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Detrimental Effects of Effortful Physical Exertion on a Working Memory Dual-Task in Older Adults

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Action and cognition often interact in everyday life and are both sensitive to the effects of aging. The present study tested the effects of a *simple* physical action, effortful handgrip exertion, on working memory (WM) and inhibitory control in younger and older adults. Using a novel dual-task paradigm, participants engaged in a WM task with 0 or 5-distractors under concurrent physical exertion (5% vs. 30% individual maximum voluntary contraction). Effortful physical exertion, although failing to effect WM accuracy in the distractor absent condition for both age groups, reduced WM accuracy for the older, but not young adults, in the distractor-present condition. Similarly, older adults experienced greater distractor interference in the distractor-present condition under high physical exertion, indexed by slower reaction time (RT), confirmed by hierarchical Bayesian modeling of RT distributions. Our finding that a *simple* but effortful physical task results in impaired cognitive control may be empirically important for understanding everyday functions of older adults. For example, the ability to ignore task-irrelevant items declines with age and this decline is greater when simultaneously performing a physical task, which is a frequent occurrence in daily life. The negative interactions between cognitive and motor tasks may further impair daily functions, beyond the negative consequences of reduced inhibitory control and physical abilities in older adults.

Public Significance Statement

In comparison to younger adults, older adults are less likely to ignore distractors in their surrounding when simultaneously engaging in a cognitive task and an effortful physical task. These age-related differences may be amplified in situations where task demands are higher, such as having increased physical exertion or increased distractor load. This suggests that when engaging in everyday tasks that often involve concurrent physical and cognitive action, older adults' ability to ignore distracting information may be limited.

Keywords: working memory, inhibition, cognition, cognitive control, handgrip

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Working memory (WM), a core cognitive process that maintains active information online in the service of ongoing mental activities (Cowan, 2001), declines steadily with age (Brockmole & Logie, 2013; Park & Reuter-Lorenz, 2009; Xie et al., 2019). Parallel to declining mental functions, physical functions also deteriorate with age. For instance, muscle mass and strength, such as isometric handgrip strength, steadily decline (Kallman et al., 1990; Samuel et al., 2013; Vandervoort, 2002) and on average healthy older adults' isometric strength is 20%–40% weaker than younger adults (Vandervoort, 2002). Therefore, it is imperative to assess the effects of aging on physical and cognitive functions, along with their interaction.

Sedentary lifestyles in older adults, which may lead to reductions in muscle mass and strength (Samuel et al., 2013), have been associated with declines in fluid (Erickson et al., 2015) but not

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Weiwei Zhang, Weizhen Xie, and Lilian Azer designed the study. Lilian Azer and Weizhen Xie collected data. Lilian Azer and Hyung-Bum Park conducted data analyses. All authors contributed to article preparation.

De-identified data, materials, and analytic code can be downloaded from https://osf.io/4jz65. The study design, hypotheses, and analytic plan were not preregistered.

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crystallized (Burzynska et al., 2020) abilities. Declines in physical strength can be accompanied by, and potentially preceded by (Taekema et al., 2012), declines in overall cognition at similar rates in aging (Praetorius Björk et al., 2016). In addition, handgrip strength and gait can predict cognitive performance (Taekema et al., 2010) and sociocognitive well-being (Blankevoort et al., 2013). While it is well-documented that muscle strength can predict cognition (Blankevoort et al., 2013; Burzynska et al., 2020; Erickson et al., 2015; Praetorius Björk et al., 2016; Taekema et al., 2010, 2012), dual-task paradigms aim to assess the interaction between physical and cognitive functions. In fact, dual-tasks decrements are observed when assessing postural control (Doumas et al., 2009; Rapp et al., 2006) and locomotion (i.e., tasks involving physical movement; Hausdorff et al., 2008; Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2011, 2012). Specifically, gait speed tends to decline in older adults while simultaneously walking and talking (Plummer-D'Amato et al., 2011) or simultaneously performing a cognitive task (Hausdorff et al., 2008; Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2012), and WM suffers at the expense of simultaneously performing a postural control task (Doumas et al., 2009; Rapp et al., 2006).

Recent literature has documented strong links between cognitive and motor functions, which can often interact with each other, especially when executive function is involved (Cappiello et al., 2018; Leisman et al., 2016; H.-B. Park et al., 2021; Voelcker-Rehage & Alberts, 2007; Xie & Zhang, 2023). For instance, engaging in a concurrent handgrip task during WM maintenance can impair young adults' memory performance (Xie & Zhang, 2023). More importantly, task-irrelevant distractors during the concurrent handgrip task can more easily capture visual attention (H.-B. Park et al., 2021) and get encoded into WM (Cappiello et al., 2018) under high physical exertion. In addition, the decline in WM performance can be observed when older adults simultaneously perform a WM and precision force-tracking task, which require fine motor control and coordination, than when the WM task is done in isolation (Voelcker-Rehage & Alberts, 2007). One possibility that could account for age-related declines in cognition while engaging in a motor task could be explained by the Li and Lindenberger's (2002) multilevel model on sensory, sensorimotor, and cognitive changes that occur in aging. This model suggested that neuronal reorganization that occurs in response to age-related functional loss could lead to modifications in behavioral responses to tasks that require attentional allocation, which may not be consciously controlled. Therefore, modifications in behavior to account for age-related sensory, sensorimotor, and cognitive changes and neural reorganization could serve as a compensatory mechanism that may result in long-term flexible changes in behavior that are determined by the task demand (for a review, see Li & Lindenberger, 2002).

The close interactions between motor and cognitive functions can provide inhibition-based effects of physical effort (Cappiello et al., 2018; H.-B. Park et al., 2021; Voelcker-Rehage & Alberts, 2007; Xie & Zhang, 2023). This offers an intriguing perspective, and thus novel opportunity, to investigate functional declines in older adults while engaging in activities that involve concurrent physical exertion given the widely observed age-related declines in cognitive control. For example, older adults are more susceptible to task-irrelevant visual stimuli suggesting age-related inhibitory failures in the presence of distracting information (Kramer et al., 1994). Reduced inhibitory regulation (i.e., ability to inhibit task-irrelevant information) and heightened distractibility, captured by the inhibitory deficit hypothesis, could account for age differences in WM (Hasher & Zacks, 1988). Age-related differences in the ability to inhibit distractors present during WM tasks suggest that older adults' ability to filter out distractors is reduced, which consequently can be reflected in reduced WM capacity (i.e., the number of items held in WM at a given time; Leiva et al., 2016; McNab et al., 2015). Therefore, due to reduced inhibitory control in older adults (Hasher & Zacks, 1988), and the susceptibility to task-irrelevant distractors during a concurrent handgrip and cognitive task (Cappiello et al., 2018; H.-B. Park et al., 2021; Xie & Zhang, 2023), it is possible that age could amplify the negative effects of effortful physical action on concurrent cognitive function. Given that many daily activities concurrently engage motor and cognitive functions, aging and age-related declines in inhibitory control and physical strength will pose a unique challenge to older adults.

The present study aimed to assess the interaction between physical exertion and working memory performance when distractors were present vs. absent in younger and older adults. Note, these effects can show different characteristics and may be supported by different mechanisms in comparison to the effects of acute or habitual physical activity (Erickson et al., 2015; Pontifex et al., 2019). Specifically, we assessed the impact of simple physical exertion through an isometric hand dynamometer (i.e., an apparatus that measures participants' maximum isometric handgrip strength, which involves static contraction of the hand muscles with restricted joint movements) on WM and inhibitory control using a novel dual-task paradigm, where participants engaged in a WM task under effortful physical exertion.

The use of an isometric hand dynamometer for the concurrent handgrip task in the present study is novel in that it allows for the inclusion of participants with varying mobile abilities rather than limiting older adults' participation based on mobility. For example, prior dual-task paradigms using a gait task (Hausdorff et al., 2008; Plummer-D'Amato et al., 2011, 2012) require that participants have functional mobility and can navigate a walking course. Approximately 35% of older adults may experience mobility limitations (Cummings et al., 2014; Freiberger et al., 2020) and consequently may be excluded from dual gait task paradigms. Therefore, the present study may expand the generalizability of the findings by allowing the inclusion of participants that may not have the mobile capabilities to participate in gait dual-task studies. While a precision grip task (Voelcker-Rehage & Alberts, 2007) may also allow for the inclusion of participants with varying mobile abilities, the handgrip task utilizes a power grip, which is more ecologically valid than a precision grip. For example, the use of a power grip (i.e., gripping an item centrally located in the palm of the hand using the thumb and all fingers to transmit force) in comparison to a precision grip (i.e., gripping an item using the thumb and one finger to transmit force) may be preferred when carrying a grocery bag, gripping a stairwell or escalator railing, or while driving. In fact, drivers apply roughly 31% maximum voluntary grip force on the steering wheel when driving (Eksioglu & Kızılaslan, 2008), which is consistent to our high physical exertion condition; therefore, simulating a real-world scenario of dual power grip and cognitive task. In comparison to our novel dual-task paradigm, gait (Hausdorff et al., 2008; Plummer-D'Amato et al., 2011, 2012) and precision grip (Voelcker-Rehage & Alberts, 2007) tasks in the previous dual-task studies can be more cognitively demanding and tend to require more cognitive control than a simple isometric handgrip task (Kobayashi-Cuya et al., 2018). In addition, the inexpensive and convenient use of handgrip measurement has become widely adopted in various clinical and experimental settings as a predictor of overall health (Bohannon, 2001) and a common indicator of cognitive declines in aging (Praetorius Björk et al., 2016). Last, the use of the hand dynamometer in the present study allowed us to standardize effortful physical exertion across participants by having subject-specific exerted force that is independent of physical strength or function (see Method section). Together, the present study and task paradigm are not only grounded in the previous literature with the dual-task paradigms involving gait, postural control, or precision grip tasks, but also extend this literature with important methodological novelty and theoretical novelty (e.g., the aging aspect).

In the present study, participants performed a visual WM task with and without distractors while simultaneously exerting different levels of physical effort on the hand dynamometer. Physical exertion was operationalized as handgrip force exertion at different subject-specific maximum voluntary contraction (MVC; 5% vs. 30%), independent of individual differences in muscular strength and fitness level. Given that high physical exertion impairs spatial attention (H.-B. Park et al., 2021) and may reduce inhibitory control, it is hypothesized that (a) inhibitory control of access to WM will be compromised under high physical exertion and (b) this effect will be amplified by age. Accordingly, it was predicted that (a) worse performance in the WM task will manifest in the 5-distractor condition than the 0-distractor condition under high physical exertion, but similar performance between the two distractor conditions under low physical exertion and (b) this two-way interaction will be more pronounced in the older adults than younger adults, yielding a significant three-way interaction. The present study provides a novel contribution to existing evidence of age-related decline in inhibition (Hasher & Zacks, 1988) by investigating how physical exertion can amplify age-related susceptibility to distractors. For example, exerting greater physical force during a cognition heavy task may elicit impairments in older adults' ability to inhibit task-irrelevant stimuli (Leiva et al., 2016; McNab et al., 2015) and may consequently result in accidents.

In testing these predictions, we assessed WM task performance using an accuracy-based measure, Cowan's K (representing the number of items successfully encoded in WM, Cowan, 2001; see Data Analysis section), as well as a speed-based measure, reaction time (RT). Analyzing RT alongside accuracy provides some advantages in testing the effect of concurrent physical effort on WM. First, RTs can capture moment-by-moment fluctuations in WM processes with continuous estimates. Second, the distributional characteristics of RTs could reveal underlying cognitive processes for various experimental effects (Balota & Yap, 2011; Hohle, 1965). For instance, to account for the mixed findings regarding the effect of physical effort on cognition (i.e., positive vs. negative effects, McMorris et al., 2011), H.-B. Park et al. (2021) postulated that two opposite effects may coexist and possibly cancel each other out in single-point estimates of RTs (e.g., mean RTs). Specifically, they used a computational measurement model, the *ex-Gaussian* model (a convolution of Gaussian function with μ and σ parameters and exponential function with τ parameter), to assess dissociable effects of physical exertion on a concurrent attention task in a handgrip and attention dual-task paradigm. They found that the RT benefit was consistent across the RT distributions (i.e., faster responses captured by the ex-Gaussian μ parameter), presumably reflecting effort-mediated phasic arousal (Aston-Jones & Cohen, 2005; Davranche et al., 2006), whereas the RT cost was present exclusively at the slowest portion of RTs (i.e., infrequent but delayed responses, captured by the ex-Gaussian τ parameter). Adopting H.-B. Park et al. (2021) approach, the present study will identify the origin of the detrimental effect of concurrent physical effort on WM function and how it manifests in different manners between younger and older adults.

Method

Transparency and Openness

The participant sample size was determined by an a priori power analysis (see Participants subsection of the Method section). Data exclusions, all manipulations, and all measures are outlined in the Participants and Procedure subsections of the Method section. De-identified data, materials, and analytic code can be downloaded from https://osf.io/4jz65. The study design, hypotheses, and analytic plan were not preregistered.

Participants

An a priori power analysis for mixed-effect analysis of variance (ANOVA) suggests that a total sample size of 18–36 participants (hence n = 9–18 per age group, assuming that the correlation among repetition measures is 0.5) would provide 80% statistic power for a significant mixed-effect interaction around the medium level (Cohen's f = 0.2–0.3, Faul et al., 2009). The medium-level effect was expected based on these following considerations. First, prior research testing age-related effect on dual-task cost in the cognitive or physical domain has yielded nontrivial effect sizes (Anguera et al., 2013; Beurskens & Bock, 2012; Jaroslawska et al., 2021). For example, by one estimate (see Figure 2 in Anguera et al., 2013), the dual-task cost in the cognitive domain for older participants around the age of 70 can be about 2 times of that for younger participants around the age of 20. Second, using a different dual-task paradigm but with similar age groups, we expected that our age-related effect of concurrent physical exertion on the modified WM task performance would be attenuated as compared with the prior research (Anguera et al., 2013). Therefore, a power analysis based on a medium-level effect size was used for the present study.

We have thus attempted to ensure the minimal sample size per age group required by the power analysis assuming an equal sample size in each age group, namely, $n \geq 18$. In the end, we recruited 19 older adults (47.4% female; $M_{\text{age}} = 72.37$, $SD_{\text{age}} = 5.04$; 5.3% Black or African American, 10.5% Hispanic, 84.2% White/non-Hispanic) from local communities in Riverside County, California with monetary compensation (20$/hr). In addition, we recruited 31 undergraduate students (56.3% female; $M_{\text{age}} = 20.37$, $SD_{\text{age}} = 2.27$; 53.1% Asian, 9.4% Hispanic, 25.0% White/non-Hispanic, 9.4% more than one race, 3.1% prefer not to respond) enrolled in the Introductory to Psychology courses at University of California, Riverside. As the college participants met our inclusion criteria outlined below, we included all the eligible young participants in our subsequent analysis. Specifically, our inclusion criteria required that all participants reported normal or corrected-to-normal vision, normal color vision, and be over the age of 18-years-old. None of the participants reported a history of major neurological (e.g., mild cognitive impairment, dementia, or stroke), psychiatric (e.g., mood disorders or schizophrenia), or medical (e.g., diabetes, HIV, or drug abuse) conditions. To mitigate the impact of sample size across age groups on our analyses, we have focused on both within- and between-group comparisons and attempted to obtain converging evidence from both conventional and Bayesian hierarchical modeling techniques.

Additional data from three young and three older adults were excluded from the study due to unsuccessful handgrip recordings resulting from misuse of the hand dynamometer or arthritis. These participants were not able to complete the experiment as instructed and therefore were considered ineligible for this study. All research procedures were approved by the Institutional Review Board at the University of California, Riverside for the Attention and Memory IRB HS-12-097 protocol. Data collection occurred at the University of California, Riverside, which began in March 2018 and ended in February 2020. All participants were provided written informed consent and were compensated for their participation by course credits (undergraduate participants) or $20/hr (older adults).

Procedure

Stimuli were presented on an LCD monitor with a gray background (6.1 cd/m^2), using PsychToolbox-3 (Brainard, 1997) for MATLAB (The Math Works, Cambridge, Massachusetts) at a viewing distance of 57 cm. The monitor was calibrated with an X-Rite I1Pro spectrophotometer (X-Rite, Inc., Grand Rapids, Michigan). Participants' grip force was measured using an isometric Vernier HD-BTA hand dynamometer (Vernier, Beaverton, Oregon). Each participant first completed a brief assessment to obtain isometric MVC of grip force and then a visual WM task with a concurrent handgrip at different levels of %MVC.

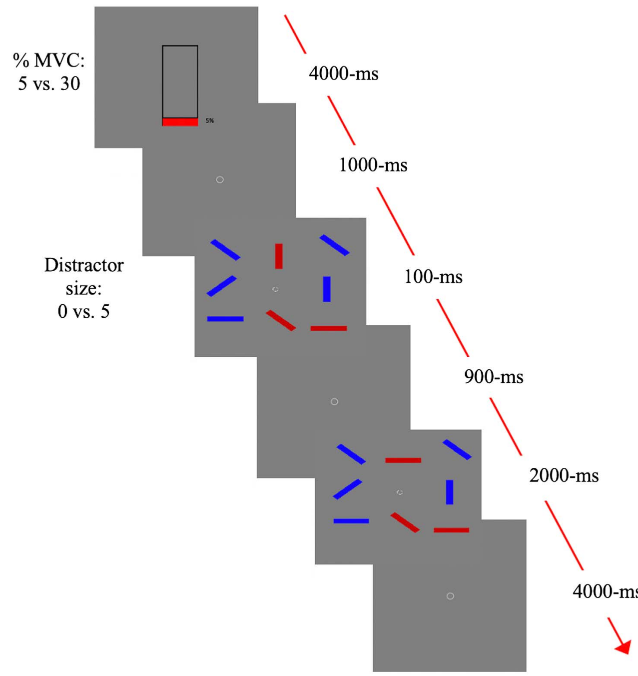
MVC Measurement

At the beginning of the experimental session, participants were instructed to hold the hand dynamometer in their left hand using maximum force for 4,000 ms with no visual feedback. This procedure was repeated 3 times. The median grip force level during the last 2,000 ms of the 4,000 ms measurement window was averaged across the trials as the MVC of each participant. Participants' initial MVC measurement was not directly used in the present study; however, each participant's MVC was measured in order to manipulate physical exertion by asking participants to grip the hand dynamometer at different levels of their initial MVC measurement.

Participants practiced across 10 trials to grip hand dynamometer and maintain their grip force at 5%, 30%, or 65% of their MVC for 4,000 ms, with real-time visual feedback of the exerted grip force, indicated by a red visual gauge of the exerted force proportional to their %MVC (Figure 1). Gripping the hand dynamometer at various levels allowed participants to get a sense of the amount of force they can exert on the device in order to successfully grip the dynamometer at the indicated level throughout the dual task. Each practice trial began with the promote "Please get ready! Please hold the handgrip at the required level AFTER you hear a beep" at the center of the

Figure 1

Stimuli and Procedure for the Concurrent Physical Exertion and Change Detection Task



Note. Each trial began with a 4,000 ms screen prompting participants to grip the hand dynamometer at the indicated level (5% or 30% MVC) followed by the memory array containing 0-distractors or 5-distractors (shown above). After a 900-ms delay interval, a test array was presented for 2,000 ms and participants were instructed to make a timed response within the 6,000 ms interval. MVC = maximum voluntary contraction. See the online article for the color version of this figure.

display for 500 ms followed by a centrally located visual gauge providing real-time feedback on the exerted grip force. The visual gauge, 4° by 6° in visual angle, showed a red bar with dynamically changing height that was proportional to the exerted grip force, relative to the required exertion marked as a black horizontal line (e.g., see first screen in Figure 1). Upon successful maintenance of the grip force at the indicated %MVC, participants were provided with an auditory "Cha-Ching" sound and visual feedback stating, "You have successfully maintained the force!" However, if participants were unsuccessful at maintaining the grip force at the indicated %MVC, they were provided with a "Beep" sound and visual feedback stating, "Not quite. Please try harder!" If participants were unable to maintain their grip force at the indicated % MVC level for more than 50% of the practice trials, they were given another set of 10 practice trials.

Hand dominance was not measured in the present study. Although handgrip strength and the MVC measure vary between hands (Incel et al., 2002), it is orthogonal to the task manipulation of physical effort in the present study. Specifically, participants were asked to grip the hand dynamometer at different levels (%) of their initial handgrip strength measurement; therefore, the amount of effort exerted on the hand dynamometer was standardized regardless of individual strength.

Concurrent Handgrip and WM Dual-Task

Next, in the concurrent handgrip and WM dual-task (Figure 1), each trial began with a screen prompting participants to initiate a left handgrip on the hand dynamometer at or slightly above 5% or 30% of their MVC. During the initial 4,000 ms, real-time visual feedback of the exerted grip force was provided similar to the practice handgrip trials. No visual feedback of force exertion was provided afterward. Participants were required to maintain the level of the required hand force throughout the visual WM change detection task until they made a response. As kinesthetic information (Ángyán et al., 2005) could be sufficient for subjective estimation of the exerted force with minimal WM load (Lowe, 1995), participants were able to successfully hold the handgrip at or slightly above the required hand strength level (96.73% overall handgrip accuracy), despite no real-time visual feedback. It was not surprising that participants could more successfully exert hand strength at 5% MVC (98.69% handgrip accuracy) than at 30% MVC (94.72% handgrip accuracy), $t(49) = 3.33$, $p = .002$, Cohen's $d = 0.48$. However, there is no significant age effect in this difference, $t(48) = -0.27$, $p = .792$, Cohen's $d = -0.04$. The subsequent analysis of WM task performance will primarily focus on the trials when participants successfully exerted hand force to the required level during the WM task.

While participants were maintaining their hand force at the required level of %MVC, they performed a visual WM task. In this task, a memory array consisting of orientation bars appeared for 100 ms. On half of the trials, this memory array displayed three red rectangular bars, while on the other half of the trials, this memory array displayed three red rectangular bars with five blue rectangular bars. These rectangular bars (5°-by-1° of visual angle in size) were randomly oriented horizontally, vertically, or diagonally and were presented at randomly selected centers within a 3-by-3 grid of an 11°-by-11° area in visual angles. Participants were required to only remember the orientation of the three red rectangular bars while ignoring any blue bars, making it a visual WM task of set size three with either 0 or 5 distractors. The memory array was followed by a 900 ms delay interval with a blank screen containing a central fixation point, after which a test array appeared and remained on screen for 2,000 ms. On half of the trials, this test array was identical to the memory array, while on the other half of the trials, one of the red orientation bars tilted either 45° or 90°. Participants were instructed to use their right index and middle fingers to press buttons on a Logitech Precision gamepad to indicate whether the test array was the same or different from the memory array, respectively, within a 4,000 ms maximum response time window. The accuracy of the change detection responses was emphasized over speed. All experimental factors including low versus high physical exertions, 0 versus 5 distractors, and change versus no change trials were randomly intermixed in each experimental block of 16 trials. The full experiment consisted of 10 blocks, yielding a total of 160 trials. These experimental trials were preceded by one block of 12 practice trials. Each experimental block obtained a 20-s break after 8 trials and all participants received a mandatory break of approximately 1 min between each block. Participants were encouraged to ask for longer breaks, as needed, to minimize fatigue. The experimental task, including breaks, took approximately 45 min to complete.

Data Analysis

Participants' change detection performance for task-relevant items was measured as Cowan's K: [(hit rate − false alarm rate) × N] (Cowan, 2001), where N is the task-relevant set size (i.e., three memory items). Higher Cowan's K values reflect a greater number of task-relevant items retained in visual WM (Supplemental Table 1). A two (younger adults vs. older adults) × two (0-distractor vs. 5-distractor) × two (5% vs. 30% MVC) mixed-effect repeated-measures ANOVA was performed on K for correct handgrip trials to investigate age-related differences across distractor and physical exertion conditions. To evaluate dual-task effects, only trials where participants' exerted grip force reached the indicated level of MVC during the WM change detection task were included in these analyses. Note, the participants were instructed to exert slightly over the required force with a range of force exertion classified as correct handgrip performance. Specifically, to qualify as a correct handgrip trial, participants were required to maintain the exerted force for no less than 5% but no greater than 30% MVC in the 5% MVC condition and no less than 25% but not greater than 55% MVC in the 30% MVC condition for more than 2/3rd of the time allocated for the memory display and delay interval. To help interpret findings from this ANOVA, we performed additional post hoc t tests to directly probe the difference between conditions/groups. We reported frequentist statistics along with Bayes factors based on post hoc Bayesian t tests (Rouder et al., 2009).

In addition, RT analyses were performed for correct handgrip trials. An outlier rejection for extremely short (<200 ms) or long (≥10,000 ms) RTs was conducted, resulting in 33 out of 8,080 total trials rejected (0.41%). For RT distributional analyses, we modeled correct RTs with ex-Gaussian function for each condition and each participant, under the hierarchical Bayesian approach developed by H.-B. Park et al. (2021). Specifically, the ex-Gaussian parameters were estimated by adopting a hierarchical Bayesian method (Rouder et al., 2005) using MatlabStan (Stan Development Team, 2016). With this approach, we estimated the grand mean of posterior parameter values at the population level, while simultaneously accounting for variabilities across subject, condition, age group, and trial levels using Markov Chain Monte Carlo (MCMC) simulations. The main effects of each population-level ex-Gaussian parameter were estimated using a general linear model, sampling from the normal distribution. In this model, the mean is a sum of the fixed effect (condition-effect, age-effect, and condition-by-age interaction) and the random effect (individual-level), and the variability describes the individual-by-condition-by-age interaction effect. We chose reasonable to noninformative priors for all parameters to cover all plausible RT effects (e.g., 0–5 s) to minimize biases in posterior distribution due to the choice of priors.

This method produces the mean of the posterior distribution (from 20,000 MCMC samplings after 20,000 warming-up) and the interval containing 95% of the posterior distribution (95% highest density interval [HDI]; J. K. Kruschke, 2011), which can be treated as a point estimate and as an analog of a frequentist confidence interval, respectively. When making a statistical inference, the HDI can serve as the strength of evidence; thus, one can reject the null hypothesis if the positive or negative side of 95% HDIs for the difference between conditions does not cross over zero (J. Kruschke, 2014).

Results

Characteristics of the Current Sample

Sample demographics for younger ($N = 31$) and older ($N = 19$) adults are shown in Table 1. While previous studies reported attenuated MVC in older adults (Samuel et al., 2013; Vandervoort, 2002), we did not observe a significant age difference in MVC in our sample, $t(48) = -0.60$, $p = .555$, Cohen's $d = -0.09$. Yet, this is unlikely due to the insensitivity of the MVC measure in the present study, as MVC was higher for men ($M = 168.92$, $SD = 64.71$) than women ($M = 139.49$, $SD = 58.08$) across both age groups, $t(48) = 4.51$, $p < .001$, Cohen's $d = 0.65$. Considering that physical exertion in the present study is manipulated as %MVC, the potential effects of the presence (or absence) of individual and group differences in physical strength manifested as MVC are largely removed. We also did not observe a significant difference in the likelihood of successful hand strength maintenance during the visual WM task between younger ($M = 97.07$, $SD = 3.91$) and older ($M = 96.31$, $SD = 4.66$) adults during the change detection task, $t(48) = -0.56$, $p = .577$, Cohen's $d = -0.08$.

Visual WM Change Detection Performance Under Concurrent Physical Exertion

Of primary interest, we investigated Cowan's K across experimental conditions and age groups in successful handgrip maintenance trials, based on a three-way mixed-design repeated-measures ANOVA with age group (younger vs. older adults) as a between-subject factor and distractor presence (absent vs. present) and physical exertion (5% vs. 30% MVC) as within-subject factors. Consistent with the effects of distractor presence commonly observed in visual WM literature, distractor size has a significant main effect on Cowan's K for task-relevant items, $F(1, 49) = 56.83$, $p < .001$, $\eta_p^2 = .54$. Observers remembered more task-relevant items in the distractor absent condition ($M = 2.46$, $SD = 0.46$) compared to the distractor present condition ($M = 2.19$, $SD = 0.60$). Furthermore, there was a significant main effect of age, $F(1, 49) = 89.81$, $p < .001$, $\eta_p^2 = .65$, such that younger adults remembered more task-relevant items ($M = 2.50$, $SD = 0.20$) than the older adults ($M = 1.84$, $SD = 0.39$). The main effect of physical effort on change detection performance was not statistically significant, $F(1, 49) = 0.07$, $p = .786$, $\eta_p^2 < .01$.

More importantly, we found a significant three-way interaction across age, distractor presence, and physical exertion, $F(1, 49) = 6.86$, $p = .012$, $\eta_p^2 = .12$. To further evaluate this interaction, we performed two separate two-way mixed-effect ANOVAs with factors of age group and physical exertion, for when distractors in the visual WM task were present or absent (i.e., 5- vs. 0-distractor conditions, respectively). When distractors were present, there was a significant interaction between age-group and concurrent physical exertion on Cowan's K, $F(1, 49) = 10.19$, $p = .002$, $\eta_p^2 = .17$. Older adults retained fewer task-relevant visual WM items under high physical exertion ($M = 1.49$, $SD = 0.49$), in comparison to low physical exertion ($M = 1.72$, $SD = 0.43$), $t(18) = 2.32$, $p = .032$, Cohen's $d = .53$, $BF_{10} = 1.99$ (Figure 2A). This pattern however was marginally significant in younger adults, $t(30) = -1.92$, $p = .065$, Cohen's $d = -.34$, $BF_{10} = 0.95$. When distractors were absent, we did not observe a significant interaction between age-group and concurrent physical exertion on Cowan's K, $F(1, 49) = 0.33$, $p = .568$, $\eta_p^2 = .01$. In other words, the extent of distractor interference (i.e., present–absent) on WM increased for older adults when exerting higher physical force (Figure 2B), leading to the significant three-way interaction.

Collectively, these results suggest that effortful physical exertion compromised the inhibition of task-irrelevant information in older adults but less so for younger adults. In contrast, physical effort had no significant effect on WM performance for either age group when distractors were absent. Consequently, older adults would find it hard to remember task-relevant items when distractors were present in WM under a higher concurrent physical exertion.

An alternative account for the age effect manifested as increased distractor interference from low to high physical exertion could be, at least in part, due to greater physical fatigue in older adults throughout the experimental session. Although the present study utilized various measures to minimize physical fatigue (e.g., frequent breaks, see Method section), we directly looked at the grip performance and age-related effects over the course of the experiment blocks.

Physical fatigue has been found to be associated with a decline in amplitude as well as systematic changes in variability of the motor output (Cortes et al., 2014; Missenard et al., 2008; Morrison et al., 2005). Two measures in this regard were thus examined, the grip force amplitude (in % of individual MVC; Figure 3A) and the variability (Figure 3B), measured from the continuous grip exertion recording during the memory array and delay interval (100 ms + 900 ms). The 10 experimental blocks were divided into five big blocks with 32 trials in each block to ensure a sufficient number of trials for this block-by-block analysis. For the median grip force, a four-way mixed-design ANOVA with the factors of age group, physical exertion, distractor presence, and block sequence (Block 1 through 5) failed to yield any significant effects, including a nonsignificant main effect of block sequence, $F(4, 196) = 1.03$, $p = .396$, $\eta_p^2 = .02$, nonsignificant block-by-age group interaction, $F(4, 196) = 0.68$,

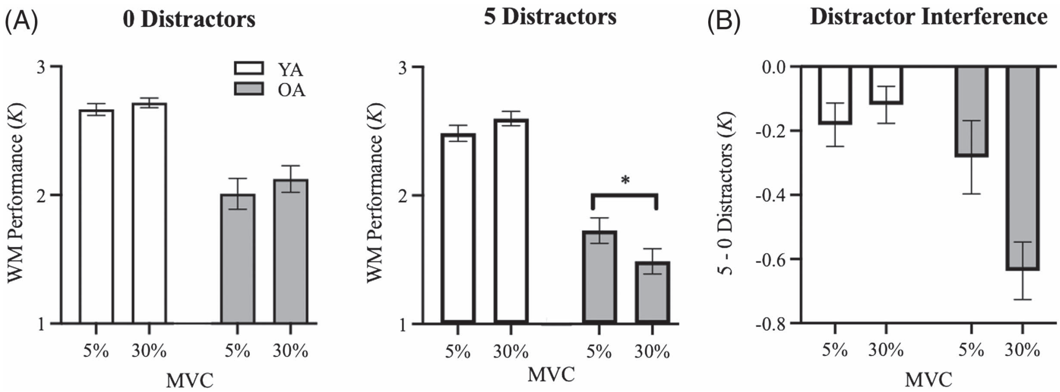
Table 1
Sample Demographics

Characteristics	Younger adults (18–28) *M (SD)/%*	Older adults (65–86) *M (SD)/%*	t/χ^2	*df*	*p*
Age (years)	20.35 (2.31)	72.37 (5.04)	—	—	—
Gender					
Female	54.80%	47.40%	.38	1	.539
MVC	149.47 (65.78)	160.37 (57.83)	−.44	47	.664
Female	126.93 (52.01)	163.21 (64.49)			
Male	176.84 (72.00)	157.82 (54.60)			
Years of education	14.08 (1.38)	15.18 (2.19)	1.85	41	.077

Note. MVC = maximum voluntary contraction.

Figure 2

Three-Way Interaction With Age Group (Younger vs. Older Adults), Distractor Size (0 vs. 5-Distractors), and Physical Effort (5% vs. 30% MVC)



Note. (A) Accuracy results (K) for the change detection WM task. Cowan's K from trials with successful handgrip trials in the 0-distractor condition and the 5-distractor condition across MVC and age group. (B) The distractor interference effect (differences in K across the distractor conditions). Error bars represent standard error of mean hereafter. MVC = maximum voluntary contraction; WM = working memory; YA = younger adults; OA = older adults.
* $p = .032$.

$p = .604$, $\eta_p^2 = .01$, and nonsignificant four-way interaction between all factors, $F(4, 196) = 1.67$, $p = .160$, $\eta_p^2 = .03$, except for the significant effect of physical exertion, $F(1, 49) = 212.01$, $p < .001$, $\eta_p^2 = .82$.

The force variability over the memory interval was estimated by the mean variance of continuous grip force normalized to the required force level (i.e., variance proportional to 5% or 30% MVC physical exertion). The same four-way mixed ANOVA for the force variance again revealed no statistically significant effects, including the main effect of block sequence, $F(4, 196) = 1.32$, $p = .268$, $\eta_p^2 = .05$, the block-by-age group interaction, $F(4, 196) = 1.09$, $p = .367$, $\eta_p^2 = .04$, and the four-way interaction between all factors, $F(4, 196) = 0.60$, $p = .664$, $\eta_p^2 = .02$. These results showed no indication of increasing physical fatigue over the course of the experiment and its interaction with the age group.

Nonetheless, we further assessed whether the primary experimental effect on memory performance (i.e., the increased distractor interference under higher physical effort in older adults, but not in younger adults) varies throughout the experimental session. To ensure reasonably robust measure of the memory performance, we split the 10 experiment blocks into the first half and the second half, yielding 20 trials per condition in each half. No significant change in the interaction effect on memory performance (that is, the difference in the distractor interference effect [*Cowan's K* for 5-distractors present minus *Cowan's K* for 0-distractors present] between high physical exertion and low physical exertion, see Figure 2B for an example) was observed in younger adults (first half: $M = 0.07$, $SD = 0.76$; second half: $M = 0.01$, $SD = 0.60$), $t(30) = 0.23$, $p = .813$; Cohen's $d = -.04$; $BF_{10} = 0.20$, or older adults (first half: $M = -0.44$, $SD = 0.84$; second half: $M = 0.84$, $SD = 1.07$; $t(18) = -1.38$, $p = .184$; Cohen's $d = -.32$; $BF_{10} = 0.54$).

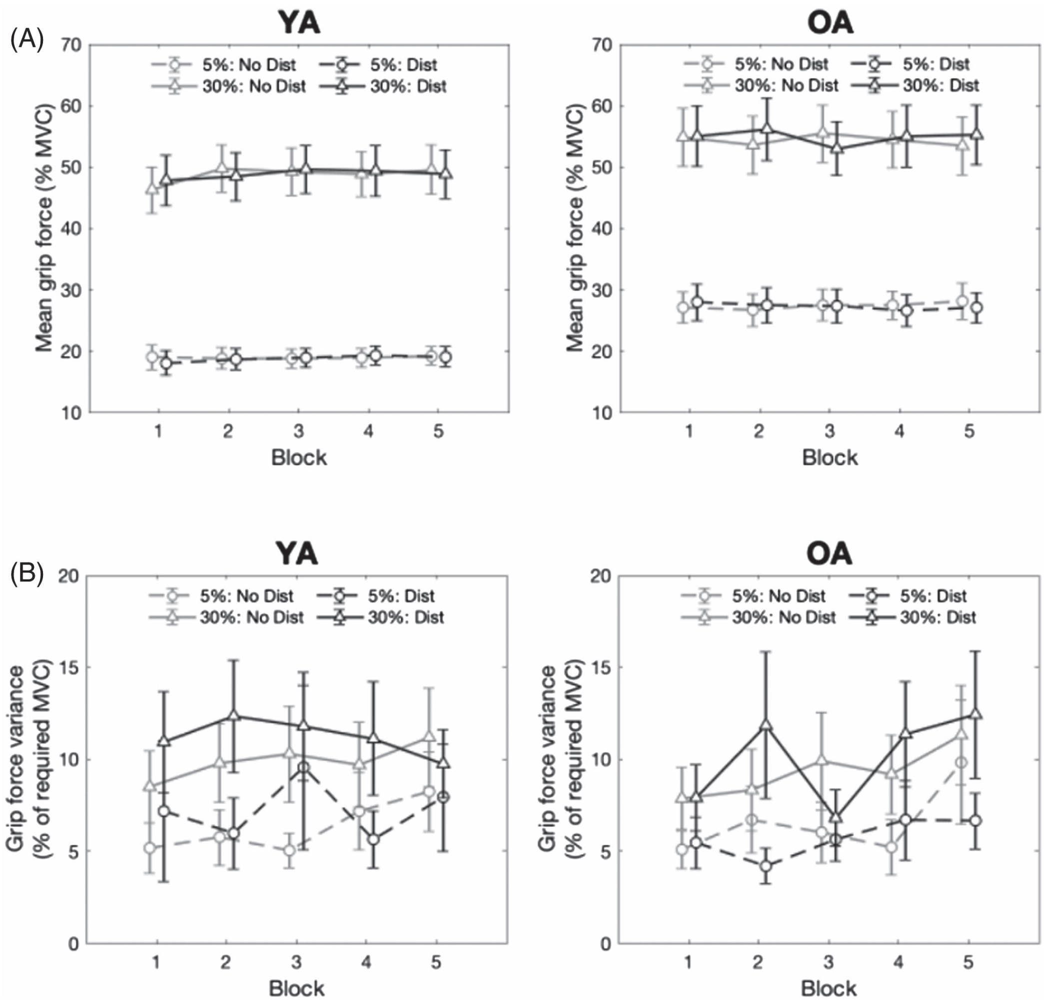
Reaction Time Effects of Concurrent Physical Exertion

Following the analyses on Cowan's K, a three-way mixed-design repeated-measure ANOVA for the correct RTs[1] (Figure 4A) was performed with two within-subject factors, distractor presence (absent vs. present), physical effort (5% vs. 30% MVC), and a between-subject factor, age group (younger vs. older adults). There were significant main effects of all three factors; for distractor presence, $F(1, 49) = 82.99$, $p < .001$, $\eta_p^2 = .63$, for age, $F(1, 49) = 19.61$, $p < .001$, $\eta_p^2 = .29$, and for physical exertion, $F(1, 49) = 4.66$, $p = .036$, $\eta_p^2 = .09$. The main effects of distractor presence and age group are conceptually in the same direction (i.e., worse performance) as the results of Cowan's K estimates. Specifically, participants' RT for the WM change detection task was slower when task-irrelevant distractors were present and in older adults than younger adults. However, physical exertion yielded an opposite effect as the one for Cowan's K. Specifically, RT was significantly *faster* under high physical effort ($M = 900.3$ ms, $SD = 263.3$ ms) compared to low effort ($M = 920.8$ ms, $SD = 283.8$ ms).

The opposite RT effects, the RT-facilitation effect of physical effort versus the RT-interference effects of distractor presence and age group, could cancel each other out and attenuate the interaction effects of these factors, in line with the findings from H.-B. Park et al. (2021). Accordingly, the three-way interaction was marginally significant, $F(1, 49) = 3.41$, $p = .071$, $\eta_p^2 = .07$. However, separate two-way mixed-effect ANOVAs for each distractor presence condition (present vs. absent) revealed an apparent asymmetry in the age-by-physical effort interaction, which was significant in the distractors present condition, $F(1, 49) = 4.18$, $p = .046$, $\eta_p^2 = .08$, but not in the distractor absent condition, $F(1, 49) = 0.05$, $p = .817$, $\eta_p^2 < .01$. In other words, the extent of RT delay due to distractor interference (i.e., present–absent) was comparable across all age groups and physical exertion conditions, except when older adults were presented with the distractors under the higher physical effort (Figure 4B).

[1] Correct RT was defined when both responses for change detection and handgrip tasks were correct. 4,569 out of 5,040 trials (90.7%) from younger adults and 2,365 out of 3,040 trials (77.8%) from older adults were submitted to RT analyses.

Figure 3
Mean Grip Force and Variability Across the Experimental Blocks



Note. (A) Mean grip force for younger adults (YA) and older adults (OA) across the experimental blocks, and (B) grip force variance during the memory and maintenance interval periods for YA and OA across the experimental blocks. MVC = maximum voluntary contraction.

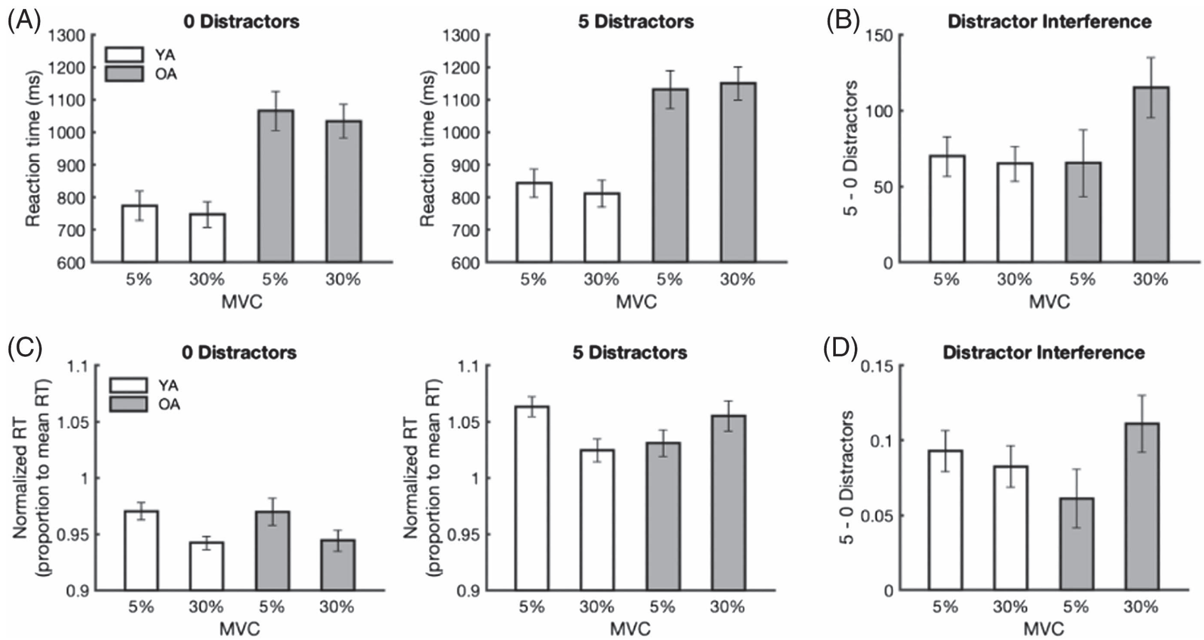
In addition to these analyses on the raw correct RT data, we further tested if the observed age difference in distractor interference under higher physical effort is due to an asymmetric scaling of the effect size arising from the difference in the overall processing speed and reaction time between the age groups.[2] It is well-established that effect of experimental manipulation typically increases with slower overall RTs (Faust et al., 1999; Verhaeghen, 2011). Especially when it comes to age-related differences, such exaggeration of RT costs may yield a misleading interpretation of RT differences often observed between age groups (Yi & Friedman, 2014). To control for the group difference in overall RT, we thus normalized the raw RTs as the proportion to individual mean RT. With normalized RTs, the condition effects manifest as the deviation from individual mean RT at 100% (Figure 4B). We repeated the same statistical analyses for the raw RTs and obtained comparable results for normalized RT. Specifically, the age-by-physical-effort interaction effects for distractor-present condition remained significant with a small increment of effect size, $F(1, 49) = 5.58$, $p = .022$, $\eta_p^2 = .10$, and it remained nonsignificant for distractor absent condition, $F(1, 49) = 0.02$, $p = .894$, $\eta_p^2 < .01$. This reaffirms the previous finding that the RT-interference effect in the distractor-present condition was mainly observed in older adults.

Hierarchical Bayesian Ex-Gaussian Analyses for Reaction Times

To further explore the nature of these opposite effects on mean RTs, we assessed whether these effects manifested on different aspects of the RT distributions, captured by our hierarchical Bayesian ex-Gaussian model, in a dissociable way. The group-level posterior mean and 95% HDI for each ex-Gaussian parameter (μ and σ for the Gaussian component and τ for the exponential component) as a

[2] We would like to thank an anonymous reviewer for suggesting this analysis using the normalized raw RTs for investigating age-related differences.

Figure 4
RT Results for the Change Detection WM Task



Note. (A) Mean RTs from trials with successful handgrip trials in the 0-distractor condition and the 5-distractor condition across MVC and age group. (B) The distractor interference effect (differences in RT across the distractor conditions, see main text for details). (C and D) Normalized RTs to the individual mean RT, where variations across conditions can be referred as deviation from 100% mean RT. RT = reaction time; WM = working memory; MVC = maximum voluntary contraction; YA = younger adults; OA = older adults.

function of age, distractor size, and physical effort are summarized in Table 2.

We reconstructed the three-way interactions for each parameter by taking the differences across conditions (i.e., the difference between age group [older − younger] for the difference between physical effort conditions [30% MVC − 5% MVC] and the difference between distractor size conditions [5-distractor − 0-distractor]; Figure 5). The resulting posteriors revealed a distinctive, opposite pattern between μ (−72.8 ms, 95% HDI [−127.6 ms, −24.0 ms]) and τ (+127.7 ms [+61.9 ms, +201.7 ms]), whereas no reliable effect was observed in σ (−19.1 ms [−60.1 ms, +18.0 ms]). Specifically, the three-way interaction in μ primarily manifested in a negative direction (i.e., RT benefit). On the contrary, the three-way interaction in τ was largely positive (i.e., RT cost). The bidirectional interaction effects on μ and τ indicate that, when irrelevant distractors were present under higher handgrip force exertion, older adults' responses were generally faster (captured by smaller μ), but at the expense of reduced inhibition of distractors which in turn resulted in an extreme delay (i.e., the slowest portion of the distribution, captured by greater τ).

Discussion

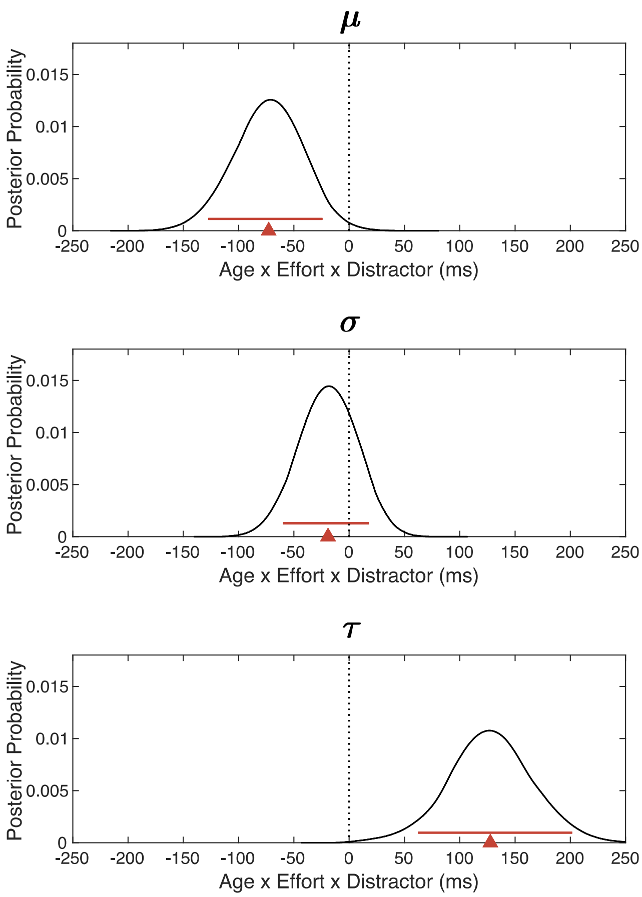
The present study investigated the effects of effortful physical exertion on cognitive control of accessing WM in younger and older adults. Effortful physical exertion (30% vs. 5% MVC), although it failed to affect WM accuracy when distractors were absent for either age

Table 2
Group-Level Posterior Mean and 95% Highest Density Interval (HDI) for Each Ex-Gaussian Parameter (μ, σ, and τ) as a Function of Age, Distractor Size, and Physical Exertion

	5% physical exertion		30% physical exertion	
Parameters	0-distractor	5-distractor	0-distractor	5-distractor
	Younger adults (*M* [$HDI_{95\%}$] in ms)			
μ	573.1 [560.6, 585.5]	591.7 [581.0, 604.3]	553.1 [541.7, 564.2]	580.4 [568.5, 592.7]
σ	82.1 [73.9, 91.9]	81.6 [73.1, 91.0]	75.4 [66.1, 83.6]	76.7 [66.8, 85.7]
τ	196.5 [181.1, 212.3]	244.3 [227.6, 260.2]	200.1 [185.1, 215.5]	232.4 [216.1, 250.3]
	Older adults (*M* [$HDI_{95\%}$] in ms)			
μ	761.0 [738.0, 784.1]	834.8 [809.9, 863.5]	773.9 [751.7, 799.6]	783.5 [758.7, 811.6]
σ	118.6 [101.7, 137.3]	138.7 [120.5, 159.8]	123.8 [105.4, 142.1]	126.7 [108.7, 151.2]
τ	304.0 [273.8, 333.5]	290.2 [260.6, 326.1]	268.6 [239.0, 297.6]	367.0 [329.7, 404.5]

Figure 5

Posterior Distributions of the Three-Way Interactions (Age Group, Distractor Size, and Physical Effort) for Each Hierarchical Bayesian Ex-Gaussian Parameters



Note. The posterior samples are fitted with a nonparametric kernel density function (solid black curves). The red triangles and the horizontal bars represent the means and 95% HDI of the posteriors of the interaction effects, respectively. HDI = highest density interval. See the online article for the color version of this figure.

group, reduced WM accuracy for the older adults, but not younger adults, when distractors were present. In other words, older adults were less likely to inhibit distracting information when engaging in an effortful physical task. Similar three-way interactions were found for mean RTs and hierarchical Bayesian ex-Gaussian analyses of RT components in the WM task. In particular, reduced inhibition in older adults, but not younger adults, under the distractor-present and higher exertion conditions manifested as a delay in the slowest portion of the RT distributions, captured by larger τ of the ex-Gaussian model of the RTs. An alternative account based on physical fatigue was further rejected. Together, these findings supported our prediction that reduced inhibitory control in WM manifested as worse performance in the change detection task for the distractor-present condition than the distractor absent condition under high physical exertion (30% MVC), which was more pronounced in older adults than younger adults.

Although the findings of the present study are consistent with some previous reports of the negative interactions between cognitive and motor tasks in older adults (Hausdorff et al., 2008; K. Z. Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2011, 2012; Voelcker-Rehage & Alberts, 2007), the experimental findings have several novel implications. For instance, prior studies have reported older adults to exhibit altered gait (Plummer-D'Amato et al., 2011, 2012), and worse cognitive performance during dual gait (Hausdorff et al., 2008; Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2012) or precision grip (Voelcker-Rehage & Alberts, 2007) tasks. These previous findings could be accounted for by the direct competition for cognitive control mechanisms across the motor and cognitive tasks. Specifically, these previous studies tend to use more demanding motor tasks (e.g., precision grip and gait) with significant involvement of cognitive control processes, as compared to the novel dual-task paradigm in the present study using an isometric handgrip task, which requires voluntary and static isometric muscle contraction (Cain & Stevens, 1971) without muscle movement (and movement of hand and objects). The handgrip task is expected to require minimal executive control and involvement of control network as opposed to gait or precision grip tasks (Kobayashi-Cuya et al., 2018). In fact, in comparison to a power grip, a precision grip elicits stronger activation in the prefrontal and posterior parietal cortices (Ehrsson et al., 2000), which are typically involved in working memory and cognitive control processes (Brass et al., 2005). One possibility could be that maintaining a precision grip could be more difficult than a power grip, therefore, the demand to maintain a precision grip could result in the need for increased cognitive control (Ehrsson et al., 2000). Empirically, our findings suggest that a simple, yet effortful physical action can negatively impact inhibitory control when distractors are present. Therefore, it could be assumed that the use of subject-specific power grip for the novel physical exertion dual-task manipulation in the present study may require less demand on cognitive control and working memory processes as opposed to other dual-task manipulations (Hausdorff et al., 2008; K. Z. Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2011, 2012; Voelcker-Rehage & Alberts, 2007).

Theoretically, our finding that older adults exhibited decreased ability to inhibit distractors in the high physical exertion condition provides strong evidence for inhibition-based theories of cognitive aging (i.e., the ability to inhibit distracting information declines with age; Hasher & Zacks, 1988). Extending on this, our findings also capture the impact of physical exertion on inhibitory control during dual-task conditions. The dual-task paradigm in the present study was adopted from Vogel and Machizawa (2004, 2005) where contralateral delay activity (CDA), an event-related potential that significantly increases in amplitude as the number of items held in memory increases and asymptotes when it reaches individuals' memory capacity, was recorded. When distractors are present, the amplitude of CDA was smaller than when distractors were not present, suggesting that cognitive control processes are responsible for regulating items that access WM and are essential for ensuring task-irrelevant items do not consume WM (Vogel et al., 2005). Increased distractibility, potentially as a result of poor inhibition, is likely due to impaired, or reduced, ability to filter out task-irrelevant stimuli, therefore attentional allocation to task-relevant items may suffer (Gaspelin & Luck, 2018; Ophir et al., 2009). The decline in cognitive inhibition for older adults observed in the present study, using the WM task adopted from Vogel and Machizawa (2004, 2005), was amplified by concurrent high physical exertion.

Dual-task decrements, which are defined as a deficit in performance for one task when simultaneously engaging in a secondary task, can offer a potential explanation for the findings in the present study. For example, gait speed (Hausdorff et al., 2008; Plummer-D'Amato et al., 2011, 2012) and precision grip variability (Voelcker-Rehage & Alberts, 2007), along with performance on cognitive tasks (Hausdorff et al., 2008; K. Z. Li et al., 2001; Lindenberger et al., 2000; Plummer-D'Amato et al., 2011, 2012; Voelcker-Rehage & Alberts, 2007), are altered during dual-task, in comparison to single-task, conditions. With the understanding that action and cognition are often intertwined in daily life, and may compete for overlapping neural mechanisms (Leisman et al., 2016), it is possible that during the simultaneous WM and handgrip task similar dual-task decrements observed within-domain are observed across domains.

The results of the present study may also be explained by an arousal-based enhancement effect (also see H.-B. Park et al., 2021), where older adults, but not younger adults, in the present study had reduced inhibition when distractors were present during high physical exertion condition. This effect was manifested as opposite patterns in the μ and τ components of the ex-Gaussian analyses of the WM task RTs. It is however possible that the two effects observed in the present study may stem from the same neurocognitive mechanism. For example, high physical exertion can yield heightened arousal which in turn increases norepinephrine (NE) released in the locus coeruleus (LC; Nielsen & Mather, 2015) and the LC-NE system is modulated by distractor interference (Aston-Jones & Cohen, 2005). Its subsequent effect on cognition seems more pronounced in tasks involving executive functions (e.g., working memory and inhibitory control; Mather & Harley, 2016; Mather et al., 2016). Therefore, arousal stemming from high physical exertion in the present study for older adults may have resulted in increased distractor interference and speeded responses. One possibility is that cognitive functions that are typically negatively impacted by age, such as the ability to inhibit distractors (for a review, see Mather & Harley, 2016), may depend on the LC-NE pathway. Arousal and the LC-NE responses to arousal can increase cortical activity when initial activation levels are high, that is for novel or salient information, but it can alternatively dampen cortical activity in regions where activation is low, that is for less salient information. Specifically, arousal and the LC-NE system are associated with the ability to selectively attend to task-relevant information and inhibit task-irrelevant information (Dahl et al., 2022). However, when salient and nonsalient information was presented, younger adults had increased processing and parahippocampal place area (PPA)-LC functional connectivity for only salient information, while older adults had increased processing and PPA-LC functional connectivity for both salient and nonsalient information (Lee et al., 2018). It is possible that older adults in the present study were processing task-irrelevant distractors and task-relevant information similarly and their ability to inhibit task-irrelevant information and selectively attend to task-relevant information may be impaired despite increased arousal/activation of the LC-NE system.

In addition to this novel theoretical significance, our findings that a simple physical task resulted in impaired cognitive control may be empirically important for understanding everyday functions of older adults. Daily functions involving the need to attend to task-relevant information and inhibit task-irrelevant information may become difficult due to the negative interactions between cognitive and motor tasks, and consequently may increase the risk of injury. Age-related differences in grip strength (e.g., Kallman et al., 1990) were not replicated in the present study. This is likely due to a large percentage of high-functioning abilities of community subjects that volunteered for the experiment (i.e., a sampling bias). Consistent with this interpretation, older adults in the present study reported continued driving ability, which may indicate high-functioning abilities and preserved grip strength since it has been previously reported that on average drivers apply roughly 31% maximum voluntary grip force on the steering wheel (Eksioglu & Kızılaslan, 2008), as compared to 30% MVC at the high physical exertion condition in the present study. However, it is important to note that the current findings are expected to generalize across individual differences in grip and physical strength, given that the novel physical exertion manipulation in the present study is operationalized as the proportion of individual MVC. Nonetheless, future research needs to recruit a more representative sample of older adults.

Using a novel paradigm, the present study demonstrated that concurrent effortful physical action can be detrimental to WM, especially in older adults. Reduced inhibitory control and physical abilities may pose a problem for the aging population, considering cognitive and motor actions are rarely engaged in isolation in everyday life. As muscle mass and strength decline with age (Kallman et al., 1990; Samuel et al., 2013; Vandervoort, 2002), varying manipulations across different motor tasks should be considered for future research. Moreover, this effect should be examined in various clinical populations with reduced grip strength in which the same physical activities can be more effortful. For example, grip strength is reduced in schizophrenic patients compared to healthy adults and is positively associated with WM (Firth et al., 2018). However, research on concurrent physical effort in relation to individuals' handgrip strength is still sparse. Future studies should examine the relationship between concurrent effortful physical action in other domains of cognition in healthy and clinical populations. In addition, future studies should examine pupil dilation in response to physical exertion during a cognitive task as a proxy for LC activation (Liu et al., 2017) in order to gain a better understanding of how heightened arousal in the presence of distractors (LC-NE system; Xie et al., 2022) may reduce inhibitory control during a concurrent effortful physical and cognitive task. Last, the use of a handgrip device, compared to gait tasks, may allow future studies to explore the underlying neural mechanisms to better understand the interaction between physical and cognitive action using functional MRI. Given that age-related atrophy in cortical regions involved in motor function can result in motor deficit, and motor control in older adults may rely on a more widespread network than in younger adults (for a review, see Seidler et al., 2010), it is imperative to assess age-related brain changes in functional and structural cortices involved in motor and cognitive function, along with their interaction.

The present study did not include single-task conditions as the primary research interest was to investigate reduced inhibitory control under effortful physical exertion. However, single-task conditions would provide useful data for further exploration of dual-task costs and insightful understanding of age-related differences in cognitive vs. motor task prioritization. Another caveat of the present study includes the lack of information collected regarding hand dominance. While the amount of force exerted on the hand dynamometer was standardized across participants, it is likely that participants using their dominant hand (i.e., left-hand dominant participants) to grip the hand dynamometer perceived the grip task to be less effortful while performing the dual task compared to those using their nondominant hand (i.e., right-hand dominant participants). Last, the present study includes differences in compensation for participation between younger and older adults. Future studies should consider comparable compensation across experimental groups.

Conclusions

With the analyses of accuracy, RT, and hierarchical Bayesian ex-Gaussian analyses of RT, the present study found that effortful physical exertion (30% vs. 5% MVC) reduced cognitive control of access to WM for older adults, but not younger adults. In other words, older adults in the present study were less likely to inhibit distractor items and prevent them from being encoded into WM when simultaneously exerting high physical effort, which is consistent with inhibition-based theories of cognitive aging (Inhibitory Deficit Hypothesis; Hasher & Zacks, 1988) and some previous findings that report the negative interactions between cognitive and motor tasks in older adults (Plummer-D'Amato et al., 2011, 2012; Voelcker-Rehage & Alberts, 2007). Overall, our findings highlight the importance of age-related declines in WM and cognitive control, which may be amplified in situations where concurrent motor action takes place, such as in everyday tasks that involve a cognitive and motor component.

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