://doi.org/10.1146/annurev.psych.59.103006.093629>

- Haith, A. M., Pakpoor, J., & Krakauer, J. W. (2016). Independence of Movement Preparation and Movement Initiation. *Journal of Neuroscience*, 36(10), 3007–3015.
<https://doi.org/10.1523/JNEUROSCI.3245-15.2016>
- Hardwick, R. M., Forrence, A. D., Costello, M. G., Zackowski, K., & Haith, A. M. (2022). Age-related increases in reaction time result from slower preparation, not delayed initiation. *Journal of Neurophysiology*, 128(3), 582–592. <https://doi.org/10.1152/jn.00072.2022>
- Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, 108(3), 356–388. <https://doi.org/10.1037/0096-3445.108.3.356>
- Hasher, L., & Zacks, R. T. (1988). Working Memory, Comprehension, and Aging: A Review and a New View. In *Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). Elsevier. [https://doi.org/10.1016/S0079-7421\(08\)60041-9](https://doi.org/10.1016/S0079-7421(08)60041-9)
- Hübner, R., Steinhauser, M., & Lehle, C. (2010). A dual-stage two-phase model of selective attention. *Psychological Review*, 117(3), 759–784. <https://doi.org/10.1037/a0019471>
- Ketcham, C. J., Stelmach, G. E., Birren, J., & Schaie, K. W. (2001). Age-related declines in motor control. *Handbook of the Psychology of Aging*, 5, 313–348.
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychological Review*, 97(2), 253.
- Lee, T. G., Sellers, J., Jonides, J., & Zhang, H. (2024). The forced-response method: A new chronometric approach to measure conflict processing. *Behavior Research Methods*, 57(1), 15. <https://doi.org/10.3758/s13428-024-02516-y>

- Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, 12(4), 523–553. [https://doi.org/10.1016/0010-0285\(80\)90019-5](https://doi.org/10.1016/0010-0285(80)90019-5)
- Luck, S. J., Gaspelin, N., Folk, C. L., Remington, R. W., & Theeuwes, J. (2020). Progress toward resolving the attentional capture debate. *Visual Cognition*, 1–21. <https://doi.org/10.1080/13506285.2020.1848949>
- Nicosia, J., Cohen-Shikora, E. R., & Balota, D. A. (2021). Re-examining age differences in the Stroop effect: The importance of the trees in the forest (plot). *Psychology and Aging*, 36(2), 214–231. <https://doi.org/10.1037/pag0000599>
- Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences*, 16(5), 292–305. <https://doi.org/10.1016/j.tics.2012.04.005>
- Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, 51(1), 195–203. <https://doi.org/10.3758/s13428-018-01193-y>
- Perfect, T. J. (1994). What Can Brinley Plots Tell Us About Cognitive Aging? *Journal of Gerontology*, 49(2), P60–P64. <https://doi.org/10.1093/geronj/49.2.P60>
- Ratcliff, R., Thapar, A., & McKoon, G. (2001). The effects of aging on reaction time in a signal detection task. *Psychology and Aging*, 16(2), 323–341. <https://doi.org/10.1037/0882-7974.16.2.323>
- Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review*, 25(5), 1695–1716. <https://doi.org/10.3758/s13423-017-1384-7>

Rey-Mermet, A., Gade, M., & Oberauer, K. (2018). Should we stop thinking about inhibition?

Searching for individual and age differences in inhibition ability. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 44(4), 501–526.

<https://doi.org/10.1037/xlm0000450>

Ridderinkhof, K. R. (2002). Activation and suppression in conflict tasks: Empirical clarification through distributional analyses. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action* (1st ed., pp. 494–519). Oxford University Press.

Ridderinkhof, K. R., Forstmann, B. U., Wylie, S. A., Burle, B., & Van Den Wildenberg, W. P.

M. (2011). Neurocognitive mechanisms of action control: Resisting the call of the Sirens.

WIREs Cognitive Science, 2(2), 174–192. <https://doi.org/10.1002/wcs.99>

Ridderinkhof, K. R., van den Wildenberg, W. P. M., Wijnen, J., & Burle, B. (2004). Response

Inhibition in Conflict Tasks Is Revealed in Delta Plots. In *Cognitive neuroscience of attention* (pp. 369–377). The Guilford Press.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition.

Psychological Review, 103(3), 403–428. <https://doi.org/10.1037/0033-295X.103.3.403>

Salthouse, T. A. (2004). What and When of Cognitive Aging. *Current Directions in*

Psychological Science, 13(4), 140–144. [https://doi.org/10.1111/j.0963-](https://doi.org/10.1111/j.0963-7214.2004.00293.x)

[7214.2004.00293.x](https://doi.org/10.1111/j.0963-7214.2004.00293.x)

Servant, M., & Evans, N. J. (2020). A diffusion model analysis of the effects of aging in the

Flanker Task. *Psychology and Aging*, 35(6), 831–849.

<https://doi.org/10.1037/pag0000546>

- Stoffels, E. J., & Van Der Molen, M. W. (1988). Effects of visual and auditory noise on visual choice reaction time in a continuous-flow paradigm. *Perception & Psychophysics*, 44(1), 7–14. <https://doi.org/10.3758/BF03207468>
- Ulrich, R., Schröter, H., Leuthold, H., & Birngruber, T. (2015). Automatic and controlled stimulus processing in conflict tasks: Superimposed diffusion processes and delta functions. *Cognitive Psychology*, 78, 148–174. <https://doi.org/10.1016/j.cogpsych.2015.02.005>
- Verhaeghen, P. (2011). Aging and Executive Control: Reports of a Demise Greatly Exaggerated. *Current Directions in Psychological Science*, 20(3), 174–180. <https://doi.org/10.1177/0963721411408772>
- Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience & Biobehavioral Reviews*, 26(7), 849–857. [https://doi.org/10.1016/S0149-7634\(02\)00071-4](https://doi.org/10.1016/S0149-7634(02)00071-4)
- Veríssimo, J., Verhaeghen, P., Goldman, N., Weinstein, M., & Ullman, M. T. (2021). Evidence that ageing yields improvements as well as declines across attention and executive functions. *Nature Human Behaviour*, 6(1), 97–110. <https://doi.org/10.1038/s41562-021-01169-7>
- Voelcker-Rehage, C. (2008). Motor-skill learning in older adults—A review of studies on age-related differences. *European Review of Aging and Physical Activity*, 5(1), 5–16. <https://doi.org/10.1007/s11556-008-0030-9>
- Wong, A. L., Goldsmith, J., Forrence, A. D., Haith, A. M., & Krakauer, J. W. (2017). Reaction times can reflect habits rather than computations. *eLife*, 6, e28075. <https://doi.org/10.7554/eLife.28075>

Zhang, H., Sellers, J., Lee, T. G., & Jonides, J. (2024). The temporal dynamics of visual attention. *Journal of Experimental Psychology: General*.

<https://doi.org/10.1037/xge0001661>