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Reduced Inhibitory Control Under Effortful Physical Exertion During Dual-Task Conditions

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Lilian Azer

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Dedication

To my parents, Dr. Wageh Azer and Eman Basta, my brother Mena Azer, and my husband, Dr. Joseph Yacoub

ABSTRACT OF THE DISSERTATION

Reduced Inhibitory Control Under Effortful Physical Exertion During Dual-Task Conditions

by

Lilian Azer

Doctor of Philosophy, Graduate Program in Psychology
University of California, Riverside, June 2023
Dr. Weiwei Zhang, Chairperson

Physical action and cognition are often entangled in our daily lives. To understand the impact of effortful physical action on cognition, the work presented in this dissertation used a *simple*, yet effortful, physical action (i.e., effortful handgrip exertion) during cognitive tasks to investigate 1) the effect of a simultaneous effortful physical and cognitive action on inhibitory control and 2) arousal induced by physical exertion. Physical exertion was operationalized as different levels (low versus high) of the maximal voluntary contraction (MVC) exerted on an isometric hand dynamometer, which is an apparatus that measures participants' maximum isometric handgrip strength and involves static contraction of the hand muscles with restricted joint movements. Across different task paradigms, effortful physical exertion impaired observers' ability to ignore distractors, or task-irrelevant items, and successfully recall/detect task-relevant items. While physical and cognitive effort often interact with one another, they can even exhibit similar behavioral and neural effects. For instance, pupillary response, such as pupil dilation, typically increases with cognitive or physical effort, indicating increased arousal and Locus Coeruleus-Norepinephrine (LC-NE) activity. Given that pupillary response is a proxy for LC-NE activity, the work in the present dissertation also aimed to examine the impact of engaging in a concurrent effortful physical and cognitive task on task evoked pupil responses (TEPR). Replicating prior work, effortful physical exertion induced greater pupillary response in comparison to lower physical exertion. However, high cognitive load and the interaction between physical exertion and cognitive load was not significant. The finding that a *simple* yet effortful physical task results in impaired cognitive control may be empirically important for understanding everyday functions of older and younger adults. For example, the ability to ignore task-irrelevant items may decline with age and this decline is greater when simultaneously performing a physical task.

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Chapter 1. General Introduction

1.1 Introduction

Throughout our daily life we often engage in simultaneous motor and cognitive actions. For example, when planning to prepare a healthy meal you may find yourself navigating through the grocery store as you locate the necessary ingredients. In the grocery store you may push a shopping cart, or carry a shopping basket, as you walk through the aisles. During this time, the physical action you are engaging in includes the act of walking as you grip the shopping cart, or basket. At the same time, you are engaging in the cognitive task requiring you to remembering the healthy ingredients you must purchase for your meal (task-relevant items) and utilizing inhibitory control to avoid purchasing unhealthy items that are not relevant for your goal (task-irrelevant items). This task, like many tasks we engage in during our daily life, involves Working Memory (WM; a core cognitive process that maintains active information online in the service of ongoing mental activities, Cowan, 2001) and inhibitory control (the ability to inhibit task-irrelevant information and attend to task-relevant information, Diamond, 2013).

Inhibitory control is a key component of cognitive control and may allow (or restrict) distracting information to gain access to WM (Vogel 2004, 2005). For instance, when distractors are present during a WM task, cognitive control processes actively regulate the items that access WM to ensure that only task-relevant items gain access to WM while task-irrelevant items do not consume WM (Vogel et al., 2005). In fact, the relationship between WM and cognitive control may be bidirectional where cognitive control processes work to inhibit task-irrelevant items from gaining access to WM (Vogel et al., 2005) and individual differences in WM capacity could modulate the recruitment of cognitive control (Engle & Kane, 2004; Redick, 2014).

In addition to the bidirectional relationship between WM and cognitive control (Engle & Kane, 2004; Vogel et al., 2005; Redick, 2014), arousal stemming from the task demand, or as an index of task effort, on WM and cognitive control may vary depending on the task conditions (Lambourne & Tomporowski, 2010; Tomporowski & Qazi, 2020; Unsworth & Robison, 2017; van der Wel & van Steenbergen, 2018). For instance, according to the locus coeruleus-norepinephrine (LC-NE) account of working memory capacity and attentional control (Unsworth & Robison, 2017) arousal may play a critical role for individual differences in WM performance and effort produced due to task demand. That is, observers have better WM precision (Xie & Zhang, 2016) and faster WM consolidation (Xie et al., 2022) under conditions of heightened arousal. The locus coeruleus (LC) is a small nucleus in the brainstem which releases norepinephrine (NE) during states of arousal (Aston-Jones & Cohen, 2005). Reduced LC-NE activity in low working memory capacity individuals can result in greater mind-wandering, and therefore more lapses of attention, compared to high working memory capacity individuals (Unsworth & Robison, 2017). Extending on this, van der Wel and van Steenbergen (2018) discussed an arousal-based account of effort exertion during tasks involving cognitive control. This account suggested that tasks involving inhibition, which is one of the cognitive control domains, may increase pupil dilation as an index of arousal when effort and task demand are high (van der Wel and van Steenbergen, 2018).

Furthermore, exercise-induced arousal on cognitive performance may produce differential performance outcomes depending on sequential or simultaneous engagement, mode of motor task, and intensity of the motor action in relation to the cognitive task (Lambourne & Tomporowski, 2010; Tomporowski & Qazi, 2020). For example, chronic habitual exercise and moderate intensity acute bouts of exercise improves WM, processing speed, attention, and executive functions (for a review see Erickson et al., 2015; Lambourne & Tomporowski, 2010). These results are supported by the inverted-U hypothesis (Davey, 1973; Yerkes & Dodson, 1908) which suggests that moderate, but not low or high, exercise intensity may produce optimal arousal for task performance. However, trial-by-trial investigation of effortful physical action in dual task conditions using isometric handgrip contractions may induce heightened arousal but at the expense of task performance (Azer et al., 2023; Park et al., 2021). For example, effortful physical action can produce physiological arousal (Nielsen & Mather, 2015) but, in line with the inhibitory control hypothesis, the effects of concurrent physical effort may impair cognitive task performance due to increased distractor interference (Azer et al., 2023; Park et al., 2021).

The work presented in this dissertation will focus on the impact of effortful physical action on cognitive functioning. The empirical research in this dissertation aims to provide an inhibitory control account and an arousal-based account of physical exertion on perception and cognition. Specifically, the work presented in this dissertation aims to assess task performance under effortful physical exertion during working memory and perception tasks that involve attending to task-relevant information and inhibiting task-irrelevant information. Furthermore, this dissertation aims to investigate effortful physical exertion and cognitive load on pupillary response as an index of arousal (Lui et al., 2017). Together, the work presented in this dissertation will highlight the importance of understanding the impact of physical effort on cognitive processes involving inhibitory control and arousal along with the translational implications.

1.2 Cognitive-Motor Interaction

The evolutionary bases and shared neural mechanisms for the cognitive-motor interaction have been recently documented (Leisman et al., 2016). In fact, Leisman et al. argued that postural muscles and normal development of postural control may be the bases for binding cognitive and motor action. This claim further asserts that it is possible that cognition evolved in parallel to postural development. In line with this, Leisman et al. discussed overlapping neural mechanisms that may represent both motor and cognitive processes where the role of attention and working memory are argued to serve motor processes. Moreover, frontoparietal regions (i.e., prefrontal and parietal cortices; Ikkai & Curtis, 2011; Gerver et al., 2020) and the basal ganglia (Middleton & Strick, 2000) are said to be associated with higher-order cognitive functions and are implicated in cognitive and motor processes. Prefrontal and posterior parietal cortices are typically involved in working memory and cognitive control processes (Brass et al., 2005) while the basal ganglia is thought to bridge cognitive and motor actions (Leisman et al., 2016) and connectivity between the basal ganglia and prefrontal cortices may even be involved in cognitive and inhibitory control processes (Casey et al., 2001; Nagano-Saito et al., 2014).

In addition to Leisman et al. ‘s (2016) evolutionary bases and shared neural mechanisms for the cognitive-motor interaction, the premotor theory of attention emphasizes the critical roles of oculomotor activities in orienting spatial attention (Rizzolatti et al., 1994; Shepard & Metzler, 1971). This is particularly important in natural vision in which human observers actively seek information from the environment by frequently directing the oculomotor system (i.e., eye movements) toward events deemed important beyond their fixation point (Irwin, 1991; Rizzolatti et al., 1994).

Recent literature has documented strong links between cognitive and motor functions (for a review see Leisman et al., 2016; Irwin, 1991; Rizzolatti et al., 1994). These links have been observed across sequential (Loprinzi & Kane, 2015; Kato et al., 2018; Washio et al., 2021; Saez de Asteasu et al., 2017; Zhu et al., 2017; Suzuki et al., 2012) and simultaneous (Park et al., 2021; Tomporowski et al., 2017; Xie & Zhang, 2023; Haudorff et al., 2008; Li et al., 2001; Lindenberger et al. 2000, Plummer-D’Amato et al., 2011, 2012; Doumas et al., 2009; Rapp et al., 2005; Voelcker-Rehage & Alberts, 2007) cognitive and motor actions involving varying intensities of physical action. However, the impact of physical action on cognition varies under these two observations (sequential vs. simultaneous) and the engagement of control networks (i.e., prefrontal and posterior parietal cortices) during the simultaneous cognitive and motor tasks (Ehrsson et al., 2000; Lim et al., 2021).

On one hand, acute bouts of exercise and chronic habitual exercise are effective in improving memory performance (for a review see Loprinzi et al., 2021). These effects can be observed when the physical activity is performed prior to a cognitive task. For example, chronic exercise, which is defined as multiple instances of engagement in physical exercise over a period of time, can improve WM performance (Loprinzi et al., 2021; Rathore & Lom, 2017; Suzuki et al., 2012) and subjective cognitive function (Miyawaki et al., 2017). Similarly, acute bouts of physical exercise, which are defined as engaging in one session of physical exercise, prior to the memory task have also been demonstrated to enhance post-exercise memory performance (Loprinzi et al., 2021). In fact, studies have reported that acute bouts of exercise are effective in improving executive functions (i.e., working memory, attention, inhibition) across younger (Loprinzi & Kane, 2015; Kato et al., 2018; Washio et al., 2021) and older (Saez de Asteasu et al., 2017; Zhu et al., 2017; Suzuki et al., 2012) adults.

On the other hand, simultaneously engaging in a physical action while performing a cognitive task may impair performance on one or both domains. For instance, older adults experience dual-task decrements (i.e., impairments in one or both domains) when engaging in concurrent dual cognitive and gait (Haudorff et al., 2008; Li et al., 2001; Lindenberger et al. 2000, Plummer-D’Amato et al., 2011, 2012), postural control (Doumas et al., 2009; Rapp et al., 2005), or precision grip (Voelcker-Rehage & Alberts, 2007) tasks. Similarly, younger adults had impaired visual search (Park et al., 2021), long term memory (Tomporowski et al., 2017), and working memory (Xie & Zhang, 2023) performance when simultaneously engaging in an effortful physical handgrip task. While studies assessing dual-task decrements and the effect of physical effort using a handgrip task may produce similar outcomes on cognitive performance, they tend to use a more demanding motor task (e.g., gait, postural control, precision grip) that may require significant involvement of cognitive control compared to the handgrip task. The handgrip task involves voluntary and static isometric muscle contraction (Cain et al., 1971) without muscle movement and movement of the hand or objects. In fact, the handgrip tasks may require minimal executive control and involvement of control networks as opposed to gait (Lim et al., 2021), postural control (Mahoney et al., 2016), or precision grip tasks (Ehrsson et al., 2000). Lastly, the handgrip task allows for trial-by-trail analysis of effortful physical exertion on cognitive function (Azer et al., 2023; Park et al., 2021; Xie & Zhang, 2023) unlike prior dual cognitive and motor action studies (Doumas et al., 2009; Haudorff et al., 2008; Li et al., 2001; Lindenberger et al. 2000, Plummer-D'Amato et al., 2011, 2012; Rapp et al., 2005; Tomporowski et al., 2017; Voelcker-Rehage & Alberts, 2007). Therefore, the present dissertation uses a novel dual-task paradigm to investigate the effect of a simple effortful motor task that requires minimal involvement of cognitive control on working memory and perception.

Chronic and acute physical activity in comparison to dual motor and cognitive tasks may differentially impact cognitive functioning where chronic and acute physical activity that occurs prior to the cognitive task may improve cognitive function (Loprinzi & Kane, 2015; Kato et al., 2018; Washio et al., 2021; Saez de Asteasu et al., 2017; Zhu et al., 2017; Suzuki et al., 2012) and effortful physical action that occurs during the cognitive task may impair cognitive function (Park et al., 2021; Tomporowski et al., 2017; Xie &

Zhang, 2023; Haudorff et al., 2008; Li et al., 2001; Lindenberger et al. 2000, Plummer-D'Amato et al., 2011, 2012; Doumas et al., 2009; Rapp et al., 2005; Voelcker-Rehage & Alberts, 2007). The impact of chronic, acute, and dual task physical action on cognitive function may be due to effort exerted during the motor task and an arousal-based effect. Exercise induced arousal from chronic and acute physical exercise can enhance post memory performance (Lambourne & Tomporowski, 2010) while high arousal induced by high effort during concurrent effortful physical exertion may impair cognitive performance (Azer et al., 2023; Park et al., 2021). The present dissertation will focus on how effort during concurrent physical and cognitive action may impact cognitive function, specifically working memory, inhibitory control, and perception when distractors are present, and the role arousal may play on task performance.

1.3 Effort in Cognitive and Motor Tasks

According to the Cambridge Dictionary, effort is defined as engaging in a physical or mental activity to achieve a goal when the task demand is high. Similarly, exertion is defined as engaging in a mental or physical task that requires high cognitive or physical demand, respectively. The Merriam-Webster Dictionary and the Cambridge Dictionary both suggest that exertion is synonymous with effort and defined as engagement in activities that require greater mental or physical effort. In the current dissertation, effort and exertion may be used interchangeably when discussing concurrent physical actions during a cognitive task.

While effort's dictionary definition involves engagement in a physical or mental task, the phenomena of effort has recently sparked the attention of psychologists to understand the cognitive processes and mechanisms involved in effort (Shenhav et al., 2017; Székely & Micheal, 2021; Jung et al., 2022). The following subsections will discuss decision making when engaging in effortful physical or cognitive tasks and the involvement of cognitive control during effortful tasks.

1.3.1 Shared or Separate Resources Pools of Effort During Cognitive and Motor Tasks

Cognitive and physical effort can be demanding and when given the choice, physical pain (Vogel et al., 2020) and inefficient strenuous physical tasks (Rosenbaum et al., 2014) are typically preferred over cognitive tasks in order to minimize cognitive effort (Fiske & Taylor, 1991). However, it is unclear whether cognitive and physical effort are independent of one another or share common neurocognitive mechanisms. To understand whether cognitive effort shares a common scale with physical effort, Feghhi & Rosenbaum (2019) used a two-alternative forced choice procedure to investigate if participants would choose to memorize and later recall a set of numbers during a more effortful physical task (i.e., carrying a box through a narrow gap) or a less effortful physical task (i.e., carrying a box through a wide gap). Across two experiments, Feghhi & Rosenbaum found that participants' decision making was based on task difficulty (choosing between the more effortful physical task or less effortful physical task as they memorized a set of numbers for later recall). Therefore, they concluded that cognitive and physical tasks may not be interactive of one another and could possibly draw from separate pools of resources.

Similarly, Xie and Zhang (2023) directly compared perceived effort during a WM task and effortful physical exertion to understand if effort across the cognitive and physical task share a common neurocognitive mechanism. Across three different experiments combining computational and experimental procedures, Xie and Zhang found a preference for exerting physical effort rather than mental effort. In addition, they observed a linear relationship between perceived effort across the physical and cogntive task loads suggesting that perceived effort can represent both physical and cogntive tasks when directly compared. Xie and Zhang concluded that their results suggest there may be a shared mental representation for effortfulness across both domains. Furthermore, an interaction between WM load and effortful physical exertion was observed where under high physical effort and high WM set sizes the number of retained items in WM significantly decreased (Xie & Zhang, 2023). Given that larger WM loads may compete for access to WM (Konstantinou et al., 2014; Oberauer & Lin, 2017), under high physical effort during larger WM set sizes information control was impaired (Xie & Zhang, 2023). Xie and Zhang concluded that effortful physical exertion may compete for shared resources when WM load is high. This account is inconsistent with Feghhi & Rosenbaum's (2019) account suggesting that there cognitive and motor actions may have separate resource pools. Moreover, Xie and Zhang's (2023) results suggest that engagement in one domain may have a direct impact on engagement in the other domain which may occur at the expense of control related processes (Xie & Zhang, 2023). For example, when the task demand is high, thus requiring more cognitive control, effortful physical exertion may negatively impact cognitive task performance. This is consistent with recent evidence suggesting that cognitive control processes may be more vulnerable to distractor interreference under concurrent effortful physical exertion (Azer et al., 2023; Park et al., 2021).

1.3.2 Effort and Cognitive Control

The involvement of cognitive control may be a driving factor for task performance when greater effort is required (Azer et al., 2023; Park et al., 2021; Xie & Zhang, 2023). This may involve mental effort and physical effort. For example, recent work aimed to understand mental effort as it relates to cognitive control across two different competing accounts (Shenhav et al., 2017; Székely & Micheal, 2021). According to the mechanistic account of mental effort (Shenhav et al., 2017), effort is defined as a mediating factor between information processing capacity and the task characteristics. In other words, processes that require less automaticity and may be threatened by interference from other ongoing cognitive processes may require cognitive control to intervene to maintain focus on the task-relevant goal. In addition, Shenhav et al. (2017) defined effort as a mediating factor between the fidelity (i.e., the degree of accuracy) of the information processing capacity as it reflects performance on a task. Similarly, the cost benefit theory of the phenomenology of mental effort (Székely & Micheal, 2021) suggest that effort mediates information processing capacity and cognitive control and is required to aid in optimal performance. However, this account differs from the mechanistic account of mental effort

(Shenhav et al., 2017) in that it suggests that flexibility, rather than fidelity, of information processing is mediated by effort to achieve optimal performance. Regardless, both the mechanistic account of mental effort (Shenhav et al., 2017) and the cost benefit theory of the phenomenology of mental effort (Székely & Micheal, 2021) agree and suggest that effort is the extent to which cognitive control impairs or allows for enhanced performance on tasks that require greater effort.

Cognitive control is a key component driving performance in tasks that require greater mental effort (Shenhav et al., 2017; Székely & Micheal, 2021). Physical effort on the other hand can impair cognitive control processes when the degree of effort on the physical task is high during dual-task conditions (for a review see Jung et al., 2022). According to the transient hypofrontality theory (Dietrich, 2003, 2006; Jung et al., 2022), dual task conditions that involve greater physical effort during the cognitive task may require reallocation of neural activation from the prefrontal cortex (PFC) to motor cortices to maintain the effortful physical action. Therefore, the metabolic and cognitive resources in the PFC may be reduced. The reallocation of neural activation to motor cortices during events of concurrent high physical effort may allow for optimal motor performance, however, it is at the expense of neural structures that may not be involved or essential for motor action (Jung et al., 2022). As a result, higher-order cognitive functions, such as working memory and cognitive control, may suffer under effortful physical exertion (Audiffren, 2016; Dietrich, 2003; Jung et al., 2022).

1.4 Arousal and Effort on Task Performance

Physical and mental effort can both induce arousal (Ahern & Beatty, 1979; Alnaes et al., 2014; Hayashi & Someya, 2011; Hess & Plot, 1964; Kahneman & Beatty, 1966; Krejtz et al., 2018; Nielsen & Mather, 2015; Wahn et al., 2021; Zénon et al., 2014; Zhou et al., 2022), which is typically assessed using pupillary response during, or immediately after, the effortful task. Pupils respond distinctively to varying stimuli, such as constricting in response to brightness or during near fixation and dilating during instance of darkness or in response to increased levels of arousal or effort (Mathôt, 2018). Pupil dilation is controlled by the iris dilator muscle and occurs when the sympathetic nervous system is active (Mathôt, 2018). The sympathetic nervous system is involved in arousal; thus, pupil dilation occurs as a result of increased arousal. The neural pathway associated with pupil dilation connects the iris dilator muscles to the LC (Lui et al., 2017; Mathôt, 2018). When the sympathetic nervous system is active, NE is released from the LC (Glowinski & Baldessarini, 1966; Florin-Lechner et al., 1996) and pupil dilation as a result may reflect changes in arousal during complex cognitive and motor operations (Andreassi, 2000; Joshi et al., 2016; Nielsen & Mather, 2015).

The effect of effort on arousal has typically been studied in single task conditions. For instance, effortful physical action may stimulate the sympathetic nervous system (Hautala et al., 2009; Patel & Zwibel, 2022), which in turn leads to increased pupil dilation due to increased sympathetic nervous system activation (McDougal & Gamlin, 2015; Mathôt, 2018). In fact, pupil dilation measured after dynamic effortful physical exercise indicates that greater exercise loads may induce greater pupillary response (Ishigaki et al., 1991;

Hayashi et al., 2010). In addition to the effect of dynamic exercise on arousal, static effortful physical action has also been linked to increased arousal, which is observed by measuring pupillometry during an effortful isometric handgrip task (Hayashi & Someya, 2011; Nielsen & Mather, 2015; Zénon et al., 2014). For instance, effortful isometric handgrip exercises increase pupil dilation and offers a noninvasive method to test LC stimulation through pupillary response in order to understand the effect of physiological arousal on cognitive processes (Bachman et al., 2023; Joshi et al., 2016; Liu et al., 2017).

Similar to the effect of physical effort on pupillary response as an index of arousal, mental effort (i.e., the amount of information at a given time; Sweller, 1988) studied independent of physical action induces greater task evoked pupillary responses (TEPRs; Ahern & Beatty, 1979; Alnaes et al., 2014; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022). Mental effort is often used synonymously with cognitive load (Kirschner & Kirschner, 2012; Kirchner, 2002; Sweller, 1988) where greater cognitive load is equivalent to the use of greater mental effort. TEPRs are typically studied as an index of mental effort and studies have indicated that pupils typically dilate as a function of increasing cognitive load and task difficulty (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022).

While physical and cognitive effort may both induce increased arousal when studied in isolation, effortful physical exertion using isometric handgrip may led to heightened arousal, indexed as greater pupillary response and faster working memory reaction times (Bachman et al., 2023). For instance, Bachman et al., (2023) recently demonstrated that the effects of arousal induced by handgrip exercise on a subsequent working memory task resulted in faster reaction times across older and younger participants and working memory load. However, handgrip exercises did not have an effect on the subsequent working memory task accuracy. Similar to the sequential reaction time effects observed by Bachman et al., (2023), arousal induced by an isometric handgrip task during a working memory task led to faster working memory reaction times but at the expense of distractor interference (Azer et al., 2023; Park et al., 2021).

One possibility for the effect of handgrip on reaction time and task performance could be that effortful physical exertion may lead to the release of NE from the LC (Nielsen & Mather, 2015), where the LC-NE system is modulated by distractor interference (Aston-Jones & Cohen, 2005). The LC-NE system's effect on distractor interference is more pounced in tasks involving working memory and inhibitory control (Mather & Harley, 2016; Mather et al., 2016). Specifically, hyperarousal from increased tonic LC-NE activity (i.e., irregular and elevated neuron baseline activity associated with increased cortical arousal) may result in impaired performance on cognitive tasks involving executive functions (e.g., attention, working memory, inhibition; Aston-Jones et al., 1994; Aston-Jones et al., 2001; Howell et al., 2012; Kane et al., 2017). Similarly, effortful physical exertion could also be explained by the inverted U hypothesis (Davey, 1973; Yerkes & Dodson, 1908), which suggests that optimal levels of arousal could aid in enhanced performance while a lack of arousal or too much arousal can impair performance. In other words, high physical exertion on an isometric handgrip device during cognitive tasks may produce arousal beyond the threshold for optimal performance on cognitive and behavioral tasks. Therefore, under high physical exertion faster, but more vulnerable, task performance may be observed (Azer et al., 2023; Park et al., 2021). The present dissertation will focus on whether physiological arousal induced by effortful physical exertion may impact performance on working memory and perception, along with the interactive effect between physical and cognitive effort.

1.5 Dissertation Overview

In this dissertation, I propose two separate accounts for working memory and perception under effortful physical exertion. First, I propose an inhibition-based account where under effortful physical exertion inhibitory control may suffer when task-irrelevant items are present. Specifically, Chapter 2 of the current dissertation will empirically test age-related effects of physical exertion on control of access to working memory. In addition, across two empirical studies, Chapter 3 will demonstrate that the detrimental effects of effortful physical exertion on working memory are observed in a perceptual task using face stimuli where inhibitory control, and holistic processing, are required. In contrast, effortful physical exertion may not affect overall face discrimination. In addition to the inhibition-based account, I propose an arousal-based account for effortful physical exertion on cognitive load. Chapter 4 will investigate the joint effects of effortful physical exertion and cognitive effort on pupil size as an index of arousal (Lui et al., 2017). Lastly, the final chapter will discuss the summary of findings, translational relevance, and future directions. Together, this dissertation focused on the detrimental effect of concurrent effortful physical exertion on inhibitory control and its impact on arousal.

References

Ahern, S., & Beatty, J. (1979). Pupillary responses during information processing vary with Scholastic Aptitude Test scores. *Science (New York, N.Y.)*, *205*(4412), 1289–1292. https://doi.org/10.1126/science.472746

Alnæs, D., Sneve, M. H., Espeseth, T., Endestad, T., van de Pavert, S. H. P., & Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, *14*(4), 1. https://doi.org/10.1167/14.4.1

Andreassi, J. L. (2000). Pupillary Response and Behavior. In *Psychophysiology* (4th ed.). Psychology Press.

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28,* 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Aston-Jones, G., Chen, S., Zhu, Y., & Oshinsky, M. L. (2001). A neural circuit for circadian regulation of arousal. *Nature Neuroscience*, *4*(7), 732–738. https://doi.org/10.1038/89522

Aston-Jones, G., Rajkowski, J., Kubiak, P., & Alexinsky, T. (1994). Locus coeruleus neurons in monkey are selectively activated by attended cues in a vigilance task. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *14*(7), 4467–4480. https://doi.org/10.1523/JNEUROSCI.14-07-04467.1994

Audiffren, M. (2016). The reticular-activating hypofrontality (RAH) model of acute exercise: Current data and future perspectives. In *Exercise-cognition interaction: Neuroscience perspectives* (pp. 147–166). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-800778-5.00007-4

Azer, L., Xie, W., Park, H.-B., & Zhang, W. (2023). Detrimental effects of effortful physical exertion on a working memory dual-task in older adults. *Psychology and Aging.* Advance online publication. https://doi.org/10.1037/pag0000746

Bachman, S. L., Attanti, S., & Mather, M. (2023). Isometric handgrip exercise speeds working memory responses in younger and older adults. *Psychology and Aging*. https://doi.org/10.1037/pag0000728

Casey, B. J., Durston, S., & Fossella, J. A. (2001). Evidence for a mechanistic model of cognitive control. *Clinical Neuroscience Research*, *1*(4), 267–282. https://doi.org/10.1016/S1566-2772(01)00013-5

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Davey, C. P. (1973). Physical exertion and mental performance. *Ergonomics*, *16*(5), 595–599. https://doi.org/10.1080/00140137308924550

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Dietrich, A. (2003). Functional neuroanatomy of altered states of consciousness: The transient hypofrontality hypothesis. *Consciousness and Cognition*, *12*(2), 231–256. https://doi.org/10.1016/S1053-8100(02)00046-6

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research*, *145*(1), 79–83. https://doi.org/10.1016/j.psychres.2005.07.033

Doumas, M., Rapp, M. A., & Krampe, R. Th. (2009). Working memory and postural control: Adult age differences in potential for improvement, task priority, and dual tasking. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *64B*(2), 193–201. https://doi.org/10.1093/geronb/gbp009

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

Engle, R. W., & Kane, M. J. (2003). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In *Psychology of Learning and Motivation* (Vol. 44, pp. 145–199). Elsevier. https://doi.org/10.1016/S0079-7421(03)44005-X

Erickson, K. I., Hillman, C. H., & Kramer, A. F. (2015). Physical activity, brain, and cognition. *Current Opinion in Behavioral Sciences*, *4*, 27–32. https://doi.org/10.1016/j.cobeha.2015.01.005

Feghhi, I., & Rosenbaum, D. A. (2019). Judging the subjective difficulty of different kinds of tasks. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(8), 983–994. https://doi.org/10.1037/xhp0000653

Fiske, S. T., & Taylor, S. E. (1991). *Social cognition* (2nd ed.). McGraw-Hill.

Florin-Lechner, S. M., Druhan, J. P., Aston-Jones, G., & Valentino, R. J. (1996). Enhanced norepinephrine release in prefrontal cortex with burst stimulation of the locus coeruleus. *Brain Research*, *742*(1), 89–97. https://doi.org/10.1016/S0006-8993(96)00967-5

Gerver, C. R., Neely, K. A., Kurkela, K. A., Diaz, M. T., Goodman, J. T., Blouch, S., Samimy, S., & Dennis, N. A. (2020). Shared neural recruitment across working memory and motor control tasks as a function of task difficulty and age. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *27*(6), 864–879. https://doi.org/10.1080/13825585.2019.1700898

Glowinski, J., & Baldessarini, R. J. (1966). Metabolism of norepinephrine in the central nervous system. *Pharmacological Reviews*, *18*(4), 1201–1238.

Hausdorff, J. M., Schweiger, A., Herman, T., Yogev-Seligmann, G., & Giladi, N. (2008). Dual task decrements in gait among healthy older adults: contributing factors. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *63*(12), 1335–1343.

Hautala, A. J., Kiviniemi, A. M., & Tulppo, M. P. (2009). Individual responses to aerobic exercise: The role of the autonomic nervous system. *Neuroscience and Biobehavioral Reviews*, *33*(2), 107–115. https://doi.org/10.1016/j.neubiorev.2008.04.009

Hayashi, N., & Someya, N. (2011). Muscle metaboreflex activation by static exercise dilates pupil in humans. *European Journal of Applied Physiology*, *111*(6), 1217–1221. https://doi.org/10.1007/s00421-010-1716-z

Hayashi, N., Someya, N., & Fukuba, Y. (2010). Effect of intensity of dynamic exercise on pupil diameter in humans. *Journal of Physiological Anthropology*, *29*(3), 119–122. https://doi.org/10.2114/jpa2.29.119

Hess, E. H., & Polt, J. M. (1964). pupil size in relation to mental activity during simple problem-solving. *Science (New York, N.Y.)*, *143*(3611), 1190–1192. https://doi.org/10.1126/science.143.3611.1190

Howells, F. M., Stein, D. J., & Russell, V. A. (2012). Synergistic tonic and phasic activity of the locus coeruleus norepinephrine (LC-NE) arousal system is required for optimal attentional performance. *Metabolic Brain Disease*, *27*(3), 267–274. https://doi.org/10.1007/s11011-012-9287-9

Ikkai, A., & Curtis, C. E. (2011). Common neural mechanisms supporting spatial working memory, attention and motor intention. *Neuropsychologia*, *49*(6), 1428–1434. https://doi.org/10.1016/j.neuropsychologia.2010.12.020

Ishigaki, H., Miyao, M., & Ishihara, S. (1991). Change of pupil size as a function of exercise. *Journal of Human Ergology*, *20*(1), 61–66.

Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between pupil diameter and neuronal activity in the locus coeruleus, colliculi, and cingulate cortex. *Neuron*, *89*(1), 221–234. https://doi.org/10.1016/j.neuron.2015.11.028

Jung, M., Ryu, S., Kang, M., Javadi, A.-H., & Loprinzi, P. D. (2022). Evaluation of the transient hypofrontality theory in the context of exercise: A systematic review with meta-analysis. *Quarterly Journal of Experimental Psychology (2006)*, *75*(7), 1193–1214. https://doi.org/10.1177/17470218211048807

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science (New York, N.Y.)*, *154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Kane, G. A., Vazey, E. M., Wilson, R. C., Shenhav, A., Daw, N. D., Aston-Jones, G., & Cohen, J. D. (2017). Increased locus coeruleus tonic activity causes disengagement from a patch-foraging task. *Cognitive, Affective & Behavioral Neuroscience*, *17*(6), 1073–1083. https://doi.org/10.3758/s13415-017-0531-y

Kato, K., Iwamoto, K., Kawano, N., Noda, Y., Ozaki, N., & Noda, A. (2018). Differential effects of physical activity and sleep duration on cognitive function in young adults. *Journal of Sport and Health Science*, *7*(2), 227–236. https://doi.org/10.1016/j.jshs.2017.01.005

Konstantinou, N., Beal, E., King, J.-R., & Lavie, N. (2014). Working memory load and distraction: Dissociable effects of visual maintenance and cognitive control. *Attention, Perception & Psychophysics*, *76*(7), 1985–1997. https://doi.org/10.3758/s13414-014-0742-z

Krejtz, K., Duchowski, A. T., Niedzielska, A., Biele, C., & Krejtz, I. (2018). Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. *PLOS ONE*, *13*(9), e0203629. https://doi.org/10.1371/journal.pone.0203629

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091

Leisman, G., Moustafa, A. A., & Shafir, T. (2016). Thinking, Walking, Talking: Integratory Motor and Cognitive Brain Function. *Frontiers in Public Health*, *4*. https://www.frontiersin.org/articles/10.3389/fpubh.2016.00094

Li, K. Z., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science*, *12*(3), 230–237. https://doi.org/10.1111/1467-9280.00341

Lim, S. B., Louie, D. R., Peters, S., Liu-Ambrose, T., Boyd, L. A., & Eng, J. J. (2021). Brain activity during real-time walking and with walking interventions after stroke: A systematic review. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 8. https://doi.org/10.1186/s12984-020-00797-w

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age. *Psychology and Aging*, *15*(3), 417–436. https://doi.org/10.1037//0882-7974.15.3.417

Loprinzi, P. D., & Kane, C. J. (2015). Exercise and cognitive function: A randomized controlled trial examining acute exercise and free-living physical activity and sedentary effects. *Mayo Clinic Proceedings*, *90*(4), 450–460. https://doi.org/10.1016/j.mayocp.2014.12.023

Loprinzi, P. D., Roig, M., Etnier, J. L., Tomporowski, P. D., & Voss, M. (2021). Acute and Chronic Exercise Effects on Human Memory: What We Know and Where to Go from Here. *Journal of Clinical Medicine*, *10*(21), 4812. https://doi.org/10.3390/jcm10214812

Mahoney, J. R., Holtzer, R., Izzetoglu, M., Zemon, V., Verghese, J., & Allali, G. (2016). The role of prefrontal cortex during postural control in Parkinsonian syndromes a functional near-infrared spectroscopy study. *Brain Research*, *1633*, 126–138. https://doi.org/10.1016/j.brainres.2015.10.053

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39,* e200. https://doi.org/10.1017/S0140525X15000667

Mather, M., & Harley, C. W. (2016). The locus coeruleus: essential for maintaining cognitive function and the aging brain. *Trends in cognitive sciences*, *20*(3), 214–226. https://doi.org/10.1016/j.tics.2016.01.001

Mathôt, S. (2018). Pupillometry: Psychology, Physiology, and Function. *Journal of Cognition*, *1*(1), 16. https://doi.org/10.5334/joc.18

McDougal, D. H., & Gamlin, P. D. (2015). Autonomic control of the eye. *Comprehensive Physiology*, *5*(1), 439–473. https://doi.org/10.1002/cphy.c140014

Middleton, F. A., & Strick, P. L. (2000). Basal ganglia and cerebellar loops: Motor and cognitive circuits. *Brain Research. Brain Research Reviews*, *31*(2–3), 236–250. https://doi.org/10.1016/s0165-0173(99)00040-5

Miyawaki, C. E., Bouldin, E. D., Kumar, G. S., & McGuire, L. C. (2017). Associations between Physical Activity and Cognitive Functioning among Middle-Aged and Older Adults. *The Journal of Nutrition, Health & Aging*, *21*(6), 637–647. https://doi.org/10.1007/s12603-016-0835-6

Nagano-Saito, A., Martinu, K., & Monchi, O. (2014). Function of basal ganglia in bridging cognitive and motor modules to perform an action. *Frontiers in Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnins.2014.00187

Nielsen, S. E., & Mather, M. (2015). Comparison of two isometric handgrip protocols on sympathetic arousal in women. *Physiology & Behavior*, *142*, 5-13. https://doi.org/10.1016/j.physbeh.2015.01.031

Oberauer, K., & Lin, H.-Y. (2017). An interference model of visual working memory. *Psychological Review*, *124*(1), 21–59. https://doi.org/10.1037/rev0000044

Park, H.-B., Ahn, S., & Zhang, W. (2021). Visual search under physical effort is faster but more vulnerable to distractor interference. *Cognitive Research: Principles and Implications*, *6*(1), 17. https://doi.org/10.1186/s41235-021-00283-4

Patel, P. N., & Zwibel, H. (2022). Physiology, Exercise. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK482280/

Plummer-D'Amato, P., Altmann, L. J. P., & Reilly, K. (2011). Dual-task effects of spontaneous speech and executive function on gait in aging: exaggerated effects in slow walkers. *Gait & Posture*, *33*(2), 233–237. https://doi.org/10.1016/j.gaitpost.2010.11.011

Plummer-D'Amato, P., Brancato, B., Dantowitz, M., Birken, S., Bonke, C., & Furey, E. (2012). Effects of gait and cognitive task difficulty on cognitive-motor interference in aging. *Journal of Aging Research*, *2012*, 670-677. https://doi.org/10.1155/2012/583894

Rapp, M. A., Krampe, R. T., & Baltes, P. B. (2006). Adaptive task prioritization in aging: Selective resource allocation to postural control is preserved in Alzheimer disease. *The American Journal of Geriatric Psychiatry: Official Journal of the American Association for Geriatric Psychiatry*, *14*(1), 52–61. https://doi.org/10.1097/01.JGP.0000192490.43179.e7

Rathore, A., & Lom, B. (2017). The effects of chronic and acute physical activity on working memory performance in healthy participants: A systematic review with meta-analysis of randomized controlled trials. *Systematic Reviews*, *6*(1), 124. https://doi.org/10.1186/s13643-017-0514-7

Redick, T. S. (2014). Cognitive control in context: Working memory capacity and proactive control. *Acta Psychologica*, *145*, 1–9. https://doi.org/10.1016/j.actpsy.2013.10.010

Rizzolatti, G., Riggio, L., & Sheliga, B. M. (1994). Space and selective attention. In *Attention and performance 15: Conscious and nonconscious information processing* (pp. 232–265). Cambridge, MA, US: The MIT Press.

Rosenbaum, D. A., Gong, L., & Potts, C. A. (2014). Pre-crastination: Hastening subgoal completion at the expense of extra physical effort. *Psychological Science*, *25*(7), 1487–1496. https://doi.org/10.1177/0956797614532657

Sáez de Asteasu, M. L., Martínez-Velilla, N., Zambom-Ferraresi, F., Casas-Herrero, Á., & Izquierdo, M. (2017). Role of physical exercise on cognitive function in healthy older adults: A systematic review of randomized clinical trials. *Ageing Research Reviews*, *37*, 117–134. https://doi.org/10.1016/j.arr.2017.05.007

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a rational and mechanistic account of mental effort. *Annual Review of Neuroscience*, *40*, 99–124. https://doi.org/10.1146/annurev-neuro-072116-031526

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*(3972), 701–703. https://doi.org/10.1126/science.171.3972.701

Suzuki, T., Shimada, H., Makizako, H., Doi, T., Yoshida, D., Tsutsumimoto, K., Anan, Y., Uemura, K., Lee, S., & Park, H. (2012). Effects of multicomponent exercise on cognitive function in older adults with amnestic mild cognitive impairment: A randomized controlled trial. *BMC Neurology*, *12*, 128. https://doi.org/10.1186/1471-2377-12-128

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Székely, M., & Michael, J. (2021). The sense of effort: A cost-benefit theory of the phenomenology of mental effort. *Review of Philosophy and Psychology*, *12*(4), 889–904. https://doi.org/10.1007/s13164-020-00512-7

Tomporowski, P. D., Albrecht, C., & Pendleton, D. M. (2017). Effects of isometric hand-grip muscle contraction on young adults' free recall and recognition memory. *Research Quarterly for Exercise and Sport*, *88*(1), 95–100. https://doi.org/10.1080/02701367.2016.1264567

Tomporowski, P. D., & Qazi, A. S. (2020). Cognitive-motor dual task interference effects on declarative memory: A theory-based review. *Frontiers in Psychology*, *11*, 1015. https://doi.org/10.3389/fpsyg.2020.01015

Unsworth, N., & Robison, M. K. (2017). A locus coeruleus-norepinephrine account of individual differences in working memory capacity and attention control. *Psychonomic Bulletin & Review*, *24*(4), 1282–1311. https://doi.org/10.3758/s13423-016-1220-5

van der Wel, P., & van Steenbergen, H. (2018). Pupil dilation as an index of effort in cognitive control tasks: A review. *Psychonomic Bulletin & Review*, *25*(6), 2005–2015. https://doi.org/10.3758/s13423-018-1432-y

Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *62*(3), 141-148. https://doi.org/10.1093/geronb/62.3.p141

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*(6984), 748–751. https://doi.org/10.1038/nature02447

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*(7067), 500–503. https://doi.org/10.1038/nature04171

Vogel, T. A., Savelson, Z. M., Otto, A. R., & Roy, M. (2020). Forced choices reveal a trade-off between cognitive effort and physical pain. *ELife*, *9*, e59410. https://doi.org/10.7554/eLife.59410

Wahn, B., Ruuskanen, V., Kingstone, A., & Mathôt, S. (2021). Coordination effort in joint action is reflected in pupil size. *Acta Psychologica*, *215*, 103291. https://doi.org/10.1016/j.actpsy.2021.103291

Washio, T., Suzuki, K., Saito, S., Watanabe, H., Ando, S., Brothers, R. M., & Ogoh, S. (2021). Effects of acute interval handgrip exercise on cognitive performance. *Physiology & Behavior*, *232*, 113327. https://doi.org/10.1016/j.physbeh.2021.113327

Xie, W., Lu Sing, J. L., Martinez-Flores, A., & Zhang, W. (2022). Induced negative arousal modulates the speed of visual working memory consolidation. *Emotion (Washington, D.C.)*, *22*(1), 179–197. https://doi.org/10.1037/emo0001059

Xie, W., & Zhang, W. (2023). Effortfulness of visual working memory: Gauged by physical exertion. *Journal of Experimental Psychology. General*. https://doi.org/10.1037/xge0001391

Xie, W., & Zhang, W. (2016). Negative emotion boosts quality of visual working memory representation. *Emotion (Washington, D.C.)*, *16*(5), 760–774. https://doi.org/10.1037/emo0000159

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative Neurology & Psychology*, *18*, 459–482. https://doi.org/10.1002/cne.920180503

Zénon, A., Sidibé, M., & Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00286

Zhou, C., Lorist, M. M., & Mathôt, S. (2022). Is categorization in visual working memory a way to reduce mental effort? A pupillometry study. *Cognitive Science*, *46*(9), e13194. https://doi.org/10.1111/cogs.13194

Zhu, W., Wadley, V. G., Howard, V. J., Hutto, B., Blair, S. N., & Hooker, S. P. (2017). Objectively measured physical activity and cognitive function in older adults. *Medicine and Science in Sports and Exercise*, *49*(1), 47–53. https://doi.org/10.1249/MSS.0000000000001079

Chapter 2. Detrimental Effects of Effortful Physical Exertion on a Working Memory Dual-Task in Older Adults

2.1 Chapter Abstract

Research assessing the associations of age on physical actions and cognitive processes is often conducted in isolation. However, action and cognition often interact in daily functions and deteriorate with age. Therefore, assessing how physical actions impact core cognitive abilities and how age amplifies these effects is pivotal. 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, MVC). Effortful physical exertion, although failing to affect WM accuracy with 0-distractors present for both age groups, reduced WM accuracy for the older, but not young adults, with 5-distractors present. Similarly, older adults experienced greater distractor interference with 5-distractors present under high physical exertion, indexed by slower reaction time (RT) and 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.

2.2 Introduction

Aging is inevitably associated with declines in various biological and mental functions, posing a challenge to the aging society (e.g., increased costs for societal care). Among these declines, older adults often experience a reduction in physical function and strength. Declines that accompany old age are not limited to physical function but include a reduction in key cognitive processes (e.g., working memory and recognition memory, Park & Reuter-Lorenz, 2009). 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 (Park & Reuter-Lorenz., 2009; Broockmole & Logie, 2013; Xie et al., 2019). Parallel to declining mental functions, physical functions also deteriorate with age, leading to increased amounts of time spent sedentary (Sparling et al., 2015). Sedentary lifestyles may be associated with age-related physiological changes, including reductions in muscle mass and physical endurance. For instance, muscle mass and muscle strength, such as isometric handgrip strength, declines with age (Samuel et al., 2013; Kallman et al.,1990; Vandervoort, 2002). On average, healthy older adults' isometric strength is 20-40% weaker than younger adults (Vandervoort, 2002). Together these changes can impact older adults' physical independence and activities of daily living (Milanović et al., 2013). Therefore, it is imperative to assess the effects of aging on physical and cognitive functions, along with their interaction.

Research assessing the effects of aging in relation to physical and cognitive processes is often conducted in isolation, however, action and cognition are often intertwined in daily functions (Leisman et al., 2016; Plummer-D'Amato et al., 2011, 2012). For example, when preparing a meal, one must consider the next physical and cognitive action needed to bring together the ingredients required and ensure that an accident does not occur, such as a stove-top fire. Recent literature has documented strong links between cognitive and motor functions (Leisman et al., 2016) in older adults. First, dual-task paradigms suggest that gait speed tends to decline in older adults while simultaneously walking and talking (Plummer-D'Amato et al., 2011) or simultaneously walking and performing a cognitive task (Haudorff et al., 2008; Plummer-D'Amato et al., 2012). Second, dual-task decrements are observed in older adults when performing a concurrent postural control and cognitive task, specifically WM suffers at the expense of simultaneously performing the postural control task (Doumas et al., 2009; Rapp et al., 2005). Third, declines in physical strength can be accompanied by, and potentially preceded by (Taekema et al., 2012), declines in overall cognition in similar rates in aging (Praetorius Björk et al., 2016). Fourth, physical strength, such as handgrip strength, and gait can predict cognitive performance (Taekema et al., 2010) and socio-cognitive wellbeing (Blankevoort et al., 2013). Fifth, the effects of aging on physical and cognitive function can interact with each other, especially when the executive function is involved in both domains (Leisman et al., 2016). For instance, WM performance declines can occur in older adults when a WM task is performed concurrently with a precision force tracking task requiring fine motor control and coordination than when the WM task is done in isolation (Voelcker-Rehage & Alberts, 2007). Lastly, sedentary lifestyles in older adults have been associated with declines in fluid (Erickson et al., 2015) but not crystallized (Burzynska et al., 2020) abilities. One possibility that could account for age-related declines in cognition while engaging in a motor task could be explained by the Li & Lindenberger's (2002) multi-level model on sensory, sensorimotor, and cognitive changes that occur in aging. This model suggested that neuronal reorganization that occurs in response of age-related functional loss could lead to modifications in behavioral responses to tasks that require attentional allocation. However, these adaptions are assumed to unlikely 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 also manifest in young adults. For instance, engaging in a concurrent handgrip task during long-term memory encoding can impair later retrieval in young adults (Tomporowski et al., 2017). More importantly, task-irrelevant distractors can more easily capture visual attention (Park et al., 2021) and get encoded into WM (Cappiello et al., 2018) under concurrent physical effort. These inhibition-based effects of physical effort provide an intriguing perspective to look at functional declines in older adults given the widely observed age-related declines in cognitive control. For instance, 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). For example, 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; Park et al., 2021), 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 motor and cognitive functions in younger and older adults by testing the effects of concurrent effortful physical action on key cognitive functioning. 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 (Pontifex et al., 2019; Erickson et al., 2015). Specifically, we assessed the impact of simple physical exertion through an isometric hand dynamometer on WM and inhibitory control using a novel dual-task paradigm, where participants engaged in a WM task under effortful physical exertion.

A hand dynamometer is an apparatus that measures participants' maximum isometric handgrip strength, which involves static contraction of the hand muscles with restricted joint movements, and has many empirical advantages. First, the use of an isometric hand dynamometer for the concurrent handgrip task in the current study allows for the inclusion of participants with varying mobile abilities rather than limiting older adults' participation based on mobility as seen in prior dual-task paradigms using a gait task (Haudorff et al., 2008; Plummer-D'Amato et al., 2011, 2012), therefore, expanding the generalizability of the findings. In fact, 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). Second, 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 the case of driving, drivers apply roughly 31% maximum voluntary grip force on the steering wheel (Eksioglu & Kiziliaslan, 2008), which is consistent to our high physical exertion condition. Therefore, simulating a real-world scenario of dual power grip and cognitive task. Third, the gait task (Haudorff et al., 2008; Plummer-D'Amato et al., 2011, 2012) and the precision grip task (Voelcker-Rehage & Alberts, 2007) in the previous dual-task paradigms can be more cognitively demanding and tend to require more cognitive control than a simple isometric handgrip task (Kobayashi-Cuya et al., 2018). Lastly, our handgrip task, as compared to the previous gait task, further allows assessment of the underlying neural mechanisms with functional MRI. Together, the current 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 were instructed to remember three briefly presented task-relevant red orientation bars with 0 or 5 task-irrelevant blue orientation bars (*0-distractor* vs. *5-distractors* conditions) in the memory array of the WM change detection task. After a short delay interval, participants reported whether the three task-relevant orientation bars changed orientation, or not, from memory to test. Physical exertion was operationalized as handgrip force exertion at different subject-specific maximum voluntary contraction (MVC, 5% versus 30%), independent of individual differences in muscular strength and fitness level. Given that high physical exertion impairs spatial attention (Park et al., 2021) and may reduce inhibitory control, it is hypothesized that 1) inhibitory control of access to WM will be compromised under high physical exertion, and 2) this effect will be amplified by age. Accordingly, it was predicted that 1) 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 2) 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 preexisting theories of age-related decline in inhibition (Hasher & Zacks, 1988). For example, exerting greater physical force during a cognition heavy task may illicit 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), 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 versus negative effects, McMorris et al., 2011), 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 universal 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 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.

2.3 General Method

2.3.1 Transparency and Openness

De-identified data, materials, and analytic code can be downloaded from https://osf.io/4jz65/?view_only=5e71834fe2354c659c90cf786bc063ad. The study design, hypotheses, and analytic plan were not preregistered.

2.3.2 Participants

An *a priori* power analysis for mixed-effect analysis of variances (ANOVA) suggests that a total sample size of 18 to 36 participants (hence $n = 9$ to 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 to 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 at the age of 70s can be about 2 times of that for younger participants at the age of 20s. Second, using a different dual-task paradigm but with similar age groups, we expected that our age-related effect of concurrent physical loads on the modified WM task performance would be attenuated as compared with the prior research (Anguera et al., 2013). Therefore, we decided to proceed with our power analysis based on a medium level effect size.

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* >= 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 with monetary compensation (20$/h). 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) at University of California, Riverside. Because the latter is a convenient sample, more students have signed up for our study than the community sample. As these additional college participants met our inclusion criteria outlined below, we had included all these 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 being 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 group 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 misuses 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. The experimental procedure was approved by the Institutional Review Board of the University of California, Riverside. All participants were provided written informed consent and were compensated for their participation by course credits (undergraduate participants) or $20/hour (older adults).

2.3.3 Procedure

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

2.3.3.1 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 participant 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 display for 500 ms followed by a centrally located visual gauge providing real-time feedback on the exerted grip force. The visual gauge, 4^{o} by 6^{o} 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 (for an example, 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 varies 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.

2.3.3.2 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, 2016), 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. Yet, it was not surprising that participants could more successfully exert hand strength at 5% MVC (98.69% handgrip accuracy) than 30% MVC (94.72% handgrip accuracy), *t*(49) = 3.33, *p* = .002, Cohen's *d* = 0.48. However, there was 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 only 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 3 red rectangular bars, while on the other half of the trials, this memory array displayed 3 red rectangular bars with 5 blue rectangular bars. These rectangular bars (5^{o}-by-1^{o} 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^{o}-by-11^{o} area in visual angles. Participants were required to only remember the orientation of the 3 red rectangular bars while ignoring any blue bars, making it a visual WM task of set size 3 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 degrees. 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. 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 1 block of 12 practice trials. Each experimental block obtained a 20-second break after 8 trials and all participants received a mandatory break of approximately one minute between each block. Participants were encouraged to ask for longer breaks, as needed, to minimize fatigue. The experimental task, including breaks, took approximately 45 minutes to complete.

2.3.4 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 (Supplementary Table 1). A two (younger adults vs. older adults) x two (0-distractor vs. 5-distractor) x 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 for 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 conventional 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 8080 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 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; Kruschke, 2011), which can be treated as a point estimate and as an analogue 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 (Kruschke, 2014).

2.4 Results

2.4.1 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.

2.4.2 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 size (0 vs. 5) and physical exertion (5% vs. 30% MVC) as within-subject factors. Consistent with the effects of distractor size 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, η^2_p = .54. Observers remembered more task-relevant items under the 0-distractor condition (*M* = 2.46, *SD* = 0.46) compared to the 5-distractor condition (*M* = 2.19, *SD* = 0.60). Furthermore, there was a significant main effect of age, *F*(1, 49) = 89.81, *p* < .001, η^2_p =.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, η^2_p <.01.

More importantly, we found a significant three-way interaction across age, distractor size, and physical exertion, *F*(1, 49) = 6.86, *p* = .012, η^2_p =.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, η^2_p = .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 observer a significant interaction between age-group and concurrent physical exertion on Cowan's *K*, *F*(1, 49) = 0.33, *p* = .568, η^2_p =.01. In other words, the extent of distractor interference (i.e., present – absent) on WM, although comparable in younger adults across physical exertion conditions, 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), 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 5 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 size, and block sequence (block 1 through 5) failed to yield any significant effects, including a non-significant main effect of block sequence, $F(4, 196) = 1.03$, $p = .396$, $\eta^2_p = .02$, non-significant block-by-age group interaction, $F(4, 196) = 0.68$, $p = .604$, $\eta^2_p = .01$, and non-significant four-way interaction between all factors, $F(4, 196) = 1.67$, $p = .160$, $\eta^2_p = .03$, except for the significant effect of physical exertion, $F(1, 49) = 212.01$, $p < .001$, $\eta^2_p = .82$.

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, $F(4, 196) = 1.32$, $p = .268$, $\eta^2_p = .05$, the block-by-age group interaction, *F*(4, 196) = 1.09, *p* = .367, η^2_p = .04, and the four-way interaction between all factors, *F*(4, 196) = 0.60, *p* = .664, η^2_p = .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 (i.e., 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).

2.4.3 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-

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[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.

subject factors, distractor size (0 vs. 5), 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 size, $F(1, 49) = 82.99$, $p < .001$, $\eta^2_p = .63$, for age, $F(1, 49) = 19.61$, $p < .001$, $\eta^2_p = .29$, and for physical exertion, $F(1, 49) = 4.66$, $p = .036$, $\eta^2_p = .09$. The main effects of distractor size 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 size and age group, could cancel each other out and attenuate the interaction effects of these factors, in line with the findings from Park et al. (2021). Accordingly, the three-way interaction was marginally significant, $F(1, 49) = 3.41$, $p = .071$, $\eta^2_p = .07$. However, separate two-way mixed-effect ANOVAs for each distractor size condition revealed an apparent asymmetry in the age-by-physical effort interaction, which was significant in the distractors present condition, $F(1, 49) = 4.18$, $p = .046$, $\eta^2_p = .08$, but not in the distractor absent condition, $F(1, 49) = 0.05$, $p = .817$, $\eta^2_p < .01$. 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).

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, $F(1, 49) = 5.58$, $p = .022$, $\eta^2_p = .10$, and it remained non-significant for distractor absent condition, $F(1, 49) = 0.02$, $p = .894$, $\eta^2_p < .01$. This reaffirms the previous finding that the RT-interference effect in the distractor-present condition was mainly observed in older adults.

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

2.4.4 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 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 [-60.1ms, +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 bi-directional 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).

2.5 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% versus 5% MVC), although it failed to affect WM accuracy at the 0-distractor condition for either age group, reduced WM accuracy for the older adults, but not younger adults, at the 5-distractor condition. 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 5-distractor 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 5-distractor condition than the 0-distractor condition under high physical exertion (30% MVC), which was more pronounced in older adults than younger adults.

These findings are consistent with some previous reports of the negative interactions between cognitive and motor tasks in older adults (Voelcker-Rehage & Alberts, 2007; Plummer-D'Amato et al., 2011, 2012). For instance, older adults exhibit altered gait when simultaneously completing a dual cognitive and motor task compared to performing the motor task alone (Plummer-D'Amato et al., 2011, 2012). Moreover, older adults tend to be negatively impacted by cognitive and motor dual-tasks, resulting in worse executive functioning performance (Voelcker-Rehage & Alberts, 2007). 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 involvements of cognitive control processes, as compared to the isometric hand grip task in the present study. In contrast, the present study has adopted a handgrip task requiring phasic isometric muscle contraction (Cain et al., 1971). It features voluntary and static contraction without muscle movement (and movement of hand and objects). This physical action 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).

Nonetheless, older adults in the present study, exhibited decreased ability to inhibit distractors in the high physical exertion condition, providing strong evidence for inhibition-based theories of cognitive aging, which postulate that the ability to inhibit distracting information declines with age (Hasher & Zacks, 1988). The dual-task paradigm in the present study was adopted from Vogel et al. (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, were recorded. When distractors are present, the amplitude of CDA is 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). In addition, 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). More importantly, the decline in cognitive inhibition in older adults was amplified by the concurrent high physical exertion. Dual-task decrements, which are defined as a deficit in performance for one task as a result of simultaneously completing a secondary task, can offer a potential explanation for the present study. For example, gait speed (Hausdorff et al., 2008; Plummer-D'Amato et al., 2011, 2012) or precision grip variability (Voelcker-Rehage & Alberts, 2007) is altered during a dual-task in comparison to a single-task. 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 Park et al., 2021), which manifested as opposite patterns in μ and τ components of the ex-Gaussian analyses of the WM task RTs in the present study. It is however possible that the two effects may stem from the same neurocognitive mechanism. For example, 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 (Mather & Harley, 2016; Mather et al., 2016). Therefore, arousal stemming from high physical exertion for older adults may result 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 (see for a review 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., 2020). However, when salient and non-salient 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 non-salient information (Lee et al., 2018). Therefore, older adults' ability to inhibit 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 may become difficult due to the negative interactions between cognitive and motor tasks, and consequently the risk of injury increases. Age-related declines 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 & Kiziliaslan, 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 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 (Samuel et al., 2013; Kallman et al.,1990;

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. Lastly, 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.

One cavate of the present study includes differences in compensation for participation between younger and older adults. Future studies should consider comparable compensation across experimental groups. Another limitation of the present study includes the lack of information collected regrading 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 non-dominant hand (i.e., right hand dominant participants). Lastly, 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 of cognitive vs. motor task prioritization.

2.5.1 Conclusions

With the analyses of accuracy, RT and Hierarchical Bayesian ex-Gaussian Analyses of RT, the present study found that effortful physical exertion (30% versus 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 (Voelcker-Rehage & Alberts, 2007; Plummer-D’Amato et al., 2011, 2012). 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.

References

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., Kong, E., Larraburo, Y., Rolle, C., Johnston, E., & Gazzaley, A. (2013). Video game training enhances cognitive control in older adults. *Nature*, *501*(7465), 97–101. https://doi.org/10.1038/nature12486

Ángyán, L., Téczely, T., & Karsai, I. (2005). Learning to produce predicted static handgrip forces. *Acta Physiologica Hungarica*, *92*(1), 11–18. https://doi.org/10.1556/aphysiol.92.2005.1.2

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28,* 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Azer, L., Xie, W., Park, H.-B., & Zhang, W. (2022). *Detrimental Effects of Effortful Physical Exertion on a Working Memory Dual-Task in Older Adults*. https://osf.io/4jz65/

Balota, D. A., & Yap, M. J. (2011). Moving beyond the mean in studies of mental chronometry: The power of response time distributional analyses. *Current Directions in Psychological Science, 20*(3), 160–166. https://doi.org/10.1177/0963721411408885

Beurskens, R., & Bock, O. (2012). Age-Related Deficits of Dual-Task Walking: A Review. *Neural Plasticity*, *2012*, e131608. https://doi.org/10.1155/2012/131608

Blankevoort, C. G., Scherder, E. J. A., Wieling, M. B., Hortobágyi, T., Brouwer, W. H., Geuze, R. H., & van Heuvelen, M. J. G. (2013). Physical predictors of cognitive performance in healthy older adults: a cross-sectional analysis. *PloS One*, *8*(7), e70799. https://doi.org/10.1371/journal.pone.0070799

Bohannon, R. W. (2001). Dynamometer Measurements of Hand-Grip Strength Predict Multiple Outcomes. *Perceptual and Motor Skills*, *93*(2), 323–328. https://doi.org/10.2466/pms.2001.93.2.323

Burzynska, A. Z., Voss, M. W., Fanning, J., Salerno, E. A., Gothe, N. P., McAuley, E., & Kramer, A. F. (2020). Sensor-measured sedentariness and physical activity are differentially related to fluid and crystallized abilities in aging. *Psychology and Aging*, *35*(8), 1154–1169. https://doi.org/10.1037/pag0000580

Brass, M., Ullsperger, M., Knoesche, T. R., von Cramon, D. Y., & Phillips, N. A. (2005). Who comes first? The role of the prefrontal and parietal cortex in cognitive control. *Journal of Cognitive Neuroscience*, *17*(9), 1367–1375. https://doi.org/10.1162/0898929054985400

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: A study of 55,753 participants aged 8–75. *Frontiers in Psychology*, *4*, 12. https://doi.org/10.3389/fpsyg.2013.00012

Cappiello, M., Xie, W., & Zhang, W. (2018). The mental muscle: Effects of concurrent effortful physical action on visual working memory. *Journal of Vision, 18*(10), 705. https://doi.org/10.1167/18.10.705

Cortes, N., Onate, J., & Morrison, S. (2014). Differential effects of fatigue on movement variability. Gait & Posture, 39(3), 888-893. https://doi.org/10.1016/j.gaitpost.2013.11.020

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Cain, W. S., & Stevens, J. C. (1971). Effort in sustained and phasic handgrip contractions. *The American Journal of Psychology*, *84*(1), 52–65. https://doi.org/10.2307/1421224

Dahl, M. J., Mather, M., & Werkle-Bergner, M. (2022). Noradrenergic modulation of rhythmic neural activity shapes selective attention. Trends in Cognitive Sciences, 26(1), 38–52. https://doi.org/10.1016/j.tics.2021.10.009

Davranche, K., Audiffren, M., & Denjean, A. (2006). A distributional analysis of the effect of physical exercise on a choice reaction time task. *Journal of Sports Sciences, 24*(3), 323–329. https://doi.org/10.1080/02640410500132165

Doumas, M., Rapp, M. A., & Krampe, R. Th. (2009). Working Memory and Postural Control: Adult Age Differences in Potential for Improvement, Task Priority, and Dual Tasking. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *64B*(2), 193–201. https://doi.org/10.1093/geronb/gbp009

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

Eksioglu, M., & Kızılaslan, K. (2008). Steering-wheel grip force characteristics of drivers as a function of gender, speed, and road condition. *International Journal of*

Industrial Ergonomics, *38*(3), 354–361. https://doi.org/10.1016/j.ergon.2008.01.004

Erickson, K. I., Hillman, C. H., & Kramer, A. F. (2015). Physical activity, brain, and cognition. *Current Opinion in Behavioral Sciences*, *4*, 27–32. https://doi.org/10.1016/j.cobeha.2015.01.005

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Faust, M. E., Balota, D. A., Spieler, D. H., & Ferraro, F. R. (1999). Individual differences in information-processing rate and amount: implications for group differences in response latency. *Psychological Bulletin*, *125*(6), 777-799.

Firth, J., Stubbs, B., Vancampfort, D., Firth, J. A., Large, M., Rosenbaum, S., … Yung, A. R. (2018). Grip strength is associated with cognitive performance in schizophrenia and the general population: A UK Biobank study of 476559 participants. *Schizophrenia Bulletin*, *44*(4), 728–736. https://doi.org/10.1093/schbul/sby034

Gaspelin, N., & Luck, S. J. (2018). The Role of Inhibition in Avoiding Distraction by Salient Stimuli. *Trends in Cognitive Sciences*, *22*(1), 79–92. https://doi.org/10.1016/j.tics.2017.11.001

Hausdorff, J. M., Schweiger, A., Herman, T., Yogev-Seligmann, G., & Giladi, N. (2008). Dual Task Decrements in Gait among Healthy Older Adults: Contributing Factors. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *63*(12), 1335–1343.

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine*, *29*(4), 737–752. https://doi.org/10.1016/j.cger.2013.07.002

Hasher, L., & Zacks, R. T. (1988). *Working memory, comprehension, and aging: A review and a new view*. In G. H. Bower (Ed.), The psychology of learning and motivation (Vol. 22 pp. 193-225). San Diego, CA: Academic Press.

Hohle, R. H. (1965). Inferred components of reaction times as functions of foreperiod duration. *Journal of Experimental Psychology, 69*(4), 382–386. https://doi.org/10.1037/h0021740

Incel, N. A., Ceceli, E., Durukan, P. B., Erdem, H. R., & Yorgancioglu, Z. R. (2002). Grip strength: Effect of hand dominance. *Singapore Medical Journal*, *43*(5), 234–237.

Jaroslawska, A. J., Rhodes, S., Belletier, C., Doherty, J. M., Cowan, N., Neveh-Benjamin, M., Barrouillet, P., Camos, V., & Logie, R. H. (2021). What affects the magnitude of age-related dual-task costs in working memory? The role of stimulus domain and access to semantic representations. *Quarterly Journal of Experimental Psychology (2006)*, *74*(4), 682–704. https://doi.org/10.1177/1747021820970744

Kallman, D. A., Plato, C. C., & Tobin, J. D. (1990). The role of muscle loss in the age-related decline of grip strength: cross-sectional and longitudinal perspectives. *Journal of Gerontology*, *45*(3), 82-88. https://doi.org/10.1093/geronj/45.3.M82

Kobayashi-Cuya, K. E., Sakurai, R., Sakuma, N., Suzuki, H., Yasunaga, M., Ogawa, S., et al. (2018). Hand dexterity, not handgrip strength, is associated with executive function in Japanese community-dwelling older adults: a cross-sectional study. *BMC Geriatrics*, *18*(1), 192. https://doi.org/10.1186/s12877-018-0880-6

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: beyond a unitary view of inhibitory processing in attention. *Psychology and Aging*, *9*(4), 491–512. https://doi.org/10.1037/0882-7974.9.4.491

Kruschke, J. K. (2011). Bayesian assessment of null values via parameter estimation and model comparison. *Perspectives on Psychological Science, 6*(3), 299–312. https://doi.org/10.1177/1745691611406925

Kruschke, J. (2014). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan*. Academic Press.

Lee, T.-H., Greening, S. G., Ueno, T., Clewett, D., Ponzio, A., Sakaki, M., & Mather, M. (2018). Arousal increases neural gain via the locus coeruleus–noradrenaline system in younger adults but not in older adults. Nature Human Behaviour, 2(5), 356–366. https://doi.org/10.1038/s41562-018-0344-1

Leisman, G., Moustafa, A. A., & Shafir, T. (2016). Thinking, walking, talking: Integratory motor and cognitive brain function. *Frontiers in Public Health*, *4*. https://doi.org/10.3389/fpubh.2016.00094

Li, K. Z. H., & Lindenberger, U. (2002). Relations between aging sensory/sensorimotor and cognitive functions. *Neuroscience and Biobehavioral Reviews*, *26*(7), 777–783. https://doi.org/10.1016/s0149-7634(02)00073-8

Liu, Y., Rodenkirch, C., Moskowitz, N., Schriver, B., & Wang, Q. (2017). Dynamic Lateralization of Pupil Dilation Evoked by Locus Coeruleus Activation Results from Sympathetic, Not Parasympathetic, Contributions. Cell Reports, 20(13), 3099–3112. https://doi.org/10.1016/j.celrep.2017.08.094

Lowe, B. D. (2016). Repeatability of magnitude production in isometric, hand-grip force estimation: A working-memory approach. *Perceptual and Motor Skills, 80*(2), 659–667. https://doi.org/10.2466/pms.1995.80.2.659

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39,* e200. https://doi.org/10.1017/S0140525X15000667

Mather, M., & Harley, C. W. (2016). The Locus Coeruleus: Essential for Maintaining Cognitive Function and the Aging Brain. *Trends in cognitive sciences*, *20*(3), 214–226. https://doi.org/10.1016/j.tics.2016.01.001

McMorris, T., Sproule, J., Turner, A., & Hale, B. J. (2011). Acute, intermediate intensity exercise, and speed and accuracy in working memory tasks: A meta-analytical comparison of effects. *Physiology & Behavior, 102*(3–4), 421–428. https://doi.org/10.1016/j.physbeh.2010.12.007

Milanović, Z., Pantelić, S., Trajković, N., Sporiš, G., Kostić, R., & James, N. (2013). Age-related decrease in physical activity and functional fitness among elderly men and women. *Clinical Interventions in Aging*, *8*, 549–556. https://doi.org/10.2147/CIA.S44112

Missenard, O., Mottet, D., & Perrey, S. (2008). Muscular fatigue increases signal-dependent noise during isometric force production. *Neuroscience Letters*, *437*(2), 154-157. https://doi.org/10.1016/j.neulet.2008.03.090

Morrison, S., Kavanagh, J., Obst, S. J., Irwin, J., & Haseler, L. J. (2005). The effects of unilateral muscle fatigue on bilateral physiological tremor. Experimental brain Brain researchResearch, 167(4), 609-621. https://doi.org/10.1007/s00221-005-0050-x

Nielsen, S. E., & Mather, M. (2015). Comparison of two isometric handgrip protocols on sympathetic arousal in women. *Physiology & Behavior*, *142*, 5-13. https://doi.org/10.1016/j.physbeh.2015.01.031

Ophir, E., Nass, C., & Wagner, A. D. (2009). Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(37), 15583–15587. https://doi.org/10.1073/pnas.0903620106

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*, 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Park, H.-B., Ahn, S., & Zhang, W. (2021). Visual search under physical effort is faster but more vulnerable to distractor interference. *Cognitive Research: Principles and Implications*, *6*(1), 17. https://doi.org/10.1186/s41235-021-00283-4

Plummer-D'Amato, P., Altmann, L. J. P., & Reilly, K. (2011). Dual-task effects of spontaneous speech and executive function on gait in aging: exaggerated effects in slow walkers. *Gait & Posture*, *33*(2), 233–237. https://doi.org/10.1016/j.gaitpost.2010.11.011

Plummer-D'Amato, P., Brancato, B., Dantowitz, M., Birken, S., Bonke, C., & Furey, E. (2012). Effects of gait and cognitive task difficulty on cognitive-motor interference in aging. *Journal of Aging Research*, *2012*, 670-677. https://doi.org/10.1155/2012/583894

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise*, *40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Praetorius Björk, M., Johansson, B., & Hassing, L. B. (2016). I forgot when I lost my grip-strong associations between cognition and grip strength in level of performance and change across time in relation to impending death. *Neurobiology of Aging*, *38*, 68–72. https://doi.org/10.1016/j.neurobiolaging.2015.11.010

Rapp, M. A., Krampe, R. T., & Baltes, P. B. (2006). Adaptive task prioritization in aging: Selective resource allocation to postural control is preserved in Alzheimer disease. *The American Journal of Geriatric Psychiatry: Official Journal of the American Association for Geriatric Psychiatry*, *14*(1), 52–61. https://doi.org/10.1097/01.JGP.0000192490.43179.e7

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*(2), 225–237. https://doi.org/10.3758/PBR.16.2.225

Samuel, D., Wilson, K., Martin, H. J., Allen, R., Sayer, A. A., & Stokes, M. (2013). Age associated changes in hand grip and quadriceps muscle strength ratios in healthy adults. *Aging Clinical and Experimental Research*, *24*(3), 245–250. https://doi.org/10.1007/BF03325252

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews*, *34*(5), 721–733. https://doi.org/10.1016/j.neubiorev.2009.10.005

Sparling, P. B., Howard, B. J., Dunstan, D. W., & Owen, N. (2015). Recommendations for physical activity in older adults. *BMJ (Clinical Research Ed.)*, *350*, h100. https://doi.org/10.1136/bmj.h100

Taekema, D. G., Gussekloo, J., Maier, A. B., Westendorp, R. G. J., & de Craen, A. J. M. (2010). Handgrip strength as a predictor of functional, psychological and social health. A prospective population-based study among the oldest old. *Age and Ageing*, *39*(3), 331–337. https://doi.org/10.1093/ageing/afq022

Taekema, D. G., Ling, C. H. Y., Kurrle, S. E., Cameron, I. D., Meskers, C. G. M., Blauw, G. J., … Maier, A. B. (2012). Temporal relationship between handgrip strength and cognitive performance in oldest old people. *Age and Ageing*, *41*(4), 506–512. https://doi.org/10.1093/ageing/afs013

Tomporowski, P. D., Albrecht, C., & Pendleton, D. M. (2017). Effects of isometric hand-grip muscle contraction on young adults' free recall and recognition memory. *Research Quarterly for Exercise and Sport*, *88*(1), 95–100. https://doi.org/10.1080/02701367.2016.1264567

Vandervoort, A. A. (2002). Aging of the human neuromuscular system. *Muscle & Nerve*, *25*(1), 17–25. https://doi.org/10.1002/mus.1215

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

Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *62*(3), 141-148. https://doi.org/10.1093/geronb/62.3.p141

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*(6984), 748–751. https://doi.org/10.1038/nature02447

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*(7067), 500–503. https://doi.org/10.1038/nature04171

Xie, W., Berry, A., Lustig, C., Deldin, P., & Zhang, W. (2019). Poor sleep quality and compromised visual working memory capacity. *Journal of the International Neuropsychological Society*, *25*(6), 583–594. https://doi.org/10.1017/S1355617719000183

Xie, W., Lu Sing, J. L., Martinez-Flores, A., & Zhang, W. (2022). Induced negative arousal modulates the speed of visual working memory consolidation. *Emotion (Washington, D.C.)*, *22*(1), 179–197. https://doi.org/10.1037/emo0001059

Yi, Y., & Friedman, D. (2014). Age-related differences in working memory: ERPs reveal age-related delays in selection- and inhibition-related processes. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition*, *21*(4), 483–513. https://doi.org/10.1080/13825585.2013.833581

Tables

Table 1.

Sample Demographics

	Younger Adults (18-28)	Older Adults (65-86)			
Characteristics	Mean (*SD*)/%	Mean (*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)			
Female	126.93 (52.01)	163.21 (64.49)	-.44	47	.664
Male	176.84 (72.00)	157.82 (54.60)			
Years of Education	14.08 (1.38)	15.18 (2.19)	1.85	41	.077

Table 2.

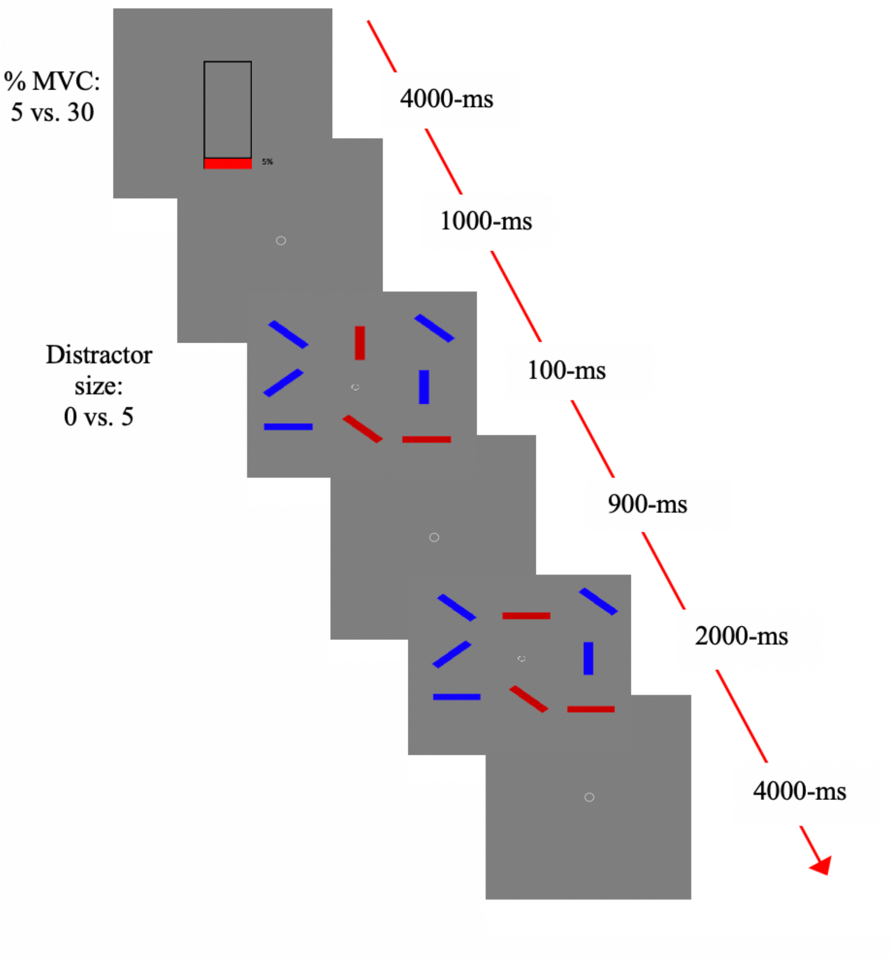
Group-level posterior mean and 95% highest density interval (HDI) for each ex-Gaussian parameter (μ, σ, and τ) as a function of age, distractor size, and physical exertion.

Parameters	5% Physical Exertion		30% Physical Exertion	
	0-Distractor	5-Distractor	0-Distractor	5-Distractor
	Younger Adults (mean [$\text{HDI}_{95\%}$] 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 (mean [$\text{HDI}_{95\%}$] 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]

Figures

Figure 1.

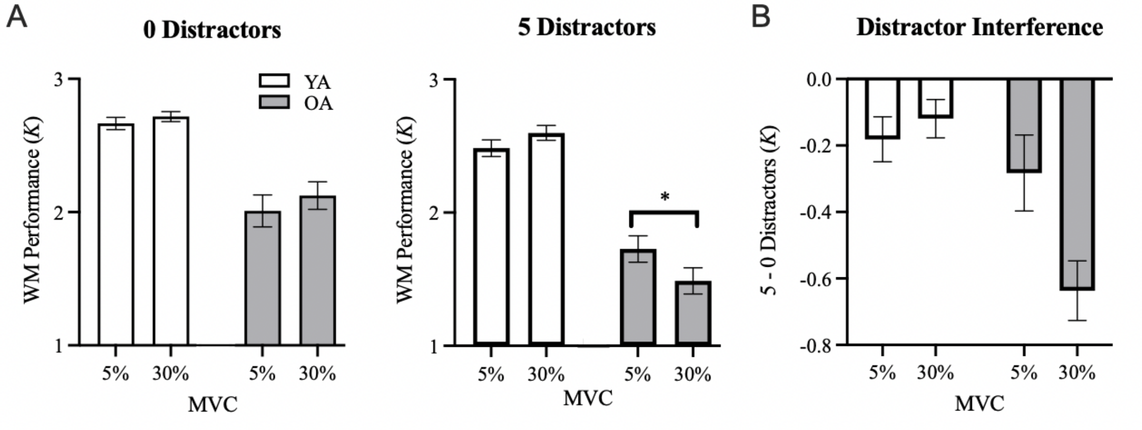
Stimuli and procedure for the concurrent physical exertion and change detection task



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 zero-distractors or five-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.

Figure 2.

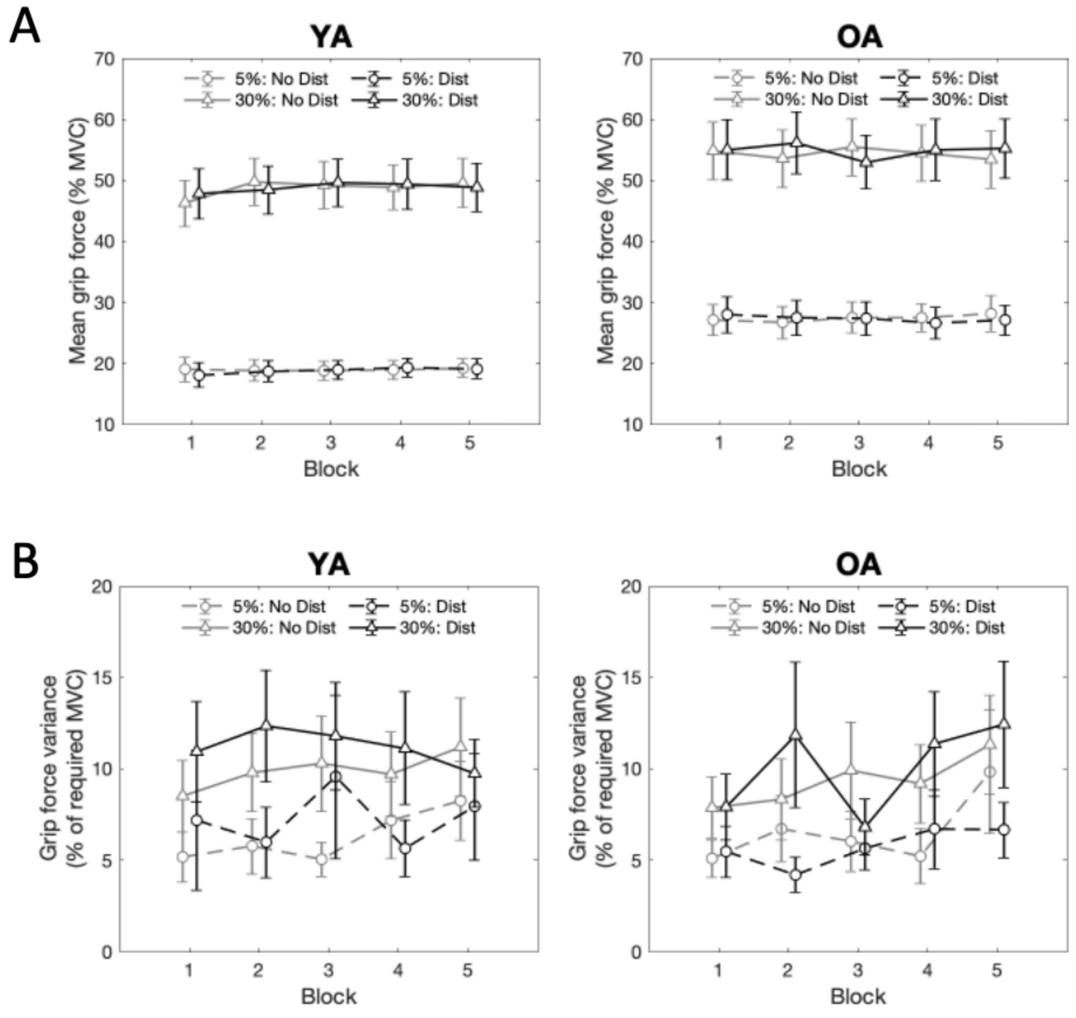
Three-way interaction with age group (younger vs. older adults), distractor size (0 vs. 5-distractors), and physical effort (5% vs. 30% MVC).



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.

Figure 3.

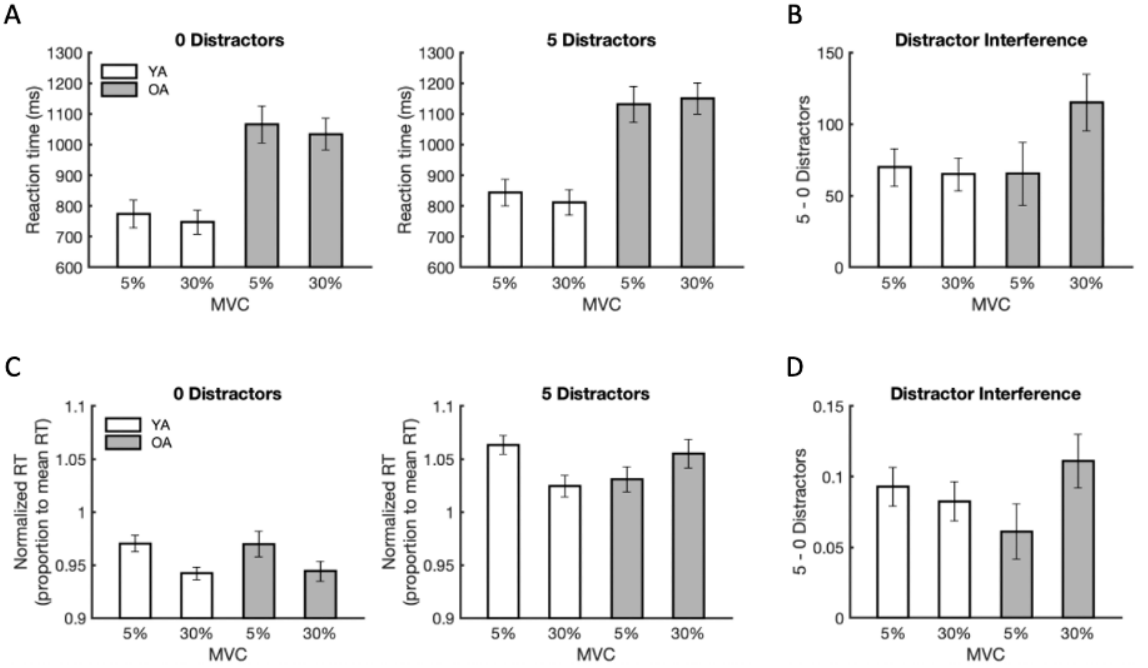
Mean grip force and variability across the experimental blocks.



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 younger adults (YA) and older adults (OA) for YA and OA across the experimental blocks.

Figure 4.

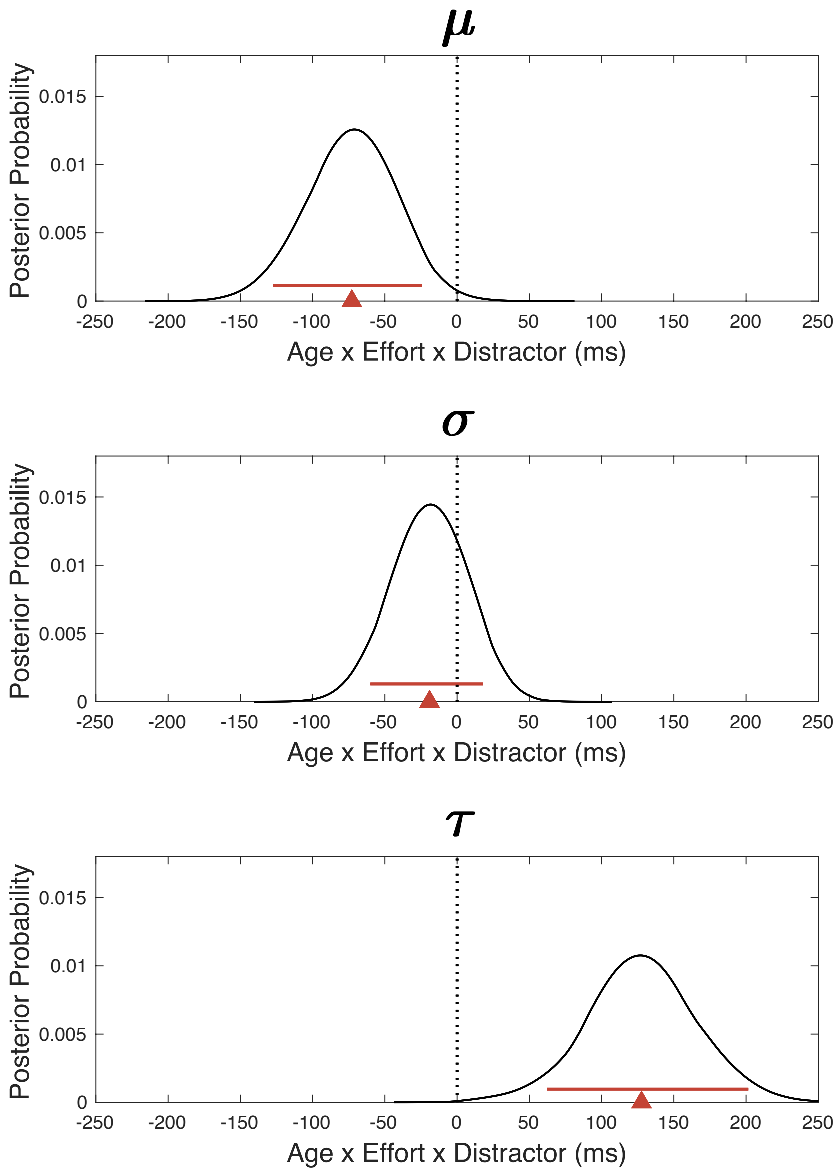
RT results for the change detection WM task.



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-D) Normalized RTs to the individual mean RT, where variations across conditions can be referred as deviation from 100% mean RT.

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.

Chapter 3. Impaired Inhibitory Control for the Le Grand Face Task under Increased Effortful Physical Exertion

3.1 Abstract

Face processing involves the recruitment of specialized cortical networks that are not typically shared with other complex cognitive functions. Recently, experimental paradigms assessing holistic face processing, such as the composite face effect (CFE) of the Le Grand face task, suggest that the Le Grand face task may require additional reliance on cognitive control mechanisms. Concurrent effortful physical exertion may negatively impact cognitive control. Therefore, Experiment 1 of the present study investigated the interaction between motor and cognitive functions using the Le Grand face task as a measure that requires reliance inhibitory control mechanisms. Using a novel dual-task paradigm, participants engaged the Le Grand face task under concurrent physical exertion (5% vs 45% individual maximum voluntary contraction, MVC). In Experiment 2 of the present study, we investigated overall face discrimination under effortful physical exertion. Under high concurrent physical effort cognitive control (Experiment 1) but not overall face discrimination (Experiment 2) was impaired. These results may be empirically important for understanding how physical exertion may impair the ability to inhibit task-irrelevant items using stimuli that we encounter daily (i.e., faces).

3.2 Introduction

Reflecting on what a typical month in your life looks like, think about how many people, and thus faces, you may encounter. This can include a trip to the grocery store, a leisure or brisk walk through a college campus, or an outing at a restaurant where you are bound to passively view many, if not hundreds, of faces on a given month. In fact, on average, we can recall and recognize approximately 5,000 faces of those we directly socially interact with and those that we may not socially interact with but are known famous figures (Jenkins et al., 2018). This is only a fraction of the many faces that we may actively and passively encounter in our lives. Face processing and recognition involves the recruitment of its own specialized cortical network that is not typically shared with other complex cognitive functions (Kanwisher & Yovel, 2006). However, experimental paradigms assessing holistic face processing, such as the composite face effect (CFE) of the Le Grand face task (Le Grand et al., 2004), may require additional reliance on cognitive control mechanisms (Fitousi, 2020; Chen et al., 2022). Inhibitory control, which involves the ability to inhibit task-irrelevant information and attend to task-relevant information (Diamond, 2013), is impaired while simultaneously performing a task involving cognitive and physical actions (Azer et al., Under Revision; Park et al., 2021). Many of the daily activities that we engage in as we actively or passively view faces involve engagement in a simultaneous physical activity (e.g., pushing a heavy shopping cart in the grocery store, leisure or brisk walking, cycling on a city street, etc.); therefore, understanding the impact of engaging in a concurrent physical action on inhibitory control in natural scenes, such as face processing, is imperative.

Face processing is unique, unlike other complex cognitive processes, and has its own specialized neural mechanism, the fusiform face area (FFA; for a review see Kanwisher & Yovel, 2006). The FFA has robust activation in response to faces and is sensitive to face configurations (Kanwisher & Yovel, 2006;, Liu et al., 2010). In addition to configural face information, the FFA is sensitive to detecting featural information and integrating both featural and configural information into a holistic representation (Liu et al., 2010). Therefore, faces are processed as non-decomposed wholes rather than individual segments (i.e., eyes, nose, mouth).

Maurer et al. (2002) suggested that holistic face processing may involve three aspects: 1) first order relations, which include featural information that define a face, such as two eyes, a nose, and a mouth, 2) the detection of first order relations is automatically viewed as a gestalt rather than individual segments, and 3) second order relations, which include detection of spatial distance for featural information (i.e., configural information). Evidence for holistic encoding in face processing includes the composite face effect (CFE; Young et al., 1987; Le Grand et al., 2004), which is a more robust measure of holistic face processing than other paradigms, such as the face inversion task (Maurer et al., 2002). The original CFE task by Young et al. (1987) showed participants aligned and misaligned composite top and bottom face halves of familiar and unfamiliar faces intermixed. In this task, participants were more prone to error, and had slower reaction time, when identifying the top two face composites in the aligned vs. the misaligned condition. To date, many variations of the CFE task have been used to study holistic processing (Hole, 1994; Le Grand et al., 2004; Richler et al., 2009; Michel et al., 2016)

While the CFE has been previously been attributed to holistic face processing (Young et al., 1987; Hole, 1994; Le Grand et al., 2004; Michel et al., 2016; Azer & Zhang, 2019), recent accounts suggest that the CFE may engage working memory, cognitive control, and attentional mechanisms rather than, or in addition to, holistic processing (Fitousi, 2020; Chen et al., 2022). In fact, Fitousi (2020) suggested that the composite face task is not a pure measure of holistic processing, and instead is a measure of working memory, cognitive control, and selective attention. In this study, observers completed the full and partial design of the CFE task with 1) unfamiliar composite faces, and 2) familiar/famous composite faces and the ex-Gaussian parameter Tau (τ) for reaction time, rather than the traditional mean reaction time analysis, was computed. The ex-Gaussian τ component is hypothesized to reflect 1) working memory, cognitive control, and attentional processes (Schmiedek et al., 2007), 2) task conflict (Steinhauser & Hübner, 2009), and 3) object-based attention (Spieler et al., 2000). Across the full and partial CFE task design for familiar and unfamiliar faces, the ex-Gaussian τ parameter for reaction time showed that participants required significantly longer reaction times for the aligned, compared to the misaligned, condition (Fitousi, 2020). This pattern was not observed for the other ex-Gaussian Mu (μ) and Sigma (σ) parameters (Fitousi, 2020), which represent response or stimulus related processes on reaction time (Schmitz & Wilhelm, 2016). Thus, Fitousi (2020) concluded that the CFE task is primarily associated with working memory, cognitive control, and attentional processes and may not reflect holistic processing.

Ex- Gaussian modeling of behavioral performance suggested that the CFE task may not be directly related to holistic processing and is associated with alternative cognitive mechanisms (Fitousi, 2020). To further investigate the role of attentional, working memory, and control mechanisms on the CFE, Chen et al. (2022) investigated neural substrates while participants performed the CFE task to determine if additional networks, beyond the FFA, were involved. Replicating prior studies (for a review see Kanwisher & Yovel, 2006), the FFA elicited stronger activation in the aligned, compared to the misaligned, condition (Chen et al., 2022). In addition, the bilateral insula and medial frontal cortex elicited stronger activation in response to the aligned, compared to the misaligned, condition. These two regions are involved in monitoring ongoing actions, cognitive control, and goal-directed attention (Ridderinkhof et al., 2004; Brass et al., 2005; Craig, 2009; Menon & Uddin, 2010). Combined, Fitousi (2020) and Chen et al. (2022) both demonstrated that the CFE task (partial and full design; familiar and unfamiliar faces) may be more appropriately described as a measure of cognitive control rather than a measure of holistic face processing. Therefore, CFE measured using the Le Grand face task (Le Grand et al., 2004) in the present study is used as a measure of cognitive control for stimuli that we possess expertise for in a natural scene given our periodic exposure to faces.

As faces, and other stimuli, are processed in natural scenes during everyday activities, on many occasions we simultaneously engage in concurrent physical activity, such as encountering others during a leisure or brisk walk or pushing a shopping cart as we actively or passively view faces in a grocery store. The close interaction between motor and cognitive functions thus elicits an in-depth investigation and understanding of the impact of engaging in a dual task on cognition. For instance, long-term memory retrieval is impaired when participants simultaneously engaged in a concurrent physical task (i.e., physical exertion on a hand dynamometer) during memory encoding (Tomporowski et al., 2017). More importantly, task-irrelevant distractors can get encoded (Cappiello et al., 2018; Azer et al., Under Revision) and capture visual attention (Park et al., 2021) more easily during concurrent physical exertion. In other words, participants are vulnerable to distractor interference as a result of reduced inhibitory control while engaging in a simultaneous motor and cognitive action (Cappiello et al., 2018; Park et al., 2021; Azer et al., Under Revision).

The present study aimed to assess the interaction between motor and cognitive functions using a sample of undergraduate college students by testing the effects of effortful physical exertion on key cognitive processes. Recent studies (Cappiello et al., 2018; Park et al., 2021; Azer et al., Under Revision) suggest that these effects may be supported by different mechanisms than the effects of acute or habitual physical activity, in isolation, on cognition (Pontifex et al., 2019; Erickson et al., 2015). Specifically, we assessed the impact of a *simple* yet effortful physical task on inhibitory control for face stimuli using the partial design of the Le Grand face task (Le Grand et al., 2004) by manipulating physical exertion on an isometric hand dynamometer using the novel dual-task paradigm where participants completed the Le Grand face task under effortful physical exertion. An isometric hand dynamometer is an apparatus that involves static contraction of the hand muscles with restricted joint movements and measures participants' maximum isometric handgrip strength. The use of an isometric hand dynamometer for the concurrent handgrip task in the present study is an inexpensive, convenient, and inclusive measurement tool that is widely adopted in clinical and experimental settings as an indicator of cognitive functioning (Praetorius Björk et al., 2016) and predictor of overall health (Bohannon, 2001). The use of a hand dynamometer promotes inclusivity in that it expands the generalizability of dual-task paradigms to include those with limited mobility unlike the use of a gait task which requires participants to perform a dual walking and cognitive task (Haudorff et al., 2008; Plummer-D'Amato et al., 2011, 2012), thus consequently limiting the participant inclusion criteria.

In the present study, cognitive control for stimuli from natural scenes was measured using the CFE of the Le Grand face task (Le Grand et al., 2004). In this task, participants were briefly presented two sequential displays of composite faces consisting of top and bottom face halves (Figure 1). Participants reported if the top face halves of the two sequential displays are the same or different while ignoring the task-irrelevant bottom face halves, which were always different. On half of the trials, the two sequentially presented faces were misaligned by shifting the face halves horizontally half a face in width to the left (misaligned condition). On the other half of the trials, the top and the bottom face halves of the two sequentially presented faces were properly aligned (aligned condition). The bottom face halves in both conditions were task-irrelevant and served as distractors that required active inhibition to successfully recall the task-relevant top face halves. While the bottom face halves are task-irrelevant, they can empirically and phenomenologically interfere with judgment of the top face halves (Le Grand et al., 2004; Fitousi, 2020; Chen et al., 2022)). In fact, when the two face halves are aligned, thus requiring greater inhibitory control to inhibit the task-irrelevant bottom face halves, the bottom face halves interfere with participants' ability to accurately detect if the top face halves are the same or different due to holistic processing (Le Grand et al., 2004) and reduced inhibitory control (Fitousi, 2020; Chen et al., 2022). However, when the two face halves are misaligned, holistic processing is disrupted and less inhibitory control is required, allowing participants to accurately detect if the two top face halves are the same or different (Le Grand et al., 2004; Fitousi, 2020; Chen et al., 2022). The CFE is the difference in performance between the aligned and misaligned conditions; therefore, operationally serving as reduced inhibitory control due to the task-irrelevant bottom face halves.

Inhibitory control, which involves the ability to inhibit task-irrelevant information and attend to task-relevant information (Diamond, 2013), is impaired while simultaneously performing a task involving cognitive and physical functions (Cappiello et al., 2018; Park et al., 2021; Azer et al., Under Revision). Concurrent physical exertion using a hand dynamometer in the present study was operationalized as exerted handgrip force at different participant-specific maximum voluntary contraction (MVC, 5% versus 45%) levels, independent of individual differences in muscular strength and fitness level. The use of a power grip (i.e., handgrip; gripping an item centrally located in the palm of the hand using the thumb and all fingers to transmit force) for the physical exertion manipulation in the present study is more ecologically valid and tends to require less cognitive control ((Kobayashi-Cuya et al., 2018) than the of use of other grip physical exertion paradigms, such as precision grip (i.e., gripping an item using the thumb and one finger to transmit force). For example, a power grip, in comparison to a precision grip, may be preferred when pushing a shopping cart, carrying a bag of groceries, or driving. In fact, individuals on average exert 31% maximum voluntary grip force on a steering wheel while driving (Eksioglu & Kiziliaslan, 2008) and approximately 10 – 20% maximum voluntary grip force while carrying a 11 – 22-pound shopping bag, respectively, while waking (Ramadan et al., 2018).

We hypothesize that the CEF observed in previous studies (Young et al., 1987; Hole, 1994; Le Grand et al., 2004; Michel et al., 2016; Fitousi, 2020; Chen et al., 2022) will be replicated in the present study. However, given that concurrent physical exertion may reduce inhibitory control (Azer et al., Under Revision) and spatial attention (Park et al., 2021), we predict worse performance on the Le Grand face task, operationalized as larger CFE, will manifest in the aligned condition, than the misaligned face condition, under high physical exertion (45% MVC) due to reduced cognitive control from the task-irrelevant bottom face halves. Hence, under low physical exertion (5% MVC) performance between the aligned and misaligned conditions will be similar, yielding a significant two-way interaction between physical exertion and face alignment.

In addition to investigating the effect of concurrent physical exertion on cognitive control using CFE of the Le Grand face task (Le Grand et al., 2004), overall face discrimination was also assessed using the Glasgow Face Matching Test (GMFT; Burton et al., 2010). In this task, participants reported whether two sequentially presented faces had the same or different identity. The GMFT was selected for the present study over other face identification tasks (Bruce et al., 1999) given that it is a face matching task rather than a face memory task (Burton et al., 2010) and thus minimizes the involvement of visual short-term memory (Xie & Zhang, 2017). The goal of the present study was to investigate the impact of concurrent physical exertion on cognitive control using real world stimuli, such as faces; therefore, face discrimination was investigated under effortful physical exertion to assess if the dual-task conditions impact overall face discrimination. We predict that overall face discrimination assessed using the GFMT should be intact under physical exertion and recruitment of inhibitory control is minimal. In other words, face discrimination accuracy will be comparable across the high (45% MVC) and low (5% MVC) physical exertion conditions.

3.3 General Method

3.3.1 Experiment 1

3.3.1.1 Participants

An *a priori* power analysis for repeated-measures within factors analysis of variances (ANOVA) suggests that a total sample size of 36 participants (4 repeated-measured conditions) would provide 95% statistic power for a significant mixed-effect interaction at a medium level (*F* = 0.25, Faul et al., 2009). Hence, the present study recruited 40 undergraduate students (60% Female, 37.5% Male, 2.5% Prefer not to respond; $M_{age} = 19.78$, $SD_{age} = 2.49$; 55.0% Asian, 15.0% Hispanic, 17.5% White/Non-Hispanic, 2.5% More than one race, 2.5% American Indian or Alaska Native, 7.5% Prefer not to respond) from University of California, Riverside. Sample demographics are shown in Table 1. Inclusion criteria required that all participants reported normal or corrected-to-normal vision, normal color vision and over the age of 18-years-old.

Additional data from 10 undergraduate students were excluded from the study due to unsuccessful handgrip recordings resulting from misuses of the hand dynamometer or misunderstanding of the study instructions. These participants were unable to complete the experiment as instructed, and therefore were considered ineligible for this study. The experimental procedure was approved by the Institutional Review Board of the University of California, Riverside. All participants were provided written informed consent and were compensated for their participation by course credits.

3.3.1.2 Procedure

Stimuli were presented on an LCD monitor with a grey background (6.1 cd/m^2), using PsychToolbox-3 (Brainard, 1997) for Matlab (The Math Works, Cambridge, MA) at a viewing distance of 57 cm. The monitor was calibrated with an X-Rite I1Pro spectrophotometer (X-Rite, Inc., Grand Rapids, MI). Participants' handgrip force was measured at the beginning of the experiment using an isometric Vernier HD-BTA hand dynamometer (Vernier, Beaverton, OR). Each participant first completed a brief assessment to obtain isometric maximum voluntary contraction (MVC) of grip force and then the Le Grand face task with a concurrent handgrip at different levels of %MVC using the isometric Vernier HD-BTA hand dynamometer (Vernier, Beaverton, OR).

3.3.1.2.1 MVC Measurement. To measure MVC**,** participants were instructed to hold the hand dynamometer in their left hand and squeeze it using maximum force for 4,000 ms with no visual feedback at the beginning of experimental session. This procedure was repeated for three consecutive trials. The median grip force level during the last 2,000 ms of the 4,000 ms measurement window in each trial was averaged across the three trials as the MVC of each participant. Each participant's MVC was used to manipulate physical exertion by asking them to grip the hand dynamometer at different levels (5% vs. 45%) of their initial MVC measurement during the dual task; therefore, standardizing the amount of physical effort exerted regardless of individual strength. Initial MVC measurement was not directly used in the present study.

After obtaining initial MVC measurement, participants practiced gripping the hand dynamometers at different levels of their maximum grip strength for 4,000 ms with real-time visual feedback indicated by a red gauge illustrating their exerted grip force (Figure 1B). Each practice trial began with the promote, "*Please get ready! Please hold the handgrip at the required level AFTER you hear a beep*" centrally displayed for 500 ms. Following the prompt, a centrally displayed visual gauge appeared providing real-time feedback of the exerted grip force. The visual gauge, 4^{o} by 6^{o} in visual angle, showed a red bar with dynamically changing height that was proportional to the exerted grip force and a black horizontal line marked relative to the required exertion level (for an example, see first screen in Figure 1). If participants were able to successfully maintain the grip force at the indicated level of their MVC (i.e., 5, 20, 45, 65, or 90%), an auditory "Cha-Ching" sound and visual feedback stating, "*You have successfully* *maintained the force*!" appeared to indicate a correct physical exertion trial. However, if participants were unable to maintain the grip force at the indicated level of their MVC, an auditory "Beep" sound and visual feedback stating, "*Not quite. Please try harder!"* appeared to indicate an unsuccessful physical exertion trial. Participants were given another set of 10 practice trials if they were unable to maintain their grip at the indicated level of their MVC for more than half the trials.

3.3.1.2.2 Concurrent Handgrip and Le Grand Face Dual-Task. Following practice of the grip task in isolation, participants were instructed to perform the concurrent handgrip and Le Grand dual task (Figure 1). Each trial began with a 4,000 ms screen with real-time visual feedback of the exerted grip force prompting participants to grip the hand dynamometer, using their left hand, at or slightly above 5% or 45% of their MVC. No visual feedback of force exertion was provided after the initial 4,000 ms, which allowed participants to adjust the exerted force at the appropriate level. Participants were required to maintain the exerted force during the Le Grand face task and were asked to release their grip prior to making a response on the Le Grand face task. Kinesthetic information (Ángyán et al., 2005), such as gripping and maintaining grip force at a given level, is sufficient for subjective appraisal of exerted force without visual information and requires minimal WM load (Lowe, 2016). There were no significant differences in MVC in between males (*n* = 15; *M* = 122.53, *SD* = 44.63) and females (*n* = 24; *M* = 119.25, *SD* = 38.67), *t*(37) = 0.24, *p* = .809, Cohen's *d* = 0.08.

Participants successfully maintained exerted handgrip force at or slightly above the required level (5% or 45% of their MVC), 83.96% overall handgrip accuracy, without real-time visual feedback. However, it was not surprising that participants' overall handgrip accuracy for the 5% MVC condition (96.95% handgrip accuracy) was significantly higher than the overall handgrip accuracy for the 45% MVC condition (70.96% handgrip accuracy), *t*(39) = 5.34, *p* < .001, Cohen's *d* = 1.17. There was no significant difference for handgrip accuracy for the 5% MVC (*t*(39) = 0.17, *p* = .866, Cohen's *d* = 0.03) or the 45% MVC (*t*(39) = - 1.77, *p* = .085, Cohen's *d* = 0.17) conditions across the different alignment conditions (aligned vs. misaligned). The subsequent analysis for the CFE for the Le Grand face task will primarily focus on the trials when participants successfully exerted hand force to the required level during the task.

While participants maintained their handgrip force at, or slightly above, 5% or 45% of their MVC, they simultaneously performed the Le Grand face task, a visual WM task. In this task, two sequentially composite faces were presented for 200 ms each, with a 300 ms inter-stimulus-interval. On half of the trials, either the top or the bottom halves of the two sequentially presented faces were shifted horizontally half a face in width to the left (misaligned condition, Figure 1A) and were presented within a 7.2° × 7.2° rectangular area. On the other half of the trials, the top and the bottom face halves of the two sequentially presented faces were properly aligned (aligned condition, Figure 1A) and were presented a 4.8° × 7.2° rectangular area. In the both conditions, participants were required to report whether the task-relevant top halves of the two sequentially presented faces were the same or different, while ignoring the task-irrelevant bottom face halves, which were always different. The bottom face halves in both conditions served as distractors that required active inhibition in order to successfully recall the task-relevant top halves. The same or different trials for top face halves were equally likely. The present study used a partial design in order to fit the entire experiment within a one hour session, compared to the complete Le Grand face task design, which also includes a condition where the bottom face halves were the same (e.g., Richler et al., 2011).

The misaligned and aligned conditions were blocked and counterbalanced across participants while the same and different trials were randomly mixed within experimental blocks. Participants were instructed to use their right index and middle fingers to press buttons on a Logitech Precision gamepad to indicate whether the two top face halves were the same or different, while ignoring the bottom face halves, after viewing the two sequentially presented composite faces, within an 8,000 ms maximum response time window. Response time (RT) and accuracy were recorded. All experimental factors including low (5%) versus high (45%) physical exertions and same versus different top face halves conditions were randomly intermixed in each of the misaligned and aligned experimental blocks. The misaligned and aligned conditions each contained 24 *same* trials and 24 *different* trials in each block, yielding a total of 96 trials across the two experimental blocks. The experimental trials were preceded by one block of 12 practice trials. Participants were given a 30-second break after every 16 trails in both experimental blocks and a mandatory break of approximately one minute between each block. Participants were encouraged to ask for longer breaks, as needed, to minimize fatigue. The experimental task, including breaks, took approximately 40 minutes to complete.

3.3.1.3 Data Analysis

To calculate the composite face effect (CFE) of the accuracy for the Le Grand face task, the accuracy for the aligned trials were subtracted to the accuracy for the misaligned trials (Table 2). To calculate the CFE for reaction time (RT), the median RT for the misaligned trails were subtracted to the median RT for the aligned trails (Table 2; Konar et al., 2010; Le Grand et al., 2004). Only the RTs for the correct Le Grand face task response trails were used in this analysis. To evaluate dual-task effects, only trials where participants' exerted grip force was at or slightly above the indicated level of MVC during Le Grand face task were classified as correct handgrip trails and included for analysis. 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 40% but not greater than 70% MVC in the 45% MVC condition for more than 2/3rd of the time allocated for the sequential composite face presentation and interstimulus interval.

3.3.1.4 Results

3.3.1.4.1 Le Grand Face Task Performance Under Concurrent Physical Exertion. Of primary interest, we investigated accuracy across experimental conditions in successful handgrip maintenance trials, based on a two-way mixed-design repeated-measures ANVOA with face alignment (aligned vs. misaligned) and physical exertion (5% vs. 45% MVC) as within-subject factors. Consistent with the effects commonly observed in CFE literature (Young et al., 1987; Hole, 1994; Le Grand et al., 2004; Michel et al., 2016; Azer & Zhang, 2019), face alignment has a significant main effect on accuracy, *F*(1, 39) = 13.97, *p* = .001, η^2_p = .26. It was not surprising that accuracy for the misaligned condition (85.78%) was significantly higher than accuracy for the aligned condition (80.79%). The main effect of physical exertion on accuracy for CFE was not statistically significant, *F*(1, 39) = 1.14, *p* = .293, η^2_p = .03.

More importantly, we found a significant two-way interaction between face alignment and physical exertion, *F*(1, 39) = 4.77, *p* = .035, η^2_p =.11, (Figure 2A). To further evaluate this interaction, we performed post hoc analyses for face alignment and physical exertion. First, we performed two separate paired samples t-tests to investigate the effect of face alignment accuracy on physical exertion. In other words, we assessed the accuracy for the aligned and misaligned conditions separately under the two physical exertion conditions. For the aligned condition, observers' accuracy was significantly lower under high physical exertion (45% MVC; *M* = .79, *SD* = 0.10) in comparison to low physical exertion (5% MVC; *M* = .83, *SD* = 0.09), *t*(39) = 2.17, *p* = .036, Cohen's *d* = .42. For the misaligned condition, there was no significant difference in observers' accuracy under the high physical exertion (45% MVC; *M* = .87, *SD* = 0.10) and low physical exertion (5% MVC; *M* = .85, *SD* = 0.10) conditions, *t*(39) = - .99, *p* = .328, Cohen's *d* = .20. Next, we performed two separate paired samples t-tests to investigate the effect of physical exertion on face alignment accuracy. In other words, we assessed the accuracy for the two physical exertion conditions separately under face alignment. For the high physical exertion condition, observers' accuracy was significantly lower for the aligned face (*M* = .79, *SD* = 0.10) than the misaligned face (*M* = .87, *SD* = 0.10) condition, *t*(39) = - 4.11, *p* < .001, Cohen's *d* = .20. For the low physical exertion condition, there was no significant difference in observers' accuracy for the aligned face (M = .83, SD = 0.09) than the misaligned face (M = .85, SD = 0.10) conditions, t(39) = -1.24, p = .222, Cohen's d = .21. Collectively, these results suggest that effortful physical exertion compromised observers' inhibition of the task-irrelevant bottom face halves in order to accurately determine if the task-relevant face halves were the same or different in identity.

3.3.1.4.2 Reaction Time Effects of Concurrent Physical Exertion. Following the analyses on accuracy, we investigated RT across experimental conditions in successful handgrip maintenance trials, based on a two-way mixed-design repeated-measures ANOVA with face alignment (aligned vs. misaligned) and physical exertion (5% vs. 45% MVC) as within-subject factors. We did not observe a significant two-way interaction across face alignment and physical exertion on RT, F(1, 39) = 1.33, p = .257, η^2_p =.03, (Figure 2B). However, given the primary interest of the present study was to assess the impact of concurrent effortful physical action on conative control when task-irreverent items were present, accuracy of the CFE is of primary interest to determine if task-irrelevant information (i.e., bottom face halves) impairs inhibitory control under effortful physical exertion.

3.3.2 Experiment 2

Experiment two served as a control experiment to test if physical exertion impaired inhibitory control or if face processing and thus recognition was impaired by concurrent physical exertion.

3.3.2.1 Participants

An *a priori* power analysis for repeated-measures within factors analysis of variances (ANOVA) suggests that a total sample size of 34 participants (2 repeated-measured conditions) would provide 80% statistic power for a significant mixed-effect interaction at a medium level ($F = 0.25$, Faul et al., 2009). Therefore, the present study recruited 40 undergraduate students (47.5% Female, 45.0% Male, 7.5% Prefer not to respond; $M_{\text{age}} = 19.06$, $SD_{\text{age}} = 1.39$; 30.0% Asian, 25.0% Hispanic, 22.5% White/Non-Hispanic, 2.5% More than one race, 2.5% American Indian or Alaska Native, 10% Prefer not to respond) from University of California, Riverside. Sample demographics are shown in Table 1. Inclusion criteria required that all participants reported normal or corrected-to-normal vision, normal color vision and over the age of 18-years-old.

The experimental procedure was approved by the Institutional Review Board of the University of California, Riverside. All participants were provided written informed consent and were compensated for their participation by course credits.

3.3.2.2 Procedure

3.3.2.2.1 MVC Measurement. MVC measurement procedure for Experiment 2 was identical to Experiment 1.

3.3.2.2.2 Concurrent Handgrip and modified Glasgow Matching Face Test (GFMT) Dual-Task. Following practice of the grip task in isolation, participants were instructed to perform the concurrent handgrip and Glasgow Matching Face Task (GFMT) dual task (Figure 3). Each trial began with a 4,000 ms screen with real-time visual feedback of the exerted grip force prompting participants to grip the hand dynamometer, using their left hand, at or slightly above 5% or 45% of their MVC. No visual feedback of force exertion was provided after the initial 4,000 ms, which allowed participants to adjust the exerted force at the appropriate level. Like Experiment 1, participants were required to maintain the exerted grip force during the GFMT dual-task and were asked to release their grip prior to making a response. There was a significant difference in MVC in between males (*n* = 18; *M* = 139.00, *SD* = 56.82) and females (*n* = 19; *M* = 103.11, *SD* = 44.42), *t*(35) = 2.13, *p* = .041, Cohen's *d* = 0.70.

Participants successfully maintained exerted handgrip force at or slightly above the required level (5% or 45% of their MVC), 87.45% overall handgrip accuracy, without real-time visual feedback. However, it was not surprising that participants' overall handgrip accuracy for the 5% MVC condition (95.98% handgrip accuracy) was significantly higher than the overall handgrip accuracy for the 45% MVC condition (78.93% handgrip accuracy), *t*(39) = 3.17, *p* = .003, Cohen's *d* = 0.73. The subsequent analysis for the GFMT will primarily focus on the trials when participants successfully exerted hand force to the required level during the task.

As participants maintained their exerted grip force at the indicated level, they simultaneously were presented stimuli from the modified GFMT, which is a two-interval forced choice task using face stimuli adopted from Burton et al. (2010). In this task, 76 pairs of gray-scale front-view Caucasian faces were randomly selected from the GFMT dataset (for details, see Burton et al., 2010). The selected GFMT stimuli were subtended within a 5° × 7° in visual angel. On each trail, the two face pairs were sequentially presented for 17 ms each with a 400 ms inter-stimulus-interval. The sequential

presentation of the GFMT face pairs in the present study is different from the original GFMT side-by-side simultaneous presentation to match the sequential presentation of composite face stimuli in Experiment 1. On half of the trials, the face pairs had matching identities while the other half of the trials had different identities. Participants were required to report whether the two sequentially presented faces had the same or different identities while ignoring task-irrelevant differences in visual features, such as subtle differences in contrast, face contours, viewing angles, hairstyle, etc.
Subtle differences in visual features for the same face pair condition mimics face recognition in natural vision (Burton et al., 2010).

Participants were instructed to use their right index and middle fingers to press buttons on a Logitech Precision gamepad to indicate whether the two face pairs were the same or different after viewing the two faces, within an 8,000 ms maximum response time window. Response time (RT) and accuracy were recorded. All experimental factors including low (5%) versus high (45%) physical exertions and same versus different face identities were randomly intermixed in the experiment. The same face identity condition contained 38 trials and the different face identity condition contained 38 trials. The experimental trials were preceded by one block of 12 practice trials. Participants were given a 30-second break after every 16 trails and were encouraged to ask for longer breaks, as needed, to minimize fatigue. The experimental task, including breaks, took approximately 30 minutes to complete.

3.3.2.3 Data Analysis

Participants' GFMT performance was measured as accuracy where higher values reflect successful maintenance, and detection, of same or different face identities (Table 3). A paired samples t-test was performed for accuracy on correct handgrip trials to investigate face discrimination under physical exertion. To evaluate dual-task effects, only trials where participants' exerted grip force was at, or slightly above, the indicated level of MVC during the GFMT were included for analysis. 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 40% but not greater than 70% MVC in the 45% MVC condition for more than 2/3rd of the time allocated for the sequential GFMT face presentation and interstimulus interval.

In addition, RT analyses were performed for correct handgrip trials to evaluate dual-task effects on face discrimination under low and high physical exertion using a paired samples t-test.

3.3.2.4 Results

3.3.2.4.1 GFMT Performance Under Concurrent Physical Exertion. To investigate if physical exertion impaired face discrimination, rather than inhibitory control as observed in Experiment 1, we assessed accuracy for the GFMT performance on discrimination of face identity across physical exertion conditions (5% vs. 45% MVC). Consistent with our prediction, there was no significant difference for observers' ability to discriminate if the two face identities were the same or different across the high

(45% MVC; *M* = .81, *SD* = 0.10) and low (5% MVC; *M* = .82, *SD* = 0.11) physical exertion conditions, *t*(39) = - .67, *p* = .504, Cohen's *d* = .10, (Figure 4A).

3.3.2.4.2 Reaction Time Effects of Concurrent Physical Exertion. Next, we investigated RT across experimental conditions in successful handgrip maintenance trials, based on a paired samples t-test for face discrimination under across physical exertion (5% vs. 45% MVC). There was a significant difference for observers' ability to discriminate if the two face identities were the same or different across the high (45% MVC; *M* = 685.8 ms, *SD* = 182.7) and low (5% MVC; *M* = 709.9 ms, *SD* = 167.1 ms) physical exertion conditions, *t*(39) = 2.97, *p* = .005, Cohen's *d* = .14, (Figure 4B). That is, observers were faster to make a same or different judgment for the GFMT under high physical exertion than under low physical exertion.

3.4 General Discussion

The present study investigated the effects of effortful physical exertion on 1) CFE using the Le Grand face task (Experiment 1; Le Grand et al., 2004) and 2) overall face discrimination using the GFMT (Experiment 2; Burton et al., 2010). While the CFE is typically studied as a measure of holistic face processing (Young et al., 1987; Hole, 1994; Le Grand et al., 2004; Michel et al., 2016), recently it has been attributed to other complex cognitive processes, such as cognitive control ((Fitousi, 2020; Chen et al., 2022). In Experiment 1, CFE was operationalized as the difference in performance between the aligned and misaligned face conditions. Observers may exhibit greater reduction in inhibitory control in the aligned, compared to the misaligned, condition due to greater distracter interference and reduced ability to inhibit the task-irrelevant bottom face halves (Fitousi, 2020; Chen et al., 2022). Effortful physical exertion (45% versus 5% MVC), reduced observers' ability to accurately identify if the two sequentially presented task-relevant top face halves were of the same, or different, identity while ignoring the task-irrelevant bottom face halves. In other words, participants were less likely to inhibit distracting information (i.e., bottom face halves) when simultaneously engaging in an effortful physical task.

In Experiment 2, we aimed to test if physical exertion impaired inhibitory control or if face processing and thus face discrimination was impaired by concurrent physical exertion. As we predicted, overall face discrimination assessed using the GFMT was intact under physical exertion and recruitment of inhibitory control was minimal. These findings support our prediction that reduced inhibitory control, manifested as greater CFE accuracy (i.e., inability to inhibit the task-irreverent information), was observed under concurrent high physical exertion (45% MVC) and did not impair overall face discrimination.

These findings are consistent with some previous reports investigating the negative interaction between dual cognitive and motor tasks (Cappiello et al., 2018; Park et al., 2021; Azer et al., Under Revision). For instance, younger (Cappiello et al., 2018; Park et al., 2021) and older (Azer et al., Under Revision) adults were less likely to inhibit task-irrelevant information under effortful physical exertion. However, these effects were tested using simple lab generated stimuli whereas the present study is novel in that it aimed to assess this interaction using stimuli that we encounter daily (i.e., faces). The use of face stimuli may provide additional ecological validity to understanding the deleterious impacts of concurrent cognitive and motor actions on inhibitory control. Nonetheless, it is important to note that CFE in the present study was tested using the Le Grand face task as a measure of cognitive control (Fitousi, 2020; Chen et al., 2022) for stimuli that we possess expertise for in a natural scene rather than a measure of holistic processing (Young et al., 1987; Hole, 1994; Le Grand et al., 2004; Michel et al., 2016; Azer & Zhang, 2019). While face processing is unlike other complex cognitive processes and has its own unique specialized neural mechanism (FFA; Kanwisher & Yovel, 2006), using the CFE Chen et al. (2022) demonstrated that neural networks associated with cognitive control (Ridderinkhof et al., 2004; Brass et al., 2005; Craig, 2009; Menon & Uddin, 2010), in addition to the FFA, elicited stronger activation during the aligned condition than the misaligned condition. Therefore, Chen et al. (2022) concluded that the CFE may be an appropriate measure of cognitive control in addition to holistic face processing.

Although the results of the present study did not find a significant interaction between CFE RT and physical exertion in Experiment 1, there was a significant effect of face discrimination RT under effortful physical exertion in Experiment 2. That is, observers were faster to discriminate if two face identities were the same or different when simultaneously engaging in an effortful physical task. These results are consistent with some previous seminal reports suggesting that in both athletes and non-athletes simple and choice RT may be affected by physical exertion (Delignières et al., 1994; Delignières & Brisswalter, 1995; Mouelhi Guizani et al., 2006; Reddy et al., 2014). That is, under high physical exertion athletes and non-athletes exhibited faster RT during simple and/or choice RT tasks. This may be explained by an arousal-based effect (also see Park et al., 2021; Azer et al., Under Revision), where high physical exertion may yield increased arousal leading to an increase in norepinephrine (NE) released in the locus coeruleus (LC; Nielsen & Mather, 2015). In other words, the release of NE in the LC as a result of arousal due to physical exertion can modulate speeded response times.

The novel theoretical significance of our findings suggest that physical exertion can impair inhibitory control for items we possess significant expertise on given our repeated exposure (Jenkins et al., 2018). In addition, the finding that a simple, yet effortful, physical task impaired inhibitory control may be empirically important for understanding everyday functions. Daily functions to support one basic human need, such as the processes involved in buying groceries (i.e., pushing a shopping cart or carrying a grocery bag), require power grips that involve physical exertion (Ramadan et al., 2018) and cognitive control (i.e., ignoring surrounding visual and auditory distractors and focusing on your grocery list; inhibiting impulse buys; Burton et al., 2019). These processes are also accompanied by active or passive face processing. While the results of the present study did not find that overall face discrimination was impaired under concurrent physical exertion, inhibitory control for items we commonly view in natural scenes is impaired under concurrent physical exertion. It is important to note that the current findings can be generalized across individual differences in physical and grip strength given that physical exertion was operationalized as the proportion of individual MVC in the present study.

Future research should investigate the impact of effortful physical exertion on CFE as a measure of cognitive control in older adults. Recent reports suggest that older adults' accuracy was similar for the aligned and misaligned face conditions using the composite face task (Meinhardt et al., 2016). This may support the inhibitory deficit hypothesis (Hasher & Zacks, 1988) where older adults are more susceptible to task-irrelevant distractors. Therefore, Meindhardt et al. (2016)'s finding could indeed reflect that the composite face task measures cognitive control (Fitousi, 2020; Chen et al., 2022) where older adults have impaired cognitive control (Hasher & Zacks, 1988; Park & Reuter-Lorenz, 2009) and thus perform poorly on both alignment conditions due to the task-irrelevant face halves. Nonetheless, future research should include a sample of older adults to investigate CFE under physical exertion for stimuli in natural scenes in addition lab generated stimuli (Azer et al., Under Revision).

While the present study objectively manipulated low and high physical exertion, one caveat of the present study includes the lack of measure for perceived exertion. Perceived exertion is associated with increased arousal under physical load (Köteles et al., 2020) and is associated with an increase in pupil dilation (Zénon, et al., 2014), which is a proxy measure for LC-NE activity (Auston-Jones & Cohen, 2005; Liu et al., 2017). The results for the CFE RT in the present study could be possibly explained by perceived exertion. One speculation could be that although the 45% MVC condition was more physically effortful than 5% MVC, thus requiring higher physical exertion, the sample of participants in the present study may have not perceived the high physical exertion condition to be effortful. However, this may be unlikely given that CFE accuracy under high physical exertion suffered and participants ability to inhibit the task-irrelevant face halves was impaired replicating prior studies (Park et al., 2021; Azer et al., Under Revision). Nonetheless, future studies should measure perceived exertion in order to understand the mechanisms underlying subjective and objective effortfulness on cognitive control.

3.4.1 Conclusion

Using a novel paradigm, the present study demonstrated that concurrent effortful physical exertion impaired cognitive control but not overall face discrimination. These impairments have been previously observed in younger (Park et al., 2021) and older (Azer et al., Under Revision) adults using lab generated stimuli. The novelty of the present study includes the use of using stimuli that we encounter daily (i.e., faces), which may provide ecological validity to understanding the negative interaction between concurrent cognitive and motor actions on inhibitory control. Therefore, given that motor and cognitive actions seldom occur in isolation in daily life, enhancing this understanding is pivotal.

References

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28,* 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Azer, L., Xie, W., Park, H.-B., & Zhang, W. (2023). Detrimental effects of effortful physical exertion on a working memory dual-task in older adults. *Psychology and Aging.* Advance online publication. https://doi.org/10.1037/pag0000746

Azer, L., & Zhang, W. (2019). Composite face effect predicts configural encoding in visual short-term memory. *Frontiers in Psychology*, *10*. https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02753

Brass, M., Ullsperger, M., Knoesche, T. R., von Cramon, D. Y., & Phillips, N. A. (2005). Who comes first? The role of the prefrontal and parietal cortex in cognitive control. *Journal of Cognitive Neuroscience*, *17*(9), 1367–1375. https://doi.org/10.1162/0898929054985400

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: A study of 55,753 participants aged 8–75. *Frontiers in Psychology*, *4*, 12. https://doi.org/10.3389/fpsyg.2013.00012

Bruce, V., Henderson, Z., Greenwood, K., Hancock, P. J. B., Burton, A. M., & Miller, P. (1999). Verification of face identities from images captured on video. *Journal of Experimental Psychology: Applied*, *5*, 339–360. https://doi.org/10.1037/1076-898X.5.4.339

Bud Craig, & D, A. (2009). How do you feel — now? The anterior insula and human awareness. *Nature Reviews Neuroscience*, *10*(1), Article 1. https://doi.org/10.1038/nrn2555

Burton, J. L., Gollins, J., McNeely, L. E., & Walls, D. M. (2019). Revisiting the relationship between ad frequency and purchase intentions: how affect and cognition mediate outcomes at different levels of advertising frequency. *Journal of Advertising Research*, *59*(1), 27–39. https://doi.org/10.2501/JAR-2018-031

Burton, A. M., White, D., & McNeill, A. (2010). The Glasgow Face Matching Test. *Behavior Research Methods*, *42*(1), 286–291. https://doi.org/10.3758/BRM.42.1.286

Cappiello, M., Xie, W., & Zhang, W. (2018). The mental muscle: Effects of concurrent effortful physical action on visual working memory. *Journal of Vision, 18*(10), 705. https://doi.org/10.1167/18.10.705

Chen, C., Lou, Y., Li, H., Yuan, J., Yang, J., Winskel, H., & Qin, S. (2022). Distinct neural-behavioral correspondence within face processing and attention networks for the composite face effect. *NeuroImage*, *246*, 118756. https://doi.org/10.1016/j.neuroimage.2021.118756

Delignieres, D., & Brisswalter, J. (1995). Effects of heat stress and physical exertion on simple and choice reaction time. In *European Congress on Sport Psychology: Vol. n/a* (Issue n/a, p. n/a). https://doi.org/10.1037/e672622012-022

Delignières, D., Brisswalter, J., & Legros, P. (1994). Influence of physical exercise on choice reaction time in sports experts: the mediating role of resource allocation. *Journal of Human Movement Studies*, *27*, 173–188.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135 168. https://doi.org/10.1146/annurev-psych-113011-143750

Erickson, K. I., Hillman, C. H., & Kramer, A. F. (2015). Physical activity, brain, and cognition. *Current Opinion in Behavioral Sciences*, *4*, 27–32. https://doi.org/10.1016/j.cobeha.2015.01.005

Fitousi, D. (2020). Decomposing the composite face effect: Evidence for non-holistic processing based on the ex-Gaussian distribution. *Quarterly Journal of Experimental Psychology (2006)*, *73*(6), 819–840. https://doi.org/10.1177/1747021820904222

Grand, R. L., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science*, *15*(11), 762–768. https://doi.org/10.1111/j.0956-7976.2004.00753.x

Hole, G. J. (1994). Configurational factors in the perception of unfamiliar faces. *Perception*, *23*(1), 65–74. https://doi.org/10.1068/p230065

Jenkins, R., Dowsett, A. J., & Burton, A. M. (2018). How many faces do people know? *Proceedings. Biological Sciences*, *285*(1888), 20181319. https://doi.org/10.1098/rspb.2018.1319

Kanwisher, N., & Yovel, G. (2006). The fusiform face area: A cortical region specialized for the perception of faces. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *361*(1476), 2109–2128. https://doi.org/10.1098/rstb.2006.1934

Konar, Y., Bennett, P. J., & Sekuler, A. B. (2010). Holistic Processing Is Not Correlated With Face-Identification Accuracy. *Psychological Science*, *21*(1), 38–43. https://doi.org/10.1177/0956797609356508

Köteles, F., Teufel, B., Körmendi, J., Ferentzi, E., & Szemerszky, R. (2020). Cardioceptive accuracy is associated with arousal but not with valence and perceived exertion under physical load. *Psychophysiology*, *57*(9), e13620. https://doi.org/10.1111/psyp.13620

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2004). Impairment in holistic face processing following early visual deprivation. *Psychological Science*, *15*(11), 762–768. https://doi.org/10.1111/j.0956-7976.2004.00753.x

Liu, J., Harris, A., & Kanwisher, N. (2010). Perception of face parts and face configurations: an fMRI study. *Journal of Cognitive Neuroscience*, *22*(1), 203–211. https://doi.org/10.1162/jocn.2009.21203

Liu, Y., Rodenkirch, C., Moskowitz, N., Schriver, B., & Wang, Q. (2017). Dynamic Lateralization of Pupil Dilation Evoked by Locus Coeruleus Activation Results from Sympathetic, Not Parasympathetic, Contributions. Cell Reports, 20(13), 3099–3112. https://doi.org/10.1016/j.celrep.2017.08.094

Maurer, D., Grand, R. L., & Mondloch, C. J. (2002). The many faces of configural processing. *Trends in Cognitive Sciences*, *6*(6), 255–260. https://doi.org/10.1016/S1364-6613(02)01903-4

Meinhardt, G., Persike, M., & Meinhardt-Injac, B. (2016). The Composite Effect Is Face-Specific in Young but Not Older Adults. *Frontiers in Aging Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnagi.2016.00187

Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: A network model of insula function. *Brain Structure and Function*, *214*(5), 655–667. https://doi.org/10.1007/s00429-010-0262-0

Michel, C., Rossion, B., Han, J., Chung, C.-S., & Caldara, R. (2006). Holistic processing is finely tuned for faces of one's own race. *Psychological Science*, *17*(7), 608–615. https://doi.org/10.1111/j.1467-9280.2006.01752.x

Mouelhi Guizani, S., Bouzaouach, I., Tenenbaum, G., Ben Kheder, A., Feki, Y., & Bouaziz, M. (2006). Simple and choice reaction times under varying levels of physical load in high skilled fencers. *The Journal of Sports Medicine and Physical Fitness*, *46*(2), 344–351.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*, 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Park, H.-B., Ahn, S., & Zhang, W. (2021). Visual search under physical effort is faster but more vulnerable to distractor interference. *Cognitive Research: Principles and Implications*, *6*(1), 17. https://doi.org/10.1186/s41235-021-00283-4

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise*, *40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Praetorius Björk, M., Johansson, B., & Hassing, L. B. (2016). I forgot when I lost my grip-strong
associations between cognition and grip strength in level of performance and change across time in relation to impending death. *Neurobiology of Aging*, *38*, 68–72. https://doi.org/10.1016/j.neurobiolaging.2015.11.010

Ramadan, M. Z., Khalaf, T. M., Ragab, A. M., & AbdElgawad, A. A. (2018). Influence of shopping bags carrying on human responses while walking. *Journal of Healthcare Engineering*, *2018*, 5340592. https://doi.org/10.1155/2018/5340592

Reddy, S., Eckner, J. T., & Kutcher, J. S. (2014). Effect of acute exercise on clinically measured reaction time in collegiate athletes. *Medicine and Science in Sports and Exercise*, *46*(3), 429–434. https://doi.org/10.1249/MSS.0000000000000140

Richler, J. J., Bukach, C. M., & Gauthier, I. (2009). Context influences holistic processing of non-face objects in the composite task. *Attention, Perception & Psychophysics*, *71*(3), 530–540. https://doi.org/10.3758/APP.71.3.530

Richler, J. J., Cheung, O. S., & Gauthier, I. (2011). Holistic processing predicts face recognition. *Psychological Science*, *22*(4), 464–471. https://doi.org/10.1177/0956797611401753

Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science (New York, N.Y.)*, *306*(5695), 443–447. https://doi.org/10.1126/science.1100301

Schmiedek, F., Oberauer, K., Wilhelm, O., Süss, H.-M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology. General*, *136*(3), 414–429. https://doi.org/10.1037/0096-3445.136.3.414

Schmitz, F., & Wilhelm, O. (2016). modeling mental speed: decomposing response time distributions in elementary cognitive tasks and correlations with working memory capacity and fluid intelligence. *Journal of Intelligence*, *4*(4), Article 4. https://doi.org/10.3390/jintelligence4040013

Spieler, D. H., Balota, D. A., & Faust, M. E. (2000). Levels of selective attention revealed through analyses of response time distributions. *Journal of Experimental Psychology. Human Perception and Performance*, *26*(2), 506–526. https://doi.org/10.1037//0096-1523.26.2.506

Steinhauser, M., & Hübner, R. (2009). Distinguishing response conflict and task conflict in the Stroop task: Evidence from ex-Gaussian distribution analysis. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(5), 1398–1412. https://doi.org/10.1037/a0016467

Xie, W., & Zhang, W. (2017). Discrete item-based and continuous configural representations in visual short-term memory. *Visual Cognition*, *25*(1–3), 21–33. https://doi.org/10.1080/13506285.2017.1339157

Young, A. W., Hellawell, D., & Hay, D. C. (1987). Configurational information in face perception. *Perception*, *16*(6), 747–759. https://doi.org/10.1068/p160747

Zénon, A., Sidibé, M., & Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00286

Tables

Table 3.

Sample Demographics for Experiment 1 and 2

Characteristics	Experiment 1 Mean (*SD*)/%	Experiment 2 Mean (*SD*)/%
Age (years)	19.78 (2.49)	19.06 (1.39)
Gender		
Female	60.00%	47.50%
Male	37.50%	45.00%
Prefer not to respond	2.50%	7.50%
MVC		
Female	119.25 (38.67)	103.11 (44.42)
Male	122.53 (44.63)	139.00 (56.82)
Race/Ethnicity		
White	17.50%	22.50%
Black or African American	0%	7.50%
Hispanic or Latino	15.00%	25.55%
Native Hawaiian / Other Pacific Islander	0%	0%
Asian	55.00%	30.0%
American Indian/ Alaskan Native	2.50%	2.50%
More than one race	2.50%	2.50%
Prefer not to respond	0%	10.00%

Table 4.

Le Grand face task CFE accuracy, and RT across conditions

	Aligned		Misaligned	
	Accuracy	RT (ms)	Accuracy	RT (ms)
Physical Exertion	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
5% MVC	0.83 (0.09)	784.00 (167.56)	0.85 (0.10)	715.00 (157.04)
45% MVC	0.79 (0.10)	775.70 (198.12)	0.87 (0.10)	689.50 (134.96)

Table 5.

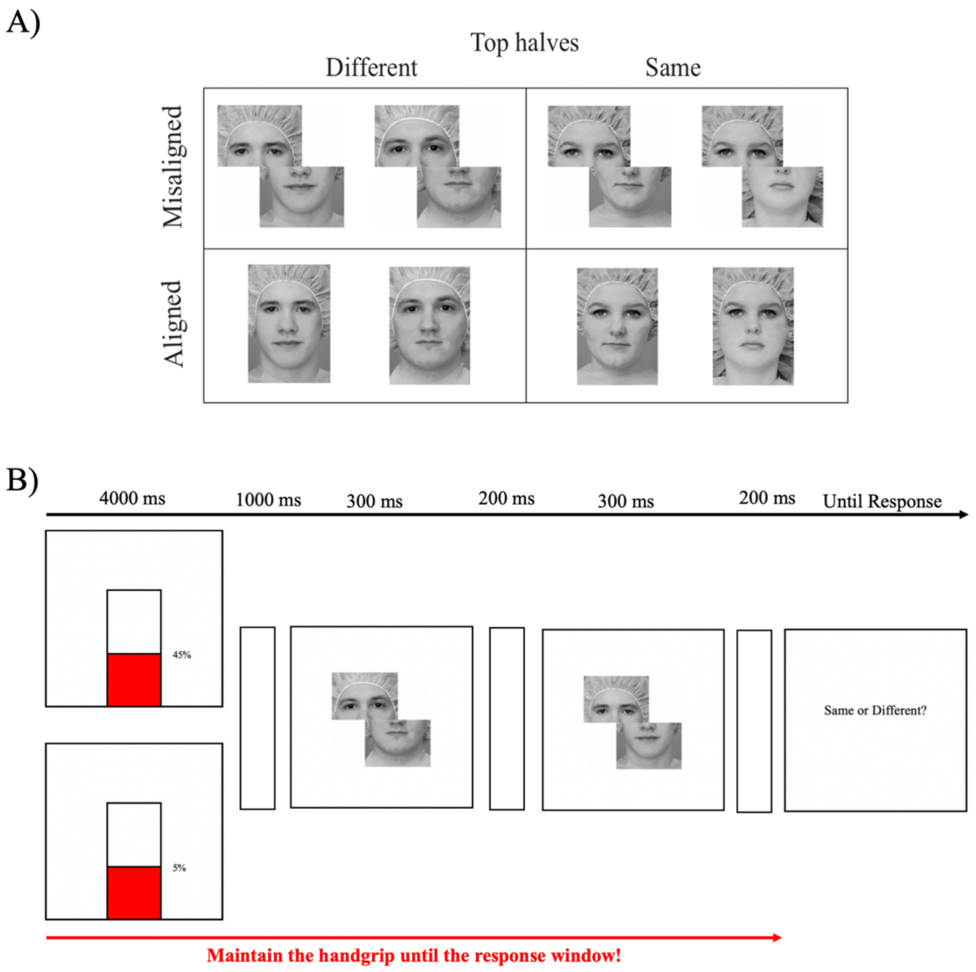
GFMT accuracy and RT across conditions

Physical Exertion	Accuracy (*SD*)	RT (ms)
5% MVC	0.81 (0.10)	709.9 (167.1)
45% MVC	0.82 (0.11)	685.8 (182.7)

Figures

Figure 6.

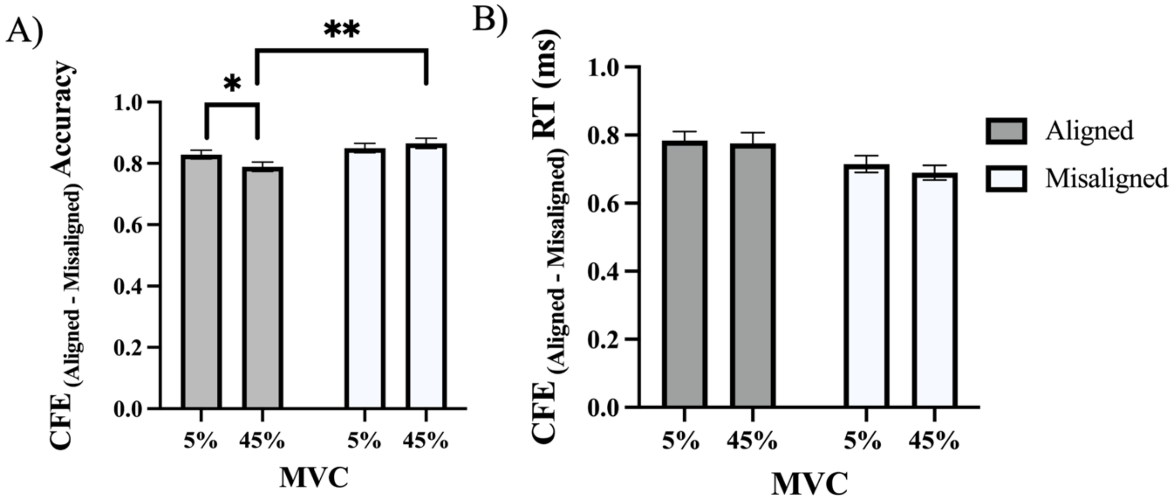
Stimuli and procedure for the concurrent physical exertion and Le Grand Face Task



Note. Each trial began with a 4,000 ms screen prompting participants to grip the Hand Dynamometer at the indicated level (5% or 45% MVC) followed by the two sequentially presented composite faces (shown above). Participants were instructed to release their grip when the response display appeared and make a same or different response for the top face halves while ignoring the task-irrelevant bottom face halves.

Figure 7.

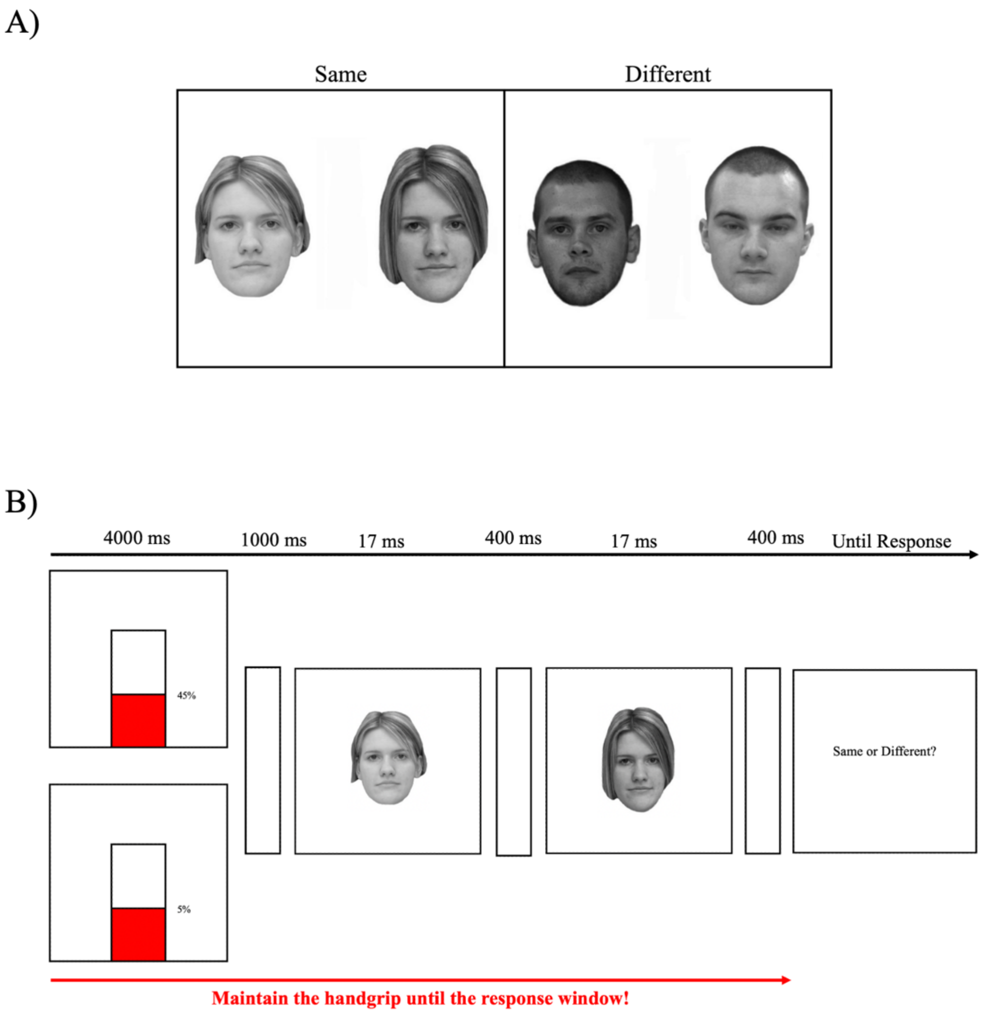
Two-way interaction with face alignment (aligned vs. misaligned), and physical effort (5% vs. 45% MVC) for CFE accuracy and RT



Note. CFE for the aligned minus misaligned conditions from trials with successful handgrip trials. (A) CFE accuracy results for the Le Grand Face Task across the face alignment and physical exertion conditions. (B) CFE RT (ms) results for the Le Grand Face Task across the face alignment and physical exertion conditions.

Figure 8.

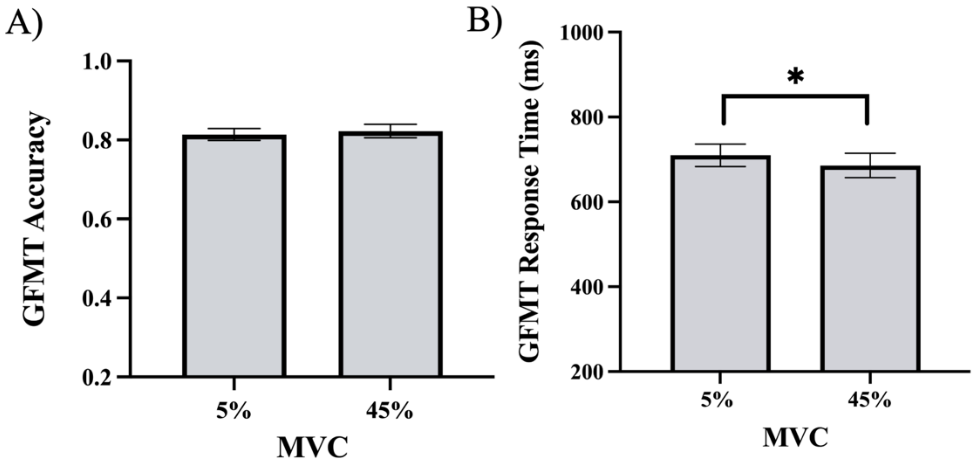
Stimuli and procedure for the concurrent physical exertion and GFMT



Note. Each trial began with a 4,000 ms screen prompting participants to grip the Hand Dynamometer at the indicated level (5% or 45% MVC) followed by the two sequentially presented faces (shown above). Participants were instructed to release their grip when the response display appeared and make a same or different identity response for the two faces.

Figure 9.

GFMT accuracy and RT



Note. (A) Accuracy results for the GFMT across the physical exertion conditions. (B) RT results for the GFMT across the physical exertion conditions.

Chapter 4. Effects of Physical and Cognitive Effort on Arousal

4.1 Chapter Abstract

Physical and cognitive effort often interact with each other and even exhibit similar behavioral and neural effects. For instance, pupillary response, such as pupil dilation, typically increases with cognitive or physical effort, indicating increased arousal and LC-NE activity. It is still unclear whether the effects of physical and cognitive effort on pupil size, a proxy measure of the LC-NE activity, are independent of one another or interactive with each other. To address this question the present study examined the impact of engaging in a concurrent effortful physical and cognitive task on task evoked pupil responses (TEPRs). Physical effort was manipulated by having participants grip a hand dynamometer at low versus high force (e.g., 5% vs. 45%) of individual strength. Cognitive effort was operationalized as Working Memory load in a Change Detection task where the participants attempted to remember 1 or 3 briefly presented orientation bars and then report, after a short retention interval, whether a randomly chosen memory item changed orientation or not. Effortful physical exertion impaired task performance under the concurrent high physical effort and high cognitive effort condition. In addition, high physical effort induced greater pupil dilation replicating prior studies. However, cognitive load and the interaction between physical effort and cognitive load did not significantly induce greater TERPs suggesting that arousal induced by physical and cognitive effort may be independent of one another.

4.2 Introduction

Our daily activities may frequently require performing tasks (e.g., grocery shopping) that involve both cognitive and motor actions. These tasks may involve maintaining a few, or many, items in memory (e.g., remembering to purchase one bundled item with all the necessary ingredients – low cognitive load vs. remembering to purchase each ingredient separately – high cognitive load) while simultaneously exerting low, or high, levels of physical exertion (e.g., pushing a shopping cart with one light object vs. pushing a shopping cart with many heavy objects). When cognitive and physical tasks are deemed effortful, they can impact pupil size in a similar manner, such that greater cognitive effort (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022) and greater physical effort (Ishigaki et al., 1991; Hayashi et al., 2010; Hayashi & Someya, 2011; Kuwamizu et al., 2022; Zénon et al., 2014) can both induce greater pupillary response. While cognitive and motor tasks seldom occur in complete isolation, the impact of cognitive load and physical exertion on task evoked pupillary responses (TEPRs) are often studied independent of one another. Therefore, the present study aims to 1) assess the relationship between cognitive load and physical exertion, and 2) examine the impact of engaging in a concurrent effortful physical and cognitive task on TEPRs.

4.2.1 Pupillary Response Studied in Single-Task Conditions

Physical exertion is defined as the act of engaging in activities that exert muscles in various ways, including exercise, initiating motion, or generating force. This may include dynamic (i.e., physical activity that requires movement of the joint) or static (i.e., physical activity that does not require movement of the joint) activity. Physical exertion may stimulate sympathetic nervous system activity while decreasing parasympathetic nervous system activity (Hautala et al., 2009; Patel & Zwibel, 2022). Pupil dilation is controlled by and occurs as a result of sympathetic nervous system activation (McDougal & Gamlin, 2015; Mathôt, 2018). Engaging in tasks where physical exertion is required, is therefore assumed to increase pupil dilation as a result of activation of the sympathetic nervous system (Ishigaki et al., 1991; Hayashi et al., 2010; Hayashi & Someya, 2011; Kuwamizu et al., 2022; Zénon et al., 2014). In fact, engaging in prolonged maximal effort (Ishigaki et al., 1991; Hayashi et al., 2010) and light (Kuwamizu et al., 2022) graded dynamic exercise loads induces greater pupil dilation when compared to resting baseline. In addition, static physical exertion using isometric handgrip can also lead to an increase in pupil dilation (Hayashi & Someya, 2011; Nielsen & Mather, 2015; Zénon et al., 2014). While exertion is defined as engaging in a physical activity, it can also be defined as the perceived use of energy that is deemed effortful (Robertson & Bruce, 1997). The magnitude of pupil dilation during actual physical exertion increases systematically with greater exertion and with perceived effort for physical exertion (Zénon et al., 2014).

In addition to the impact of physical exertion on pupillary response studied in isolation, cognitive load (i.e., the amount of information in working memory at a given time; Sweller, 1988) and its impact on pupillary response has been typically studied independent of physical action. For instance, many studies demonstrated that under greater cognitive load participants experienced larger TEPRs (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022). Specifically, during working memory tasks (WM is defined as active maintenance of information online in the service of ongoing mental activities, Cowan, 2001), greater WM loads elicited increased pupillary response (Kahneman & Beatty, 1966; Zhou et al., 2022). This effect was also observed across other experimental paradigms where cognitive load was manipulated using mental arithmetic calculations (Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018), object motion tracking (Alnaes et al., 2014; Wahn et al., 2021), and ambiguous, compared to prototypical, items stored in WM (Zhou et al., 2022).

Cognitive load is often assumed to be related to, and many times used interchangeably with, mental effort (Kirschner & Kirschner, 2012; Kirchner, 2002; Sweller, 1988). That is, greater cognitive load is assumed to be synonymous to greater mental effort. Pupillary size studied as an index of mental effort across multiple domains has found that pupils dilate as a function of cognitive load and task difficulty (Alnaes et al., 2014; Ahern & Beatty, 1979; Beatty & Kahneman, 1966; Bradshaw, 1968; Hess & Polt, 1964; Kahneman & Beatty, 1967; Krejtz et al., 2018; Wahn et al., 2021; Zhou et al., 2022). In fact, many studies have attributed greater pupillary response in relation to increasing cognitive load to greater mental effort during cognitive tasks (Alnaes et al., 2014; Wahn et al., 2021; Zhou et al., 2022).

Studied in isolation, effort (i.e., the cost associated with information-processing resources to fulfill an operation; Kool & Botvinick, 2018) across physical (Asfoura et al., 1983; Zénon et al., 2014) and cognitive (Alnaes et al., 2014; Ahern & Beatty, 1979; Beatty & Kahneman, 1966; Bradshaw, 1968; Hess & Polt, 1964; Kahneman & Beatty, 1967; Krejtz et al., 2018; Wahn et al., 2021; Zhou et al., 2022) domains can be indexed by task loads and induces greater TEPRs. However, the question remains whether the effects of physical and cognitive effort on pupillary response are independent of one another or interact with each other sharing common neurocognitive mechanisms.

4.2.2 Interaction Between Physical and Cognitive Effort

Recently, the interactive effect of concurrent physical exertion on WM performance was investigated (Xie & Zhang, 2023). Across three experiments combining computational and experimental procedures, Xie and Zhang (2023) found that when observers were given the choice, they preferred to exert physical effort rather than mental effort when the WM load was high. In addition, a linear pattern between perceived effort for physical and WM loads was observed when engaging in a concurrent physical and WM task. The number of items remembered in WM during successful grip exertion (i.e., maintaining the grip force around the indicated level) increased as a function of WM load (i.e., set size; Xie & Zhang, 2023). More importantly, Xie and Zhang (2023) found an interaction between WM load and exerted physical load. Under concurrent high physical exertion and WM set size 6 there was a significant reduction in the number of items retained in WM. These results were attributed to the negative impact of physical exertion on information control in working memory during larger set sizes (Xie & Zhang, 2023). Specifically, larger WM loads may compete for access to WM and disrupt the retention of previously encoded items (Fukuda et al., 2015; Konstantinou et al., 2014; Oberauer & Lin, 2017). Therefore, these results suggest that there may be shared mental representations of effortfulness across cognitive and motor tasks (Xie & Zhang, 2023).

Essentially, physical exertion may compete for shared resources that are required when WM load is high (Xie & Zhang, 2023). This is inconsistent from recent accounts, which suggest that cognitive and motor actions have separate resource pools and engagement in one domain may not have a direct impact on engagement in the other domain (Feghhi & Rosenbaum, 2019). Nonetheless, Xie and Zhang (2023) suggest the interactive effect between effort for WM and physical exertion loads may occur at the expense of control related processes. That is, when the task demand on cognitive control is high, concurrent physical exertion may negatively impact WM performance, but only at larger WM loads. In fact, recent evidence suggests that concurrent physical exertion may be detrimental to cognitive control processes for task performance in visual WM and visual search tasks when distractors are present (Azer et al., 2023; Park et al., 2021).

4.2.3 Pupillary Response as a Measure of Arousal

While Xie and Zhang (2023) demonstrated the behavioral interactive effect of effort on physical and cognitive load, to the best of our knowledge this effect is yet to be investigated on pupillary response during a dual physical exertion and cognitive load task. Studies assessing the impact of physical and cognitive effort on pupillary response independently (Alnaes et al., 2014; Ahern & Beatty, 1979; Asfoura et al., 1983; Beatty & Kahneman, 1966; Bradshaw, 1968; Hess & Polt, 1964; Kahneman & Beatty, 1967; Krejtz et al., 2018; Wahn et al., 2021; Zénon et al., 2014; Zhou et al., 2022) provide important information about the impact of effort on arousal using pupillary response as a proxy measure of Locus Coeruleus (LC) activity (Liu et al., 2017). For example, pupil dilation occurs when the sympathetic nervous system is active (McDougal & Gamlin, 2015;

Mathôt, 2018), which releases Norepinephrine (NE; Glowinski & Baldessarini, 1966) from the LC (Florin-Lechner et al., 1996) during tasks that involve greater physical or cognitive effort (Bornert & Bouret, 2021). LC activity and accompanying pupil dilation may reflect changes in arousal during complex cognitive functions (Andreassi, 2000; Joshi et al., 2016).

During high physical exertion, heightened arousal may be experienced leading to the release of NE from the LC (Nielsen & Mather, 2015). The LC-NE system is modulated by control processes (Aston-Jones & Cohen, 2005) and its effect on cognitive performance may be manifested during tasks that involve working memory and executive control (Mather & Harley, 2016; Mather et al., 2016). It could be that shared mental representations of effortfulness during concurrent cognitive and motor tasks and its interactive effect (Xie & Zhang, 2023) result in greater arousal (Andreassi, 2000; Joshi et al., 2016; Nielsen & Mather, 2015; Mather & Harley, 2016; Mather et al., 2016) at the expense of control processes (Azer et al., 2023; Park et al., 2021). If conditions where cognitive and physical effort are high result in greater arousal (i.e., pupil dilation and LC-NE system activation; Andreassi, 2000; Joshi et al., 2016) and the interactive effect of concurrent physical exertion and task load could disrupt WM performance during greater physical exertion and larger set sizes (Xie & Zhang, 2023), it could be assumed that an interactive effect can also be observed on the shared neurocognitive mechanism during the dual-task. However, there is a lack of evidence thus far to support this prediction.

When studied in single-task conditions, it may appear that cognitive and physical effort both share common neurocognitive mechanisms as indexed by greater pupil dilation (Alnaes et al., 2014; Ahern & Beatty, 1979; Asfoura et al., 1983; Beatty & Kahneman, 1966; Bradshaw, 1968; Hess & Polt, 1964; Kahneman & Beatty, 1967; Krejtz et al., 2018; Wahn et al., 2021; Zénon et al., 2014; Zhou et al., 2022), and therefore arousal may assume LC activity (Joshi et al., 2016; Nielsen & Mather, 2015). However, an in-depth evaluation on the impact of concurrent physical exertion and cognitive effort on TERPs is yet to be explored to better understand the interactive effect.

4.2.4 The Present Study

To investigate the relationship between cognitive load and physical exertion, along with the interactive effect of the dual task on TEPRs, we examined TERPs during a simultaneous visual WM task with high versus low cognitive load (memory set size 1 vs. 3) and high versus low physical exertion load. Physical exertion load was manipulated using an isometric hand dynamometer, which is an apparatus that measures maximum voluntary contraction (MVC), and participants were asked to grip the device at certain percentages of their MVC (5% versus 45%). Isometric handgrip muscle contraction involves activation of the hand muscles to produce a power grip (Cain & Stevens, 1971), which tends to require less cognitive control (Ehrsson et al., 2000; Guillery et al., 2013, 2017; Kobayashi-Cuya et al., 2018) than the use of a precision grip (i.e., gripping an item using the thumb and one finger to transmit force).

In the present study, participants were instructed to remember one (low cognitive load) or three (high cognitive load) briefly presented red orientation bars during the WM change detection task. Participants simultaneously exerted force on the hand dynamometer at 5% (low physical exertion) or 45% (high physical exertion) MVC, independent of individual differences in muscle strength. Given that high physical exertion (Ishigaki et al., 1991; Hayashi et al., 2010; Hayashi & Someya, 2011; Kuwamizu et al., 2022; Zénon et al., 2014) and greater cognitive loads (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022) induce TEPRs, we hypothesize greater pupillary responses will occur under 1) high physical exertion (45% MVC) and 2) greater WM loads (set size 3). Accordingly, we predict that the interactive effect between physical exertion and WM load (Xie & Zhang, 2023) will be observed on TEPRs. That is, we expect to see a significant 2-way interaction between physical exertion and WM load on pupil dilation where pupil size will be larger under the high physical effort and high WM load condition.

The present study offers a novel theoretical and empirical contribution to existing evidence on pupillary response as a proxy measure LC-NE activity (Liu et al., 2017; Joshi et al., 2016) during concurrent physical and cognitive actions. For instance, according to the Yerkes-Dodson inverted U hypothesis (Yerkes & Dodson, 1908), task-induced arousal can be both beneficial and harmful to performance depending on the level of arousal. Task induced arousal in the present study will be directly measured via pupillometry response for instances of 1) low cognitive load-low physical exertion, 2) low cognitive load-high physical exertion, 3) high cognitive load-low physical exertion, and 4) high cognitive load-high physical exertion. The relationship between physical and cognitive effort, along with the interaction between WM load and exerted physical load, suggests that there may be shared neurocognitive mechanisms for both domains (Xie &

Zhang, 2023). Therefore, the present study will directly investigate the interaction between physical and cognitive effort on pupillary response. In testing this prediction, we assessed WM task performance using accuracy and reaction time (RT; see Data Analysis).

4.3 General Method

4.3.1 Participants

An *a priori* power analysis for repeated-measures within factors analysis of variances (ANOVA) suggests that a total sample size of 28 participants (4 repeated-measured conditions) would provide 80% statistic power for a significant mixed-effect interaction at a medium level (F = 0.25, Faul et al., 2009). The present study recruited 32 undergraduate students (39.40% Female, 57.60% Male, 3.00% Prefer not to respond; M_{age} = 19.29, SD_{age} = 1.56; 33.30% Asian, 6.10% Black/African American, 18.20% Hispanic, 12.10% White/Non-Hispanic, 12.10% More than one race, 15.20% Prefer not to respond) from University of California, Riverside. Inclusion criteria required that all participants reported normal or corrected-to-normal vision, normal color vision and over the age of 18-years-old. Sample characteristics are shown in Table 1.

Additional data from 6 undergraduate students were excluded from the study due to unsuccessful handgrip recordings resulting from hand dynamometer misuse and misunderstanding of the dual-task instructions, and/or eye calibration difficulty. These participants were unable to complete the experiment as instructed, and therefore considered ineligible for the study. Experimental procedure was approved by the

Institutional Review Board at University of California, Riverside. All participants were provided and completed written informed consent. Participants were compensated with course credit for their participation.

4.3.2 Apparatus

The study took place in a moderately lit (approximately 75% brightness) windowless room with 500 lx background luminance. A video-based eye tracker (EyeLink 1000; SR Research Ltd., Ontario, Canada) recorded participants' eye-movements and pupil size at a sampling rate of 500 Hz using a stationary Desktop Mount. EyeLink 1000 uses a video camera to measure the infrared illuminator reflection on the cornea to assess gaze position. The Eyelink 1000 video camera is sensitive to light in the infrared spectrum. The size of the pupil is measured in arbitrary unit (AU), which is linearly associated with the pupil diameter. The visual WM Stimuli were presented on an LCD monitor with a grey background (42 cd/m^2), using PsychToolbox-3 (Brainard, 1997) for Matlab (The Math Works, Cambridge, MA) at a fixed viewing distance of 80 cm, which was determined by the distance of the computer monitor and a head-stabilized chin rest. The monitor was calibrated with an X-Rite I1Pro spectrophotometer (X-Rite, Inc., Grand Rapids, MI).

Handgrip force was measured using an isometric Vernier HD-BTA hand dynamometer (Vernier, Beaverton, OR) at the beginning of the experiment. The hand dynamometer measures maximum isometric handgrip strength, which involves static contraction of the hand muscles and restricted joint movements. Each participant completed a brief assessment to obtain isometric maximum voluntary contraction (MVC) of grip force using their left hand. During the concurrent handgrip and visual WM task, participants gripped the isometric Vernier HD-BTA hand dynamometer at different levels of their MVC. This is to ensure that physical exertion is standardized across participants and is independent of individual differences in muscular strength and fitness level.

Following MVC measurement, the eye tracker was calibrated using a default 9-point calibration scheme preset by EyeLink 1000. Participants fixated on a central target to capture the location of the pupil and were asked to fixate on a series of nine fixation target as they moved to varying locations on the screen by making eye movements and restricted head movements. Gaze locations were recorded. The calibration measure was validated against a second set of nine fixation targets. If the validation indicated a drift correction error of more than 1° of visual angle, the calibration and validation process was repeated until the calibration was satisfactory. This process conducted at the beginning of the dual-task experiment, when participants changed their position after a break, and/or when the eye-tracking quality reduced during the experiment.

4.3.3 Procedure

4.3.3.1 MVC Measurement

MVC was measured at the beginning of the experiment. Participants were instructed to grip the hand dynamometer in their left hand and squeeze it exerting maximum force for 4,000 ms. This procedure was repeated for three consecutive trials with no visual feedback. The median grip force level during the last 2,000 ms of the 4,000 ms measurement window in each trial was averaged across the three trials as the MVC of each participant. Participants' initial MVC measurement was not directly used in this study. Instead, participants were asked to grip the hand dynamometer at different levels (5% vs. 45%) of their initial MVC measurement. Therefore, physical exertion was standardized and was independent of differences in muscle strength and fitness level across participants.

Participants practiced maintaining their grip on the hand dynamometer at 5% and 45% of their MVC for 4,000 ms with real-time visual feedback indicated by a red visual gauge that fluctuated with respect to the exerted force for 10 practice trials (Figure 1). Each trail began with a centrally located visual prompt for 500 ms stating, "*Please get ready! Please hold the handgrip at the required level AFTER you hear a beep*." After the beep, a centrally displayed visual gauge, 4^{o} by 6^{o} in visual angle, providing real-time feedback of the exerted grip force showed a red bar with dynamically changing height that was proportional to the exerted grip (for an example, see first screen in Figure 1). Inside the visual gauge, a black horizontal line was marked relative to the required exertion level for the given trial. Participants were required to grip the hand dynamometer at, or slightly above, the black horizontal line. Successful maintenance of the grip force at the indicated level of each participant's MVC (5% or 45%) was followed by an auditory "Cha-Ching" sound and visual feedback stating, "*You have successfully maintained the force*!" Unsuccessful maintenance of the grip force at the indicated level was followed by an auditory "Beep" sound and visual feedback stating, "*Not quite. Please try harder!"* If participants were unable to maintain their grip at the indicated level of their MVC for more than half the practice trials they were given another set of 10 practice trials.

4.3.3.2 Concurrent Handgrip and Visual WM Dual Task

Following the practice of the handgrip task in isolation, participants completed the concurrent handgrip and visual WM dual-task (Figure 1). Each trial began with a centrally located, "*Get Ready*" prompt for participants to exert force with their left-handed on the hand dynamometer at or slightly above 5% or 45% of their MVC. The %MVC required for a given trial was mixed within the experimental blocks across the entire experiment. The 5% and the 45% MVC conditions were equally likely to occur across the experimental session. Real-time visual feedback of the exerted grip was provided for the first 4,00 ms allowing participants to adjust their grip above the black horizontal line corresponding with the %MVC condition. No visual feedback of force exertion was provided after the initial 4,000 ms. Participants were instructed to maintain the level of the exerted force throughout the visual WM change detection task until the test display appeared. During the test display, they were instructed to release the hand dynamometer and make a same or different judgment using the gamepad in their right hand. 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 40% but not greater than 70% MVC in the 45% MVC condition for more than 2/3rd of the time during the visual WM change detection task to be considered a correct handgrip trial. Kinesthetic information (Ángyán et al., 2005), such as gripping a hand dynamometer at different level without visual feedback, is sufficient for subjective estimation of the exerted force and requires minimal WM load (Lowe, 2016). In fact, participants were able to successfully maintain the exerted force on the hand dynamometer at or slightly above the required level for 87.32% of the overall handgrip trials despite no real-time visual feedback. As anticipated, overall handgrip accuracy for the 5% MVC condition (98.59% handgrip accuracy) was significantly higher than the overall handgrip accuracy for the 45% MVC condition (76.07% handgrip accuracy), $t(31) = 6.74$, $p < .001$. There was no significant difference for handgrip accuracy for the 5% MVC ($t(31) = 1.35$, $p = .093$) or the 45% MVC ($t(31) = 1.18$, $p = .123$) conditions across the two different visual WM loads (set size 1 vs. set size 3). The subsequent analysis for the handgrip and visual WM dual-task will focus on the trials when participants successfully exerted their grip force at the required level during the WM task.

While participants maintained their handgrip force at, or slightly above, 5% or 45% of their MVC, they simultaneously performed the visual WM task. In this task, a memory array consisting of 1 or 3 red rectangular orientations bars, which were equally likely across the experimental session, appeared for 100 ms. The rectangular bars (5^{o}-by-1^{o} of visual angle in size) were randomly oriented in a vertical, horizontal, or diagonal manner, and were presented at randomly selected centers within a 3-by-3 grid of an 11^{o}-by-11^{o} area in visual angles. Participants were required to remember the orientation of all the bars presented on a given trial. Following the memory array, a 900 ms delay interval with a blank screen containing a central fixation point appeared. Participants were instructed to fixate on the central point. Following, the test array appeared and remained on screen for 2,000 ms. On half of the trails, the orientation of the red rectangular bars in the test array were identical to the orientation of the red rectangular bars in the memory array. On the other half of the trials, one of the red rectangular orientation bars tilted either 45 or 90 degrees in comparison to the orientation of the corresponding bar in the memory array. 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. Participants were provided with an additional 4,000 ms blank response window after the test array (6,000 ms maximum response time window). Accuracy was emphasized over speed for the change detection responses.

All experimental factors including low (5%) versus high (45%) physical exertion, memory set size 1 verses memory set size 3, and change versus no change trials were randomly intermixed in each of the 5 experimental blocks consisting of 32 trials each, yielding 160 total trials. The experimental trials were preceded by 1 practice block consisting of 8 practice trials. Participants were given a 5-second break after every 16 trails in the experimental blocks and a mandatory one-minute break between each block. Participants were encouraged to ask for longer breaks, as needed, to minimize fatigue. The experimental task, including breaks, took approximately one-hour to complete.

4.3.4 Data Analysis

4.3.4.1 Visual WM Measures

Task performance was measured as accuracy. A two (low cognitive load vs. high cognitive load) x two (5% vs. 45% MVC) mixed-effect repeated-measures ANOVA was performed on performance accuracy for correct handgrip trials to investigate the number of retained items in visual WM across physical exertion conditions. Only trials where participants' successfully exerted grip force at or around the indicated level of %MVC during the WM change detection task were included for analyses. Participants were instructed to exert grip force slightly over the required level and grip exertions were classified as correct handgrip trials if participants exerted force no less than 5% but no greater than 30% MVC in the 5% MVC condition and no less than 40% but not greater than 70% MVC in the 45% MVC condition for more than 2/3rd of the time allocated for the memory display and delay interval. Additional post-hoc t-tests were performed to help interpret the findings from the two-way ANOVA.

4.3.4.2 Pupil Data

Pupil data were preprocessed and analyzed using previously established methodologies (Granholm et al., 1996; Siegle et al., 2003; Siegle et al., 2004; Xie et al., 2022). A 1,300 ms epoch (400 ms pre-memory stimulus interval and 900 ms for the delay interval) was used for the pupil size measurement window. Using previously stablished algorithms (Siegle et al., 2003, Siegle et al., 2004), artifact such as blinks were identified and rejected and/or corrected. In doing so, a linear interpolation of the pupil data was applied to trials with blinks for deblinking. Trials where eye blinks were detected at the beginning, or the end of the pupil data measurement window were rejected from further analyses. In addition, trials with more than 50% of interpolated data in the measurement window were also rejected from the analyses. Of primary interest, arousal as indexed by pupil dilation was measured during the pre-memory interval and the delay interval. This time window was selected to capture arousal under physical exertion independent of cognitive load and arousal under concurrent cognitive load and physical exertion. A two (low cognitive load vs. high cognitive load) x two (5% vs. 45% MVC) mixed-effect repeated-measures ANOVA was performed on pupil dilation for correct handgrip trials to investigate the arousal.

4.4 Results

4.4.1 WM Change Detection Performance Under Concurrent Physical Exertion

We investigated accuracy across experimental conditions in successful handgrip maintenance trials, based on a two-way mixed-design repeated-measures ANOVA with WM load (set size 1 vs. set size 3) and physical exertion (5% vs. 45% MVC) as within-subject factors (Figure 2). Consistent with the effects of load observed in the visual WM literature, WM load had a significant main effect on accuracy, $F(1, 31) = 20.76$, $p < .001$, $\eta^2_p = .40$. Observers' accuracy was greater in the low WM load condition (set size 1, $M = .91$, $SD = 0.08$) than the high WM load condition (set size 3, $M = .89$, $SD = 0.11$). Furthermore, there was a significant main effect of physical effort on accuracy ($F(1, 31) = 10.31$, $p = .003$, $\eta^2_p = .25$) such that observers' accuracy was greater in the low physical effort condition ($M = .93$, $SD = 0.08$) than the high physical effort condition ($M = .89$, $SD = 0.11$). More importantly, we found a significant two-way interaction across visual WM load and physical exertion, $F(1, 31) = 5.17$, $p = .030$, $\eta^2_p = .14$. To further evaluate this interaction, we performed post hoc analyses for low WM load and high WM load. In other words, we assessed the accuracy for the low and high WM load conditions separately under the two physical exertion conditions. For the low WM load condition, the difference in observers' accuracy was not significant across the low and high physical exertion conditions, $t(31) = 1.48$, $p = .075$, potentially due to a ceiling effect. For the high WM load condition, the difference in observers' accuracy was significantly lower for the high physical exertion condition (45% MVC; $M = .86$, $SD = 0.14$) in comparison to low physical exertion (5% MVC; $M = .92$, $SD = 0.10$), $t(31) = 3.27$, $p = .001$. Collectively, these results suggest that effortful physical exertion compromised observers' visual WM accuracy.

4.4.2 Reaction Time Under Concurrent Physical Exertion

Following the analyses on accuracy, a two-way mixed-design repeated-measure ANOVA for the correct RTs was performed with WM load (set size 1 vs. set size 3) and physical exertion (5% vs. 45% MVC) as within-subject factors (Figure 2). Correct RTs were defined as correct responses on the WM load task and handgrip task. There was a significant main effect of WM load on correct RT ($F(1, 31) = 32.23$, $p < .001$, $\eta^2_p = .51$) where observers were faster at making a correct change detection response in the low WM load condition ($M = 715.90$ ms, $SD = 166.92$ ms) than the high WM load condition ($M = 801.60$ ms, $SD = 209.39$ ms). Furthermore, there was a significant main effect of physical effort on correct RT ($F(1, 31) = 5.46$, $p = .026$, $\eta^2_p = .15$) where observers were faster at making a correct change detection response in the high physical effort condition ($M = 743.60$ ms, $SD = 187.90$ ms) than the low physical effort condition ($M = 773.80$ ms, $SD = 188.24$ ms). However, there was no significant interaction between visual WM load and physical effort on correct RT, $F(1, 31) = .42$, $p = .524$, $\eta^2_p = .01$.

4.4.3 Arousal Induced by Concurrent Cognitive Load and Physical Exertion

More importantly, arousal was assessed using pupil dilation during the handgrip only interval (400 ms pre-memory stimulus) to assess the effect of effortful physical exertion on arousal (Figure 4A). During the 400 ms pre-memory stimulus interval, there was a significant main effect of physical exertion on pupillometry, $F(1,31) = 26.79$, $p < 0.001$, $\eta^2_p = 0.46$. That is, the difference in participants' pupil size was larger under the high physical exertion condition ($M = 325.40$ a.u., $SD = 102.56$ a.u.) than the low physical exertion condition ($M = 295.46$ a.u., $SD = 92.56$ a.u.) during the 400 ms pre-memory stimulus interval. As expected, there was no significant main effect of cognitive load pupil size during the pre-memory stimulus interval, $F(1,31) = 0.56$, $p = 0.458$, $\eta^2_p = 0.02$, thus affirming our manipulation check. Lastly, we did not observe a significant interaction between physical exertion and cognitive load on pupil size, $F(1,31) = 0.08$, $p = 0.780$, $\eta^2_p = 0.00$, again confirming our manipulation check.

Next, we assessed pupil dilation during the post-memory stimulus 900 ms delay interval to investigate arousal induced under concurrent cognitive load and effortful physical exertion (Figure 4B). Similar to the 400 ms pre-memory stimulus interval, there was a significant main effect of physical exertion on pupillometry during the 900 ms post-memory delay interval, $F(1,31) = 39.85$, $p < 0.001$, $\eta^2_p = 0.54$. The difference in participants' pupil size was larger under the high physical exertion condition ($M = 319.70$ a.u., $SD = 100.68$ a.u.) than the low physical exertion condition ($M = 282.50$ a.u., $SD = 89.87$ a.u.) during the 900 ms post-memory delay interval. However, we did not observe a significant main effect for the difference in pupil size for cognitive load, $F(1,31) = 0.61$, $p = 0.441$, $\eta^2_p = 0.02$. Although the difference in pupil size for cognitive load during the 900 ms post-memory delay interval was not significant replicating prior studies (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022), the pupil dilation is conceptually in the same direction and previous studies where the difference in dilation was larger for the high cognitive load condition (*M* = 302.29 a.u., *SD* = 94.53 a.u.) than the low cognitive load condition (*M* = 299.91 a.u., *SD* = 93.95 a.u.; Figure 5). We also did not observe a significant interaction between physical exertion and cognitive load on pupil size during the 900 ms post-memory delay interval, $F(1,31) = 0.01$, $p = 0.926$, $\eta^2_p = 0.00$, which does not support our prediction that the interactive effect between physical exertion and cognitive load (Xie & Zhang, 2023) will be observed on TEPRs.

4.5 General Discussion

The present study investigated the relationship between effortful physical exertion and visual WM load, along with its effect on TEPRs during the simultaneous visual WM task with high versus low cognitive load (memory set size 1 vs. 3) and high versus low physical exertion load (5% vs. 45%). Under effortful physical exertion (45% versus 5% MVC), observers task performance was impaired under the high load condition but there was no significant difference in performance for the low load condition under high verses low physical exertion. The lack of effect in the low load condition could be possibly due to a ceiling effect in performance where observers' performance was nearly perfect across the two physical exertion conditions. The behavioral data suggest that under higher cognitive load in present study (set size 3) effortful physical exertion can impair task accuracy. However, these results are inconsistent with prior studies suggesting that at similar memory set sizes effortful physical exertion does not impair visual WM accuracy (Xie & Zhang, 2023). In fact, Xie and Zhang (2023) found that only at visual WM set size 6, effortful physical exertion impaired task accuracy. Nonetheless, it possible that under effortful physical exertion and higher cognitive loads the sum of observers' perceived effort could impair performance (Shenhav et al., 2017; Jung et al., 2022). Specifically, in line with the transient hypofrontality hypothesis, dual-task conditions requiring greater physical exertion may impaired performance tasks involving higher cognitive functions (Jung et al., 2022). That is, under effortful physical exertion reduced neural activity in the prefrontal cortex may occur as a result of recollection of resources to the motor cortices to support the physical action (Jung et al., 2022)

While the present study demonstrated the effect of effortful physical exertion on task performance across cognitive load, we did not observe any significant difference in TEPRs under concurrent physical exertion and cognitive load. That is, there was no significant difference for the dual-task effects on pupil size during the 900 ms post-memory delay interval. In addition, we did not observe any significant difference in post-memory pupil size across the cognitive load conditions, which is inconsistent with prior research reporting increased pupil size under high cognitive loads (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022). The results for TEPRs under physical exertion and cognitive load in the present study may be at conflict with the effort-accuracy tradeoff hypothesis suggesting that less invested effort could lead to lower accuracy (Payne et al., 1993). However, it is possible that observers' perceived effort for cognitive load in the present study was not a function of task performance, and therefore accuracy. For instance, it is possible that observers aim to minimize cognitive effort and hoped to maintain high levels of accuracy (Johnson & Payne, 1985). Although the accuracy differed among the high and low physical exertion conditions for high cognitive load, observers accuracy was fairly high (86% accuracy) during for the high cognitive load under effortful physical exertion condition.

Lastly, we observed a significant difference in post-memory and pre-memory pupil size across the physical exertion conditions, replicating prior work suggesting effortful physical exertion may stimulate the sympathetic nervous system (Hautala et al., 2009; Patel & Zwibel, 2022) and thus induce greater arousal, or pupil dilation (Hayashi & Someya, 2011; Nielsen & Mather, 2015; McDougal & Gamlin, 2015; Mathôt, 2018; Zénon et al., 2014). These results suggest that our manipulation of physical effort does induce greater arousal.

The lack of interaction between physical and cognitive effort on TEPRs does not support our prediction that mental effort and physical effort may share common neurocognitive mechanisms (Xie & Zhang, 2023). It could be possible that motor and cognitive actions have separate resource pools (Feghhi & Rosenbaum, 2019) and therefore separate neurocognitive mechanisms for task-induced arousal. However, engagement in one domain may have a direct impact on task performance in another domain where concurrent effortful physical exertion may impair inhibitory control (Azer et al., 2023), visual search (Park et al., 2021), and WM performance at larger WM loads (Xie & Zhang, 2023). In fact, the interaction between physical and cognitive effort on WM performance in the present study is supported by prior research suggesting that physical exertion may negatively impact cognitive task performance at the expense of control related processes (Azer et al., 2023; Park et al., 2021; Xie & Zhang, 2023). In addition, the observed increase in pupil dilation for the high physical effort condition may be supported by the Yerkes-Dodson inverted U hypothesis (Yerkes & Dodson, 1908). The Yerkes-Dodson inverted U hypothesis suggests that the level of task-induced arousal can be beneficial or harmful to performance where optimal levels of arousal can improve performance while high levels of arousal can impair performance. As observed in the present study, beyond optimal task-induced arousal by the high physical exertion condition was harmful to WM performance.

While not significant, pupil size was numerically in the same direction as prior research where observers experienced larger TEPRs under high cognitive load (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022). Nonetheless, one possibility for the inconsistent findings could be due to a direct competition between motor and cognitive dual tasks on underlying neurocognitive mechanisms. To the best of our knowledge, the present study is a novel dual task paradigm investigating pupil size under effortful physical action and cognitive load while prior research has yet to investigate underlying neurocognitive mechanisms under similar dual-task conditions. Studies investigating TEPRs across cognitive load and alternative cognitive tasks typically report increased pupil size in the dual task verses the single task condition (Wahn et al., 2016; Vogels et al., 2018); however, these studies assess TEPRs for within domain dual-tasks rather than across domain dual-task conditions.

Another possibility for the inconsistent findings for TEPRs on cognitive load could be due to resource allocation for memory items in both cognitive load conditions. For example, when cognitive load is too high observers may not have enough recourses to process the high load condition and therefore TEPRs may not be observed (Peysakhovich et al., 2015). While this is not the case for the present study, it is possible that memory set size 1 and memory set size 3 for the stimuli used in the present study may recruit equivalent resources (Xie & Zhang, 2023) and thus may not produce a significant difference arousal across both load conditions. For instance, the orientation bars used in the present study may promote gist representations or configural encoding, which can contribute to improved WM performance (Xie & Zhang, 2017). That is, the uncircled bars in the high load condition in the present study can promote configural encoding (Xie & Zhang, 2017), which supports Humphreys' configural encoding account of improved visual short-term memory performance (Delvenne et al., 2002). Therefore, mental effort across the low and high cognitive load conditions in the present study may be similar leading to no significant difference in arousal.

Future research should continue to investigate if mental and physical effort may share common neurocognitive mechanisms using stimuli or methodologies that may prevent chunking or configural encoding. For instance, the WM stimuli used in the present study may have promoted configural encoding (Xie & Zhang, 2017), which could have led to a similar perception of effort for both cognitive load conditions. This caveat could be addressed in future research by using stimuli, such as encircled bars, to prevent configural encoding (Xie & Zhang, 2017). Another cavate of the present study includes a lack of subjective measure for perceived arousal. The present study objectively measured pupil dilation as a proxy measure for LC-NE activity and arousal (Auston-Jones & Cohen, 2005; Liu et al., 2017), however, future research should consider investigating perceived arousal to better understand the relationship between objectively measured arousal and subject arousal in relation to mental effort under effortful physical exertion.

4.5.1 Conclusion

Using a novel dual-task paradigm, the present study investigated the interactive effect of physical and cognitive effort on pupillary response. Task performance was impaired under the high cognitive load and effortful physical exertion. These results replicate prior work suggesting that under higher cognitive loads effortful physical exertion can impair task accuracy (Xie & Zhang, 2023). In addition, we observed a significant difference in pre-memory and post-memory interval pupil size across effortful physical exertion where participants' pupil size was larger under the high physical exertion condition in comparison to the low physical exertion condition. Therefore, we replicated results suggesting heightened arousal under effortful physical exertion (Hayashi & Someya, 2011; Nielsen & Mather, 2015; McDougal & Gamlin, 2015; Mathôt, 2018; Zénon et al., 2014). However, we did not observe any difference in TEPRs for the interaction between physical exertion and cognitive load, which is inconsistent with our prediction. In addition, we did not observe any significant difference in post-memory pupil size across the cognitive load conditions. This result is inconsistent with prior research reporting increased pupil size under high cognitive load (Alnaes et al., 2014; Ahern & Beatty, 1979; Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966; Wahn et al., 2021; Zhou et al., 2022).

References

Ahern, S., & Beatty, J. (1979). Pupillary responses during information processing vary with Scholastic Aptitude Test scores. *Science (New York, N.Y.)*, *205*(4412), 1289–1292. https://doi.org/10.1126/science.472746

Alnæs, D., Sneve, M. H., Espeseth, T., Endestad, T., van de Pavert, S. H. P., & Laeng, B. (2014). Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. *Journal of Vision*, *14*(4), 1. https://doi.org/10.1167/14.4.1

Andreassi, J. L. (2000). Pupillary Response and Behavior. In *Psychophysiology* (4th ed.). Psychology Press.

Ángyán, L., Téczely, T., & Karsai, I. (2005). Learning to produce predicted static handgrip forces. *Acta Physiologica Hungarica*, *92*(1), 11–18. https://doi.org/10.1556/aphysiol.92.2005.1.2

Asfoura, S. S., Ayoub, M. M., Mital, A., & Bethea, N. J. (1983). Perceived exertion of physical effort for various manual handling tasks. *American Industrial Hygiene Association Journal*, *44*(3), 223–228. https://doi.org/10.1080/15298668391404680

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28,* 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Azer, L., Xie, W., Park, H.-B., & Zhang, W. (2023). Detrimental effects of effortful physical exertion on a working memory dual-task in older adults. *Psychology and Aging*, No Pagination Specified-No Pagination Specified. https://doi.org/10.1037/pag0000746

Bradshaw, J. L. (1968). Pupil Size and Problem Solving. *Quarterly Journal of Experimental Psychology*, *20*(2), 116–122. https://doi.org/10.1080/14640746808400139

Bornert, P., & Bouret, S. (2021). Locus coeruleus neurons encode the subjective difficulty of triggering and executing actions. *PLOS Biology*, *19*(12), e3001487. https://doi.org/10.1371/journal.pbio.3001487

Cain, W. S., & Stevens, J. C. (1971). Effort in sustained and phasic handgrip contractions. *The American Journal of Psychology*, *84*(1), 52. https://doi.org/10.2307/1421224

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*(1), 87–114. https://doi.org/10.1017/S0140525X01003922

Delvenne, J.-F., Braithwaite, J. J., Riddoch, M. J., & Humphreys, G. W. (2002). Capacity limits in visual short-term memory for local orientations. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition*, *21*, 681–690.

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Feghhi, I., & Rosenbaum, D. A. (2019). Judging the subjective difficulty of different kinds of tasks. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(8), 983–994. https://doi.org/10.1037/xhp0000653

Florin-Lechner, S. M., Druhan, J. P., Aston-Jones, G., & Valentino, R. J. (1996). Enhanced norepinephrine release in prefrontal cortex with burst stimulation of the locus coeruleus. *Brain Research*, *742*(1), 89–97. https://doi.org/10.1016/S0006-8993(96)00967-5

Fukuda, K., Mance, I., & Vogel, E. K. (2015). α power modulation and event-related slow wave provide dissociable correlates of visual working memory. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *35*(41), 14009–14016. https://doi.org/10.1523/JNEUROSCI.5003-14.2015

Glowinski, J., & Baldessarini, R. J. (1966). Metabolism of norepinephrine in the central nervous system. *Pharmacological Reviews*, *18*(4), 1201–1238.

Granholm, E., Asarnow, R. F., Sarkin, A. J., & Dykes, K. L. (1996). Pupillary responses index cognitive resource limitations. *Psychophysiology*, *33*(4), 457–461. https://doi.org/10.1111/j.1469-8986.1996.tb01071.x

Guillery, E., Mouraux, A., & Thonnard, J. L. (2013). Cognitive-motor interference while grasping, lifting and holding objects. *PLoS ONE*, *8*(11), 14–20. https://doi.org/10.1371/journal.pone.0080125

Guillery, E., Mouraux, A., Thonnard, J. L., & Legrain, V. (2017). Mind your grip: Even usual dexterous manipulation requires high level cognition. *Frontiers in Behavioral Neuroscience*, *11*(November), 1–11. https://doi.org/10.3389/fnbeh.2017.00220

Hautala, A. J., Kiviniemi, A. M., & Tulppo, M. P. (2009). Individual responses to aerobic exercise: The role of the autonomic nervous system. *Neuroscience and Biobehavioral Reviews*, *33*(2), 107–115. https://doi.org/10.1016/j.neubiorev.2008.04.009

Hayashi, N., & Someya, N. (2011). Muscle metaboreflex activation by static exercise dilates pupil in humans. *European Journal of Applied Physiology*, *111*(6), 1217–1221. https://doi.org/10.1007/s00421-010-1716-z

Hayashi, N., Someya, N., & Fukuba, Y. (2010). Effect of intensity of dynamic exercise on pupil diameter in humans. *Journal of Physiological Anthropology*, *29*(3), 119–122. https://doi.org/10.2114/jpa2.29.119

Hess, E. H., & Polt, J. M. (1964). pupil size in relation to mental activity during simple problem-solving. *Science (New York, N.Y.)*, *143*(3611), 1190–1192. https://doi.org/10.1126/science.143.3611.1190

Ishigaki, H., Miyao, M., & Ishihara, S. (1991). Change of pupil size as a function of exercise. *Journal of Human Ergology*, *20*(1), 61–66.

Johnson, E. J., & Payne, J. W. (1985). Effort and Accuracy in Choice. *Management Science*, *31*(4), 395–414.

Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between Pupil Diameter and Neuronal Activity in the Locus Coeruleus, Colliculi, and Cingulate Cortex. *Neuron*, *89*(1), 221–234. https://doi.org/10.1016/j.neuron.2015.11.028

Jung, M., Ryu, S., Kang, M., Javadi, A.-H., & Loprinzi, P. D. (2022). Evaluation of the transient hypofrontality theory in the context of exercise: A systematic review with meta-analysis. *Quarterly Journal of Experimental Psychology*, *75*(7), 1193–1214. https://doi.org/10.1177/17470218211048807

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science (New York, N.Y.)*, *154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Kahneman, D., & Beatty, J. (1967). Pupillary responses in a pitch-discrimination task. *Perception & Psychophysics*, *2*, 101–105. https://doi.org/10.3758/BF03210302

Kirschner, P. A. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning. *Learning and Instruction*, *12*(1), 1–10. https://doi.org/10.1016/S0959-4752(01)00014-7

Kirschner, P A, Kirschner, FC, Seel, N M.(2010). Mental effort. In *Encyclopedia of the Sciences of Learning*. Springer. https://pure.eur.nl/en/publications/7b5ca805-8751-4efd-b296-49e036e5f8cf

Kobayashi-Cuya, K. E., Sakurai, R., Sakuma, N., Suzuki, H., Yasunaga, M., Ogawa, S., Takebayashi, T., & Fujiwara, Y. (2018). Hand dexterity, not handgrip strength, is associated with executive function in Japanese community-dwelling older adults: a cross-sectional study. *BMC Geriatrics*, *18*(1), 192. https://doi.org/10.1186/s12877-018-0880-6

Konstantinou, N., Beal, E., King, J.-R., & Lavie, N. (2014). Working memory load and distraction: Dissociable effects of visual maintenance and cognitive control. *Attention, Perception & Psychophysics*, *76*(7), 1985–1997. https://doi.org/10.3758/s13414-014-0742-z

Kool, W., & Botvinick, M. (2018). Mental labour. *Nature Human Behaviour*, *2*(12), Article 12. https://doi.org/10.1038/s41562-018-0401-9

Krejtz, K., Duchowski, A. T., Niedzielska, A., Biele, C., & Krejtz, I. (2018). Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. *PloS One*, *13*(9), e0203629. https://doi.org/10.1371/journal.pone.0203629

Kuwamizu, R., Yamazaki, Y., Aoike, N., Ochi, G., Suwabe, K., & Soya, H. (2022). Pupil-linked arousal with very light exercise: Pattern of pupil dilation during graded exercise. *The Journal of Physiological Sciences*, *72*(1), 23. https://doi.org/10.1186/s12576-022-00849-x

Liu, Y., Rodenkirch, C., Moskowitz, N., Schriver, B., & Wang, Q. (2017). Dynamic lateralization of pupil dilation evoked by locus coeruleus activation results from sympathetic, not parasympathetic, contributions. *Cell Reports, 20*(13), 3099–3112. https://doi.org/10.1016/j.celrep.2017.08.094

Lowe, B. D. (2016). Repeatability of magnitude production in isometric, hand-grip force estimation: A working-memory approach. *Perceptual and Motor Skills, 80*(2), 659–667. https://doi.org/10.2466/pms.1995.80.2.659

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39,* e200. https://doi.org/10.1017/S0140525X15000667

Mather, M., & Harley, C. W. (2016). The locus coeruleus: essential for maintaining cognitive function and the aging brain. *Trends in cognitive sciences*, *20*(3), 214–226. https://doi.org/10.1016/j.tics.2016.01.001

Mathôt, S. (2018). Pupillometry: Psychology, Physiology, and Function. *Journal of Cognition*, *1*(1), 16. https://doi.org/10.5334/joc.18

McDougal, D. H., & Gamlin, P. D. (2015). Autonomic control of the eye. *Comprehensive Physiology*, *5*(1), 439–473. https://doi.org/10.1002/cphy.c140014

Nielsen, S. E., & Mather, M. (2015). Comparison of two isometric handgrip protocols on sympathetic arousal in women. *Physiology & Behavior*, *142*, 5-13. https://doi.org/10.1016/j.physbeh.2015.01.031

Oberauer, K., & Lin, H.-Y. (2017). An interference model of visual working memory. *Psychological Review*, *124*(1), 21–59. https://doi.org/10.1037/rev0000044

Park, H. B., Ahn, S., & Zhang, W. (2021). Visual search under physical effort is faster but more vulnerable to distractor interference. *Cognitive Research: Principles and Implications*, *6*(1). https://doi.org/10.1186/s41235-021-00283-4

Patel, P. N., & Zwibel, H. (2022). Physiology, Exercise. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK482280/

Payne, J. W., Bettman, J. R., & Johnson, E. J. (1993). *The Adaptive Decision Maker*. Cambridge University Press.

Peysakhovich, V., Dehais, F., & Causse, M. (2015). Pupil diameter as a measure of cognitive load during auditory-visual interference in a simple piloting task. *Procedia Manufacturing*, *3*, 5199–5205. https://doi.org/10.1016/j.promfg.2015.07.583

Robertson, R. J., & Noble, B. J. (1997). Perception of physical exertion: methods, mediators, and applications. *Exercise and Sport Sciences Reviews*, *25*(1), 407.

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a Rational and Mechanistic Account of Mental Effort. *Annual Review of Neuroscience*, *40*, 99–124. https://doi.org/10.1146/annurev-neuro-072116-031526

Siegle, G. J., Steinhauer, S. R., Stenger, V. A., Konecky, R., & Carter, C. S. (2003). Use of concurrent pupil dilation assessment to inform interpretation and analysis of fMRI data. *NeuroImage*, *20*(1), 114–124. https://doi.org/10.1016/S1053-8119(03)00298-2

Siegle, G. J., Steinhauer, S. R., & Thase, M. E. (2004). Pupillary assessment and computational modeling of the Stroop task in depression. *International Journal of Psychophysiology*, *52*(1), 63–76. https://doi.org/10.1016/j.ijpsycho.2003.12.010

Sweller, J. (1988). Cognitive load during problem solving: effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4

Vogels, J., Demberg, V., & Kray, J. (2018). The index of cognitive activity as a measure of cognitive processing load in dual task settings. *Frontiers in Psychology*, *9*. https://www.frontiersin.org/articles/10.3389/fpsyg.2018.02276

Wahn, B., Ferris, D. P., Hairston, W. D., & König, P. (2016). Pupil sizes scale with attentional load and task experience in a multiple object tracking task. *PLOS ONE*, *11*(12), e0168087. https://doi.org/10.1371/journal.pone.0168087

Wahn, B., Ruuskanen, V., Kingstone, A., & Mathôt, S. (2021). Coordination effort in joint action is reflected in pupil size. *Acta Psychologica*, *215*, 103291. https://doi.org/10.1016/j.actpsy.2021.103291

Xie, W., Lu Sing, J. L., Martinez-Flores, A., & Zhang, W. (2022). Induced negative arousal modulates the speed of visual working memory consolidation. *Emotion*, *22*, 179–197. https://doi.org/10.1037/emo0001059

Xie, W., & Zhang, W. (2017). Discrete item-based and continuous configural representations in visual short-term memory. *Visual Cognition*, *25*(1–3), 21–33. https://doi.org/10.1080/13506285.2017.1339157

Xie, W., & Zhang, W. (2023). Effortfulness of visual working memory: gauged by physical exertion. *Journal of Experimental Psychology: General*. Advance online publication. https://doi.org/10.1037/xge0001391

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, *18*(5), 459–482. https://doi.org/10.1002/cne.920180503

Zénon, A., Sidibé, M., & Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00286

Zhou, C., Lorist, M. M., & Mathôt, S. (2022). Is categorization in visual working memory a way to reduce mental effort? A pupillometry study. *Cognitive Science*, *46*(9), e13194. https://doi.org/10.1111/cogs.13194

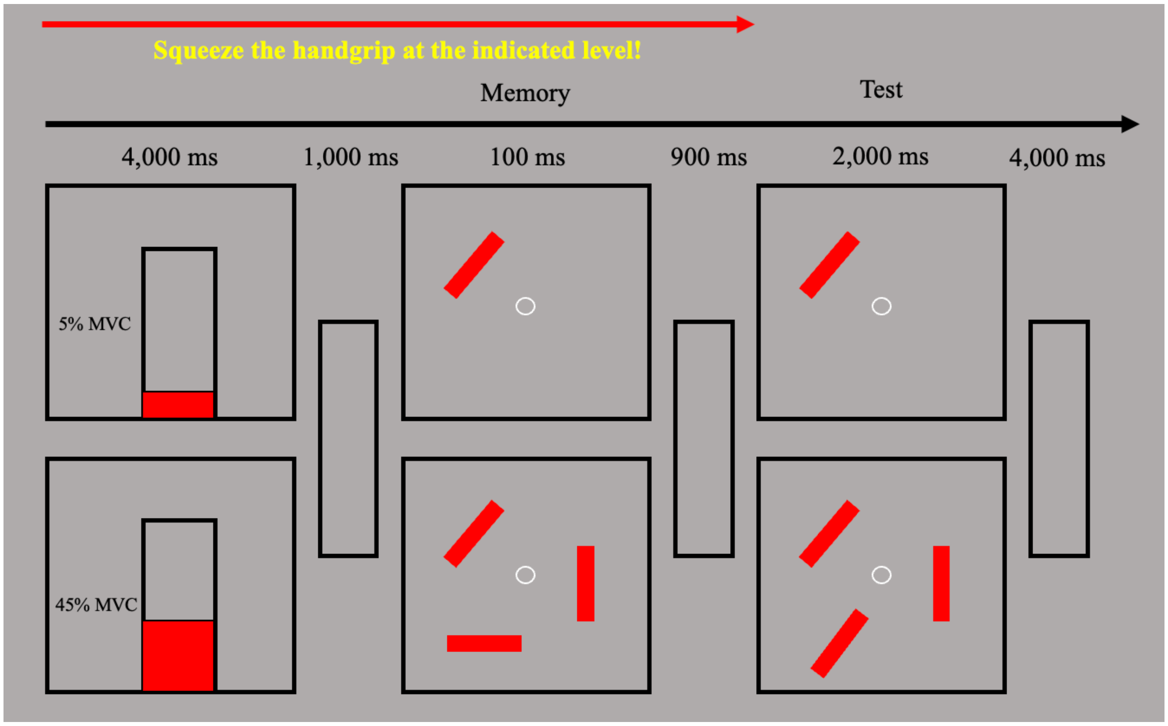
Table 6.

Sample Demographics

Characteristics	Mean (*SD*)/%	t	*df*	*p*
Age (years)	19.15 (1.41)	-	-	-
Gender		-	-	-
Female	37.50%			
Race/Ethnicity		-	-	-
Asian	32.20%			
Black/African American	6.50%			
White	12.90%			
More than one race	12.90%			
Prefer not to respond	16.10%			
MVC		3.61	30	.007
Female	98.58 (31.85)			
Male	174.47 (67.94)			

Figure 10.

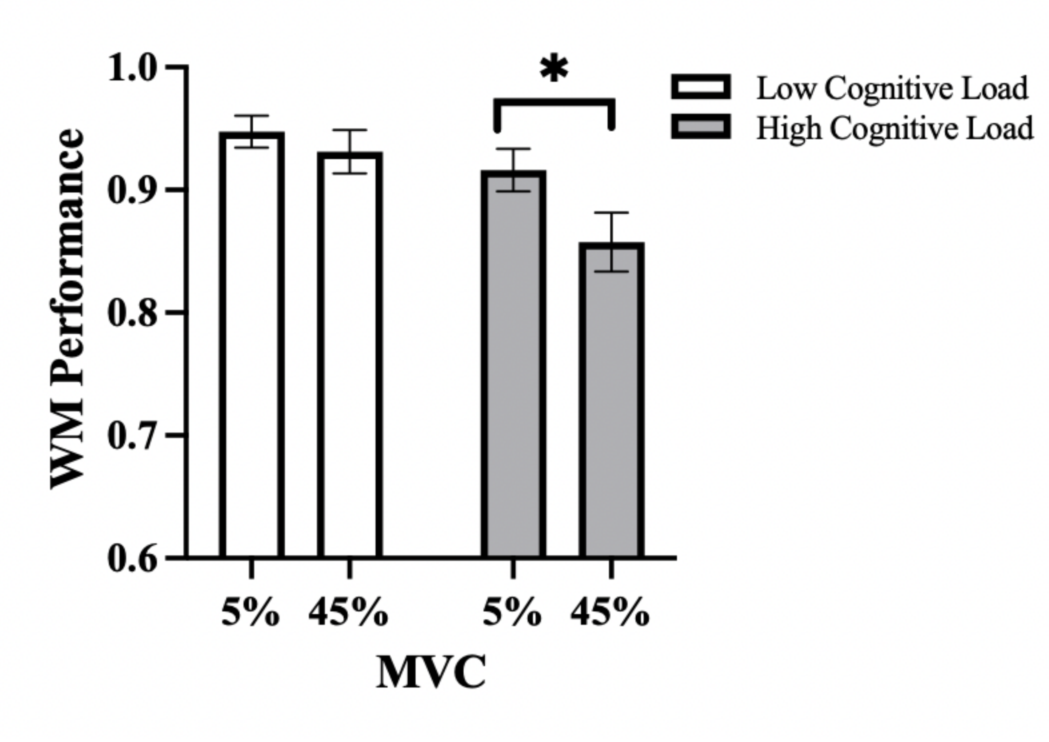
Stimuli and procedure for the concurrent physical exertion and visual WM change detection task



Note. Each trial began with a 4,000 ms screen prompting participants to grip the Hand Dynamometer at the indicated level (5% or 50% MVC). Participants were asked to maintain the squeeze until the test array. The memory array appeared for 100 ms and contained 1 memory item (low WM load) or 3 memory items (high WM load). After a 900-ms delay interval, a test array was presented for 2,000 ms and participants were instructed to make a *'same'* or *'different'* response within the 6,000 ms interval.

Figure 11.

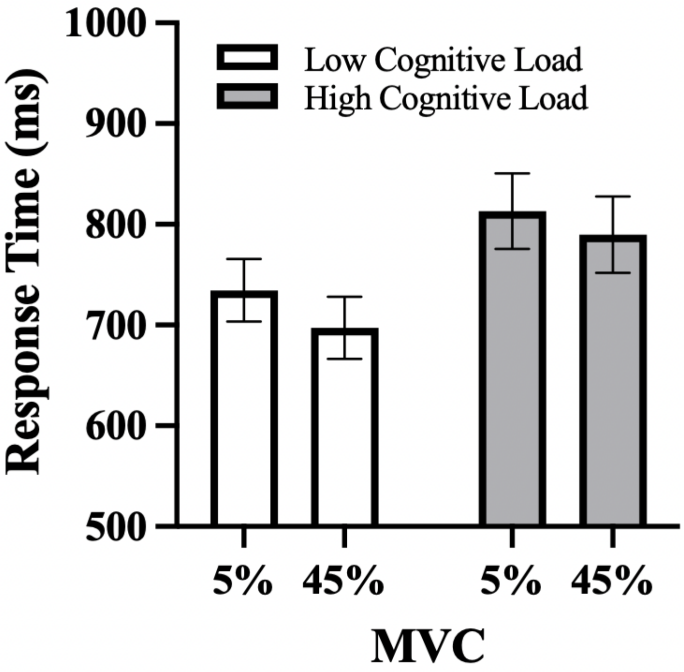
Two-way interaction with WM load (set size 1 vs. set size 3), and physical effort (5% vs. 45% MVC)



Note. Accuracy results for successful handgrip trials across WM load (low vs. high) and physical effort (5% vs. 45%).

Figure 12

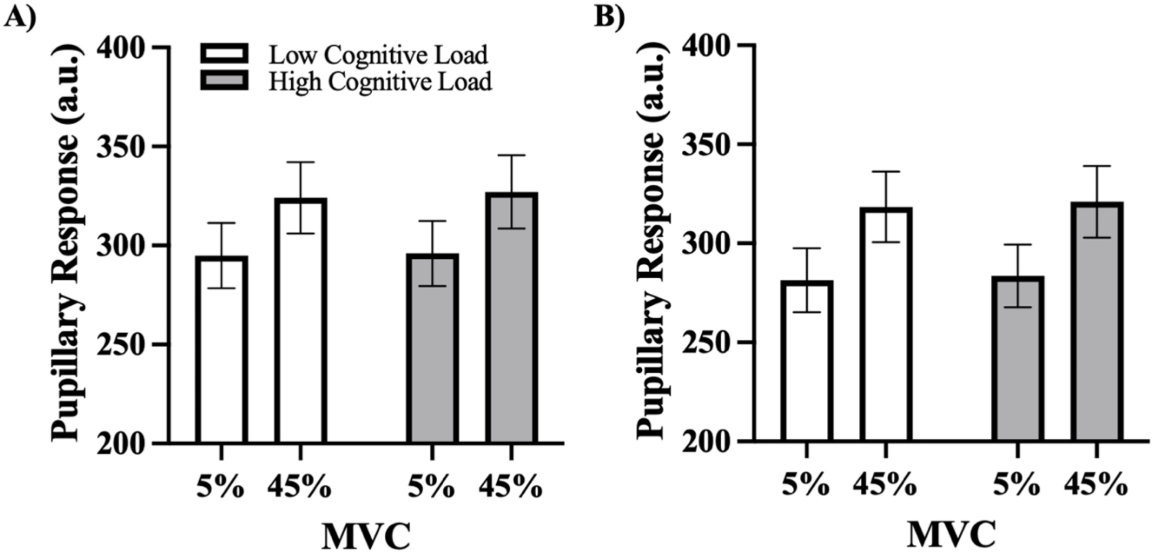
RT results for the WM task under physical effort



Note. Mean reaction times (RTs) for successful handgrip and correct WM load trials across WM load (low vs. high) and physical effort (5% vs. 45%).

Figure 13.

Pupillary Response for the WM task under physical effort



Note. Mean pupillary response for successful handgrip trials across WM load (low vs. high) and physical effort (5% vs. 45%). A) Pupillary response for the 400 ms pre-memory stimulus interval under physical effort. B) Pupillary response for the 900 ms post-memory stimulus interval under physical effort.

Chapter 5. General Discussion

5.1 Reduced Inhibitory Control and Heightened Arousal Under Effortful Physical Exertion

The research presented in this dissertation demonstrated the impact of concurrent effortful physical exertion on inhibitory control and arousal across three separate empirical studies. Chapter 2 and Chapter 3 demonstrated that older and younger adults, respectively, had reduced inhibitory control when task-irrelevant items were present under high physical effort. This effect was observed using lab generated stimuli (Chapter 2) and stimuli we encounter daily (Chapter 3) when participants were required to recall or detect task-relevant information and actively inhibit task-irrelevant information. In addition, Hierarchical Bayesian ex-Gaussian Analyses of reaction time in Chapter 2 demonstrated that reduced inhibition for older, but not younger, adults when task-irrelevant items were present under effortful physical exertion was indexed by slower reaction times. These results could be explained by an arousal-based enhancement effect (see Park et al., 2021) possibly stemming from the same neurocognitive mechanism where effortful physical exertion may yield heightened arousal thus increasing NE released by the LC (Nielsen & Mather, 2015). The LC-NE system is modulated by distractor interference (Aston-Jones & Cohen, 2005). Therefore, it is possible that reduced inhibition under high physical effort when distractors are present could result from beyond optimal levels of arousal stemming from heightened effortful physical exertion resulting in poor performance (Davey, 1973; Yerkes & Dodson, 1908).

Chapter 4 further investigated arousal stemming from effortful physical exertion during a working memory task to understand the impact of cognitive load and physical exertion on task evoked pupillary responses (TEPRs). Effortful physical exertion using isometric handgrip increased observers' pupil dilatation and thus induced heightened arousal. Previous studies have also reported induced arousal due to effortful physical exertion (Nielsen & Mather, 2015; Zénon et al., 2014). However, Chapter 4 failed to replicate results from previous studies reporting increased pupil dilation under higher cognitive load (Hess & Plot, 1964; Krejtz et al., 2018; Kahneman & Beatty, 1966). In addition, the results presented in Chapter 4 did not support the arousal-based account of concurrent effortful physical exertion and cognitive load on TEPRs. Nonetheless, task performance was impaired under high cognitive load and effortful physical exertion suggesting that physical exertion may negatively impact cognitive task performance at the expense of control related processes (Azer et al., 2023; Park et al., 2021; Xie & Zhang, 2023). Although the dual task results do not support an arousal-based account, they support an inhibitory-control account of concurrent effortful physical exertion of cognition.

Several previous studies have also investigated dual-task decrements during effortful motor tasks and have demonstrated impaired performance on one, or both, domains under dual-task conditions (Doumas et al., 2009; Plummer-D'Amato et al., 2011, 2012; Rapp et al., 2005; Voelcker-Rehage & Alberts, 2007). Similarly, Chapter 2 and Chapter 3 of the present dissertation aimed to understand the impact of effortful physical exertion on cognition using simple isometric handgrip muscle contractions and demonstrated impaired inhibitory control under high physical effort. These results may appear to be similar (i.e., worse performance during dual-task condition). However, using isometric handgrip muscle contraction rather than more complex motor actions (e.g., gait, precision grip, postural control) the present dissertation demonstrated that an effortful, yet simple, motor action can impair inhibitory control and induce heightened arousal. Isometric handgrip muscle contractions involve activation of the hand muscles to produce a power grip (Cain & Stevens, 1971), which in comparison to more complex motor actions tend to require less cognitive control and involvement of control networks ((Lim et al., 2021; Mahoney et al., 2016; Ehrsson et al., 2000; Guillery et al., 2017).

The results observed in the present dissertation are supported by effort-based accounts investigating the involvement of cognitive control in tasks where greater effort is required (Shenhav et al., 2017; Székely & Micheal, 2021; Jung et al., 2022). According to these accounts, the extent to which cognitive control may be involved in mental effort is the driving factor for task performance when greater effort is required (Shenhav et al., 2017; Székely & Micheal, 2021). Physical effort on the other hand during dual-task conditions can impair cognitive control when the degree of effort on the physical task is high (Jung et al., 2022). In line with these hypotheses, the present dissertation demonstrated an inhibition-based account for working memory and perception under effortful physical exertion where high effort impaired cognitive control when task-irrelevant information was present.

It is possible that motivation, while not directly measured in the present dissertation, can play role on task performance under effortful physical exertion. For instance, when observers were asked to squeeze a hand dynamometer at different levels of their MVC as they imaged the force they were producing was to achieve a goal of unclogging a Ketchup bottle, results indicated that the amount of force exerted was a function of task demand and task difficulty (Richter, 2015; Richter et al., 2021; Stanek & Richter, 2016; Stanek & Richter, 2021). Across these studies, force exerted was used as a measure of effort to achieve a goal based on motivation. These results were in part supported by the motivational intensity theory (Brehm & Self, 1989), which states that the amount of effort invested in a task depends on the task demand where higher task difficulty will require more energy invested in the task. In addition, the amount of effort invested in a task is determined by whether success on the task is perceived to be possible. Participants across the three empirical chapters in the present dissertation were able to successfully maintain exerted effort on the hand dynamometer at, or slightly above, the indicated level for approximately 88.87% of all trails. In line with previous research and the motivational intensity theory the results observed in the present dissertation infer that amount of effort invested in the motor task was high possibly due to motivation that task performance on the motor task and the concurrent cognitive tasks would be successful.

5.2 Translational Relevance

The work presented in this dissertation also has significant translational implications that may encourage policymakers to make future policy recommendations to provide older adults with state and/or federal funding to purchase vehicles with self-driving capabilities as an external aid. Normal age-related declines may occur in cognitive (e.g., impaired working and long-term memory and slower reaction time; Park et al., 2009) and physical (e.g., loss of muscle strength/mass; Samuel et al., 2013; Sparling et al., 2015) functions and may interact with one another leading to altered and/or impaired physical (grip, balance, and gait; Doumas et al., 2009; Rapp et al., 2006; Plummer-D'Amato et al., 2011; 2012) and cognitive (reduced distractor inhibition; Azer et al., 2023) abilities. These impairments may consequently result in detrimental outcomes, including injury or fatality while driving. In fact, while previous research has demonstrated older drivers drive less frequently than younger drivers, older adults are more likely to be involved in a car accident resulting in fatal injury (Loughran et al., 2007)[9].

Driving is a cognition-heavy task that involves the simultaneous use of physical action. The cognitive component in driving involves the ability to maintain focused attention on the task at hand (i.e., driving safely to our intended destination) and inhibiting task-irrelevant information in our surrounding environment (i.e., distracting billboards or sounds). The physical action involved in driving includes gripping the steering wheel, orienting head and eye movements to the necessary visual field, and alternating one's foot from the brake to the gas paddle. Older adults who live in areas with high traffic congestion will benefit from learning about the impact of the physical component involved in driving and how it may impact the cognitive component involved in driving. In addition, older adult may also benefit from the use of vehicles with self-driving capabilities, which may ameliorate the negative impact of engaging in a concurrent cognitive and physical task. Therefore, considering solutions such as autonomous vehicle incentive programs as an external assistive device for older adults may decrease the rate of injury due to this negative interaction. This policy recommendation may also aid in maintaining older adults' well-being given many older adults report increased depressive symptoms, social disconnectedness, and a loss of independence after driving cessation (for a review see Chihuri et al., 2016).

5.3 Future Research Directions

The collective empirical work in this dissertation provides both an inhibition-based and arousal-based account of concurrent effortful physical exertion on working memory, inhibitory control, and perception. However, there are several outstanding questions that remain to be answered in future studies.

First, for the arousal-based account to be fully understood, further research should investigate if arousal produced by effortful physical exertion impacts cognition and overlapping neurocognitive mechanisms (i.e., pupil dilation as an index of arousal) in a similar manner to arousal induced by emotion (Leuches et al., 2017; Xie & Zhang, 2016; 2022). For example, induced arousal from exposure to negative emotional valence during a working memory task boosts working memory precision (Xie & Zhang, 2016, 2022). In addition, fear perception is associated with negative emotion and heightened arousal as indexed by increased pupil dilation (Leuchs et al., 2017), which can easily capture attention (Ohman et al., 2001; Miyazawa & Iwasaki, 2009). Therefore, testing the arousal-based account of concurrent effortful physical exertion to compare arousal induced under high physical effort and negative emotion is necessary in order to draw translational connections between arousal and cognition. For instance, police officers facing a fearful situation that may evoke negative emotion, and therefore heightened arousal, may be more likely to precisely recall information in their working memory (Xie & Zhang, 2016, 2022), which captured their attention (Leuchs et al., 2017). Nevertheless, the question remains if police officers or military personal engaging in effortful physical exertion (e.g., chasing a suspect) will be able to produce the same precise recall of information as a fearful situation evoking negative emotion.

Second, to further draw translational connections and better equip policymakers with evidence to provide additional funding incentives for older adults to purchase vehicles with self-driving capabilities future research investigating effortful physical exertion while driving on cognition should be conducted. For example, imagine driving in traffic and attempting to merge onto a lane while another car is attempting to merge onto the same lane and the car in front of you suddenly breaks. You grip the steering wheel tighter and pump the breaks. Here, you are exerting greater physical force on the steering wheel, making it difficult to inhibit distracting information. While this is true for everyone, older adults may be more impacted by concurrent effortful physical exertion (tightly gripping the steering wheel) during a cognition-heavy task (driving). In fact, on average drivers exert approximately 31% maximum voluntary grip force on the steering wheel when driving (Eksioglu & Kiziliaslan, 2008), which is consistent with the effortful physical exertion condition exerted by older adults in the present dissertation. When exerting 30% maximum voluntary grip force during a working memory task, older adults' inhibitory control of access to working memory was compromised when distractors were present

(Azer et al., 2023). These results simulate a real-world scenario of dual power grip and cognitive task but assessing effortful physical exertion using maximum voluntary grip force on a steering wheel during a driving simulator may further provide applied and translational support for policy recommendations.

Lastly, while empirical research presented in this dissertation demonstrated that effortful physical exertion impaired inhibitory control and induced heightened arousal, the subjective experience of perceived exertion has yet to be assessed. For instance, ratings of perceived exertion are higher during a dual physical and cognitive task regardless of level of daily habitual exercise in comparison to single-task conditions (Condello et al., 2019). That is, higher subjective perception of effort was reported when a working memory task was performed simultaneously during a locomotor gait task. In addition, both actual and perceived physical exertion using an isometric handgrip exercise increased pupil diameter with increasing effort (Zenon et al., 2014) suggesting that both actual physical exertion and perceived exertion can similarly induce heightened arousal. Perceived exertion is measured by using the Borg ratings of perceived exertion scale (Borg, 1998), which is self-report outcome measure completed at the end of the task and asks observers to rate their perceived exertion for the motor task from *Very, very light (i.e., How you feel when lying in bed or sitting in a chair relaxed – Little to no effort)* to *Maximum exertion (i.e., How you felt with the hardest work you have ever done – Don't work this hard!)*. More recently, Padmanabhan et al., (2023) reported an empirical measure of perceived effortful physical exertion using isometric handgrip exercises with varying exertion levels. Similar to the methodology presented in this dissertation, participants’ maximum voluntary contraction (MVC) was measured, and participants were asked to grip the hand dynamometer at different levels of their MVC during the practice phase. During the test phase, participants were asked to grip the hand dynamometer at unknown levels of their MVC and report the amount of effort they perceived the during exertion trial (Padmanabhan et al., 2023). Using similar methodology as Borg (1988) and/or Padmanabhan et al. (2023), future studies should consider incorporating a subjective measure of perceived exertion to better understand the impact of perceived effortful physical exertion on inhibitory control and arousal.

References

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience, 28,* 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Azer, L., Xie, W., Park, H.-B., & Zhang, W. (2023). Detrimental effects of effortful physical exertion on a working memory dual-task in older adults. *Psychology and Aging*, No Pagination Specified-No Pagination Specified. https://doi.org/10.1037/pag0000746

Brehm, J. W., & Self, E. A. (1989). The intensity of motivation. *Annual Review of Psychology*, *40*, 109–131. https://doi.org/10.1146/annurev.ps.40.020189.000545

Borg, G. Borg's Perceived Exertion and Pain Scales; Human Kinetics: Champaign, IL, USA, 1998.

Cain, W. S., & Stevens, J. C. (1971). Effort in sustained and phasic handgrip contractions. *The American Journal of Psychology*, *84*(1), 52. https://doi.org/10.2307/1421224

Chihuri, S., Mielenz, T. J., DiMaggio, C. J., Betz, M. E., DiGuiseppi, C., Jones, V. C., & Li, G. (2016). Driving Cessation and Health Outcomes in Older Adults. *Journal of the American Geriatrics Society*, *64*(2), 332–341. https://doi.org/10.1111/jgs.13931

Condello, G., Forte, R., Monteagudo, P., Ghinassi, B., Di Baldassarre, A., Capranica, L., & Pesce, C. (2019). Autonomic Stress Response and Perceived Effort Jointly Inform on Dual Tasking in Aging. *Brain Sciences*, *9*(11), 290. https://doi.org/10.3390/brainsci9110290

Doumas, M., Rapp, M. A., & Krampe, R. Th. (2009). Working Memory and Postural Control: Adult Age Differences in Potential for Improvement, Task Priority, and Dual Tasking. *The Journals of Gerontology: Series B*, *64B*(2), 193–201. https://doi.org/10.1093/geronb/gbp009

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

Eksioglu, M., & Kızılaslan, K. (2008). Steering-wheel grip force characteristics of drivers as a function of gender, speed, and road condition. *International Journal of Industrial Ergonomics*, *38*(3), 354–361. https://doi.org/10.1016/j.ergon.2008.01.004

Guillery, E., Mouraux, A., Thonnard, J. L., & Legrain, V. (2017). Mind your grip: Even usual dexterous manipulation requires high level cognition. *Frontiers in Behavioral Neuroscience*, *11*(November), 1–11. https://doi.org/10.3389/fnbeh.2017.00220

Hess, E. H., & Polt, J. M. (1964). pupil size in relation to mental activity during simple problem-solving. *Science (New York, N.Y.)*, *143*(3611), 1190–1192. https://doi.org/10.1126/science.143.3611.1190

Jung, M., Ryu, S., Kang, M., Javadi, A.-H., & Loprinzi, P. D. (2022). Evaluation of the transient hypofrontality theory in the context of exercise: A systematic review with meta-analysis. *Quarterly Journal of Experimental Psychology (2006)*, *75*(7), 1193–1214.

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science (New York, N.Y.)*, *154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Krejtz, K., Duchowski, A. T., Niedzielska, A., Biele, C., & Krejtz, I. (2018). Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. *PloS One*, *13*(9), e0203629. https://doi.org/10.1371/journal.pone.0203629

Lim, S. B., Louie, D. R., Peters, S., Liu-Ambrose, T., Boyd, L. A., & Eng, J. J. (2021). Brain activity during real-time walking and with walking interventions after stroke: A systematic review. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 8. https://doi.org/10.1186/s12984-020-00797-w

Loughran, D. S., Seabury, S. A., & Zakaras, L. (2007). *What Risks Do Older Drivers Pose to Traffic Safety?* RAND Corporation. https://www.rand.org/pubs/research_briefs/RB9272.html

Leuchs, L., Schneider, M., Czisch, M., & Spoormaker, V. I. (2017). Neural correlates of pupil dilation during human fear learning. *NeuroImage*, *147*, 186–197. https://doi.org/10.1016/j.neuroimage.2016.11.072

Mahoney, J. R., Holtzer, R., Izzetoglu, M., Zemon, V., Verghese, J., & Allali, G. (2016). The role of prefrontal cortex during postural control in Parkinsonian syndromes a functional near-infrared spectroscopy study. *Brain Research*, *1633*, 126–138. https://doi.org/10.1016/j.brainres.2015.10.053

Miyazawa, S., & Iwasaki, S. (2009). Effect of negative emotion on visual attention: Automatic capture by fear-related stimuli. *Japanese Psychological Research*, *51*, 13–23. https://doi.org/10.1111/j.1468-5884.2009.00384.x

Nielsen, S. E., & Mather, M. (2015). Comparison of two isometric handgrip protocols on sympathetic arousal in women. *Physiology & Behavior*, *142*, 5-13. https://doi.org/10.1016/j.physbeh.2015.01.031

Ohman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology. General*, *130*(3), 466–478. https://doi.org/10.1037//0096-3445.130.3.466

Padmanabhan, P., Casamento-Moran, A., Kim, A., Gonzalez, A. J., Pantelyat, A., Roemmich, R. T., & Chib, V. S. (2023). Dopamine facilitates the translation of physical exertion into assessments of effort. *Npj Parkinson's Disease*, *9*(1), Article 1. https://doi.org/10.1038/s41531-023-00490-4

Park, H. B., Ahn, S., & Zhang, W. (2021). Visual search under physical effort is faster but more vulnerable to distractor interference. *Cognitive Research: Principles and Implications*, *6*(1). https://doi.org/10.1186/s41235-021-00283-4

Park, D. C., & Reuter-Lorenz, P. (2009). The Adaptive Brain: Aging and Neurocognitive Scaffolding. *Annual Review of Psychology*, *60*(1), 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Plummer-D'Amato, P., Altmann, L. J. P., & Reilly, K. (2011). Dual-task effects of spontaneous speech and executive function on gait in aging: Exaggerated effects in slow walkers. *Gait & Posture*, *33*(2), 233–237. https://doi.org/10.1016/j.gaitpost.2010.11.011

Plummer-D'Amato, P., Brancato, B., Dantowitz, M., Birken, S., Bonke, C., & Furey, E. (2012). Effects of Gait and Cognitive Task Difficulty on Cognitive-Motor Interference in Aging. *Journal of Aging Research*, *2012*, e583894. https://doi.org/10.1155/2012/583894

Rapp, M. A., Krampe, R. T., & Baltes, P. B. (2006). Adaptive Task Prioritization in Aging: Selective Resource Allocation to Postural Control Is Preserved in Alzheimer Disease. *The American Journal of Geriatric Psychiatry*, *14*(1), 52–61. https://doi.org/10.1097/01.JGP.0000192490.43179.e7

Richter, M. (2015). Goal pursuit and energy conservation: Energy investment increases with task demand but does not equal it. *Motivation and Emotion*, *39*, 25–33. https://doi.org/10.1007/s11031-014-9429-y

Richter, M., Mazeres, F., & Brinkmann, K. (2021). Clarity of task difficulty moderates the impact of the explicit achievement motive on physical effort in hand grip tasks. *PloS One*, *16*(6), e0252713. https://doi.org/10.1371/journal.pone.0252713

Samuel, D., Wilson, K., Martin, H. J., Allen, R., Sayer, A. A., & Stokes, M. (2012). Age-associated changes in hand grip and quadriceps muscle strength ratios in healthy adults. *Aging Clinical and Experimental Research*, *24*(3), 245–250. https://doi.org/10.1007/BF03325252

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a rational and mechanistic account of mental effort. *Annual Review of Neuroscience*, *40*, 99–124. https://doi.org/10.1146/annurev-neuro-072116-031526

Sparling, P. B., Howard, B. J., Dunstan, D. W., & Owen, N. (2015). Recommendations for physical activity in older adults. *BMJ*, *350*, h100. https://doi.org/10.1136/bmj.h100

Stanek, J. C., & Richter, M. (2021). Energy investment and motivation: The additive impact of task demand and reward value on exerted force in hand grip tasks. *Motivation and Emotion*, *45*(2), 131–145. https://doi.org/10.1007/s11031-020-09862-2

Stanek, J., & Richter, M. (2016). Evidence against the primacy of energy conservation: Exerted orce in possible and impossible handgrip tasks. *Motivation Science*, *2*, 49–65. https://doi.org/10.1037/mot0000028

Székely, M., & Michael, J. (2021). The sense of effort: A cost-benefit theory of the phenomenology of mental effort. *Review of Philosophy and Psychology*, *12*(4), 889–904. https://doi.org/10.1007/s13164-020-00512-7

Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *62*(3), 141-148. https://doi.org/10.1093/geronb/62.3.p141

Xie, W., Lu Sing, J. L., Martinez-Flores, A., & Zhang, W. (2022). Induced negative arousal modulates the speed of visual working memory consolidation. *Emotion (Washington, D.C.)*, *22*(1), 179–197. https://doi.org/10.1037/emo0001059

Xie, W., & Zhang, W. (2023). Effortfulness of Visual Working Memory: Gauged by Physical Exertion. *Journal of Experimental Psychology: General*. Advance online publication. https://doi.org/10.1037/xge0001391

Xie, W., & Zhang, W. (2016). Negative emotion boosts quality of visual working memory representation. *Emotion (Washington, D.C.)*, *16*(5), 760–774. https://doi.org/10.1037/emo0000159

Zénon, A., Sidibé, M., & Olivier, E. (2014). Pupil size variations correlate with physical effort perception. *Frontiers in Behavioral Neuroscience*, *8*. https://www.frontiersin.org/articles/10.3389/fnbeh.2014.00286