Qualification Exam Grant Proposal

Project Title: Concurrent Physical and Cognitive Effort: Effects on Memory and Perceptual Performance in Older Adults

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Project Summary

Concurrent physical and cognitive demands are ubiquitous in daily life—for example, gripping a heavy suitcase handle while remembering the orientation of airport signage arrows to locate your gate. However, healthy older adults often experience declines in both cognitive resources and arousal regulation, which may magnify performance costs under such dual-task conditions. The goal of this project is to determine how graded levels of physical effort (5% vs. 40% of maximum voluntary contraction via isometric handgrip) and cognitive effort (low vs. high stimulus similarity/discriminability) interact to influence performance across four distinct cognitive domains (working memory [CDT], long-term memory [MST], auditory discrimination [ADT], and visual discrimination [VDT]) in older adults (60–90 years). Fifty participants will complete four 75-minute sessions—one per task—in a fully counterbalanced 2×2 within-subjects design, during which continuous pupillometry will index arousal dynamics.

Aim 1 will test how concurrent physical and cognitive effort interact to affect memory accuracy and reaction time. Aim 2 will extend these analyses to perceptual domains, allowing for an examination of the *pattern* of physical–cognitive interactions across auditory and visual tasks, which will inform subsequent interpretations regarding the potential domain generality or specificity of these effort effects. Aim 3 will primarily utilize linear mixed-effects models to examine whether individual differences in cognitive reserve (estimated via the Lifetime of Experiences Questionnaire; LEQ) and arousal responsivity (indexed by task-evoked pupil dilation) moderate older adults' vulnerability to dual-task performance decrements. Guided by Resource Competition theory (shared processing limits) and the Neural Gain framework (arousal-mediated signal enhancement), this work will provide insights into how these mechanisms contribute to dual-task impairments in aging. Identifying cognitive reserve and adaptive arousal as potential protective factors will inform interventions aimed at preserving independence and safety in older populations.

Specific Aims

The overarching goal of this research is to test how concurrent physical and cognitive effort impacts memory and perceptual performance in older adults. While real-world tasks frequently involve simultaneous physical and cognitive demands (e.g., carrying a suitcase while finding your gate at the airport), these dual-task demands place significant strain on shared cognitive and physiological resources, potentially leading to performance impairments. Guided by foundational theories such as Resource Competition (RC), which posits limits on shared processing resources, and Neural Gain Theory (NGT), which addresses how arousal systems modulate neural processing efficiency, this project seeks to examine the mechanisms underlying these performance changes. *Preliminary findings from younger adults indicate minimal effects of concurrent physical and cognitive effort on memory and perceptual performance, which may be due to their ability to handle such dual-task demands, intact cognitive reserve, or optimal arousal modulation.* Critically, these effects remain unknown in older adults who often face challenges in working memory, long-term memory, and sensory discrimination as well as reduced cognitive reserve and responses to arousal. Understanding these interactions in older adults is essential for developing interventions aimed at mitigating performance declines and improving functional outcomes in aging populations. *Physical effort* refers to the exertion required to perform a physical task and is often quantified as a percentage of maximum voluntary contraction (MVC), while *cognitive effort* reflects the mental resources required to perform a task and can be manipulated by varying task difficulty, such as increasing stimulus similarity. Both types of effort place demands on limited cognitive and physiological resources, consistent with dual-task demands that arise when performing simultaneous tasks.

Previous research has provided insights into how physical and cognitive effort affects performance. Azer et al., (2023) found that higher physical effort (30% vs. 5% MVC) during concurrent working memory tasks (0 vs 5 distractors) was associated with worse performance (lower accuracy and slower reaction times) under high cognitive load in older adults, consistent with resource competition theories. **However, it remains unclear whether similar effects extend beyond working memory to long-term memory or perceptual tasks in older adults.** To address this gap, we will test the main effects of physical effort, cognitive effort, and their interaction across two memory (Aim 1: change detection [CDT] and mnemonic similarity [MST]) and two perceptual (Aim 2: auditory discrimination [ADT] and visual discrimination [VDT]) tasks.

In addition to dual-task demands, performance under concurrent physical and cognitive effort may be modulated by *cognitive reserve* and *arousal*. Cognitive reserve reflects the brain's ability to maintain function despite aging or pathology, while arousal modulation influences how physiological states affect resource allocation during demanding tasks. By examining how individual differences in cognitive reserve and arousal responsivity relate to the effects of concurrent physical and cognitive effort, this study aims to identify key moderators of dual-task performance in older adults, providing insights to inform interventions that support functional abilities in aging populations (Aim 3). These overall findings will offer novel mechanistic insights into dual-task performance under concurrent effort and help guide the development of interventions to enhance cognitive function in older adults.

Aim 1: Determine how concurrent physical and cognitive effort affects working and long-term memory performance in older adults. We will analyze performance (accuracy, reaction time) using 2 physical effort (5% vs 40% MVC) $\times$ 2 cognitive effort (low vs high stimulus similarity) ANOVAs separately for working memory (CDT) and long-term memory (MST) tasks. For working memory (**H1a**), we expect to replicate previous findings of worse performance (lower accuracy and slower reaction times) for high vs low physical effort and high vs low cognitive effort, and their interaction, where the negative effect of high physical effort on performance is largest with high cognitive effort (Azer et al., 2023). The novel aspect is testing whether these same main effects and interaction extend to long-term memory (**H1b**). Such domain-general effects would align with Resource Competition models that emphasize shared, rather than domain-specific, processing resources.

Aim 2: Test whether the effects of concurrent physical and cognitive effort extend to perceptual performance in older adults. We will analyze performance (accuracy, reaction time) using 2 physical effort (5% vs 40% MVC) $\times$ 2 cognitive effort (low vs high perceptual similarity) ANOVAs separately for visual (VDT) and auditory (ADT) discrimination tasks. For visual (**H2a**) and auditory (**H2b**) tasks, we expect main effects of physical effort, cognitive effort, and their interaction as detailed in Aim 1, which would be expected if dual task demands of concurrent physical and cognitive effort are domain general.

Aim 3: Test whether Cognitive Reserve and Arousal Responsivity moderate the impact of concurrent physical and cognitive effort on memory and perceptual performance in older adults. Building upon Aims 1 and 2, this aim examines key individual differences that may buffer against dual-task costs. We hypothesize that higher cognitive reserve (CR), estimated via the Lifetime of Experiences Questionnaire (LEQ) and reflecting resilience from lifelong enriching experiences, will attenuate the detrimental impact of concurrent physical and cognitive effort on experimental task performance (**H3a**). We further predict that more adaptive arousal modulation, indexed by pupillometry (specifically larger task-evoked pupil dilations indicative of effective phasic LC-NE responsivity), will similarly lessen these effort-induced performance decrements (**H3b**).

1 Significance

1.1 Real-World Relevance of Dual-Task Demands

Concurrent physical and cognitive demands are ubiquitous in daily life, particularly for older adults striving to maintain independence. Routine activities such as carrying groceries while mentally calculating costs, gripping medication bottles while reading instructions, or stabilizing objects during emergencies require simultaneous exertion and performance. These scenarios create challenges that older adults frequently struggle to manage effectively as cognitive and physical capacities change with age.

The public health burden of impaired dual-task performance is substantial: 37 million falls occur annually among older adults in the United States, with nearly half potentially linked to attentional lapses during combined physical-cognitive activities (CDC, 2024). Medication errors—a leading cause of emergency hospitalizations in older adults (Budnitz et al., 2011)—frequently occur during activities requiring simultaneous physical effort and decision-making, such as managing pillboxes while maintaining balance or opening child-resistant containers while reading dosage instructions. These statistics underscore the critical need to characterize how effort impacts performance under dual-task conditions in older adults.

While mobility-based paradigms (e.g., walking while talking) dominate aging research, stationary force maintenance during cognitive tasks represents an equally vital class of real-world demands. Activities like carrying objects, opening containers, or gripping assistive devices while processing information are common daily challenges faced by older adults. These stationary dual-task scenarios have received relatively less research attention despite their prevalence in everyday functioning.

These everyday dual-task demands span multiple cognitive domains: memory challenges arise when recalling medication instructions while manipulating containers; perceptual demands occur when distinguishing visual information on product labels while maintaining grip, or detecting auditory signals like alarms during physical exertion. Understanding how these different cognitive domains interact with concurrent physical demands has direct implications for preserving independence and safety in aging populations. The broader goal of the current proposal is to systematically test how concurrent physical and cognitive effort impacts memory and perceptual performance in older adults, with the ultimate aim of identifying protective factors that might mitigate age-related declines in these critical everyday functions.

Despite the clear relevance of these concurrent physical-cognitive challenges, significant gaps hinder our understanding and ability to mitigate age-related declines. **Specifically, critical barriers exist in: (1) Understanding how stationary physical effort (e.g., gripping, carrying), common in daily activities but less studied than mobility tasks, interacts with cognitive demands across different crucial domains (e.g., memory vs. perception); and (2) Resolving conflicting theoretical accounts of why these dual-task costs occur – specifically, whether they arise primarily from overall limits on processing capacity or from age-related differences in how the brain regulates attention and processing efficiency under demanding conditions.** Addressing these barriers is essential for developing a mechanistic understanding of dual-task limitations in aging.

1.2 Theoretical Models of Dual-Task Performance

1.2.1 Resource Competition Theory

Concurrent physical and cognitive tasks draw upon the brain's *finite processing resources*. This fundamental constraint often becomes more consequential with advancing age, leading to greater dual-task performance decrements. Such costs frequently manifest in both slowed reaction time and reduced accuracy across a variety of cognitive tasks (Verhaeghen et al., 2003). **Resource competition** refers to this limited capacity of the brain to efficiently allocate necessary attentional and executive resources when attempting to manage simultaneous processes or a single complex task (Wickens, 2008). Understanding the nature of these resource limitations and how they are affected by age provides a key framework for investigating dual-tasking effects in older adults.

Aging significantly impacts the efficiency of resource management, leading to increased susceptibility to performance decrements when multiple tasks or complex cognitive operations compete for limited processing capacity (Verhaeghen et al., 2003). From a Resource Competition perspective, these age-related vulnerabilities are often attributed to two primary factors: First, a prominent view is that older adults experience a reduction in the overall *processing resources* available for cognitive operations (Craik & Byrd, 1982). This can be conceptualized as a diminished pool of general-purpose attentional capacity, meaning that complex tasks or concurrent demands more readily exceed the processing limits of older adults compared to younger adults (Salthouse, 1991). Second, older adults often incur greater *resource allocation costs* when attention must be divided between multiple stimuli or tasks, or when task requirements necessitate flexible switching between different mental sets. For instance, older adults tend to exhibit larger performance costs (e.g., slower reaction times, lower accuracy) during dual-task conditions that demand divided attention (Azer et al., 2023; Voelcker-Rehage et al., 2006) and may show increased physiological effort (e.g., cardiovascular reactivity) when engaging in and switching between cognitive activities, particularly as task difficulty increases (Hess & Ennis, 2012). This reduced efficiency in managing attentional demands can be partly attributed to age-related increases in susceptibility to interference or deficits in inhibiting task-irrelevant information, which consumes valuable processing resources (Gazzaley & D'esposito, 2007; Hasher & Zacks, 1988). Collectively, a reduction in available processing capacity and less efficient allocation of attentional resources mean that older adults often operate closer to their resource limits, especially during demanding concurrent physical and cognitive tasks.

An important distinction within Resource Competition theory is whether processing resources are primarily domain-general (i.e., a common pool shared across diverse cognitive tasks; Navon & Gopher, 1979) or if multiple, *domain-specific* resource pools exist (e.g., for different sensory modalities or stages of processing; Wickens, 2008). A domain-general perspective predicts that if concurrent physical effort sufficiently depletes a central resource pool, performance impairments may be observed broadly across different cognitive tasks (working memory, long-term memory, perception). Conversely, a domain-specific view suggests that physical effort might interfere more with cognitive tasks that share specific processing resources or stages with the physical task itself, leading to differential patterns of impairment across domains (Wickens, 2008). Recognizing this distinction within Resource Competition theory is essential for interpreting how observed patterns of physical-cognitive dual-task costs in this study might reflect either generalized resource depletion or more specific interference.

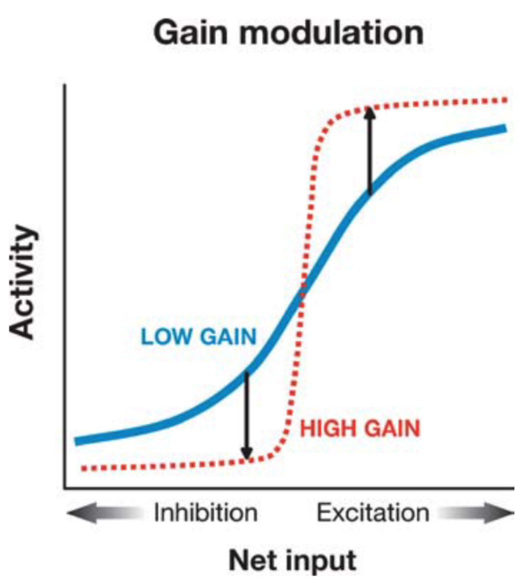

Figure 1. Adaptive Gain Theory Effect of gain modulation on nonlinear activation function. The activation (or transfer) function relates the net input of a unit to its activity state (e.g., the firing rate of a single neuron or the mean firing rate of a population). An increase in gain (dotted line) increases the activity of units receiving excitatory input (*upward arrow on right*) and decreases the activity of units receiving inhibitory input (*downward arrow on left*), thus increasing the contrast between activated and inhibited units and driving them toward more binary function. Adapted from (Servan-Schreiber et al., 1990).

In essence, Resource Competition theory posits that older adults' diminished and less efficiently allocated processing resources will render them particularly vulnerable to performance impairments when facing high concurrent physical and cognitive demands. While this framework effectively describes *what* happens under such resource-limited conditions, understanding the *dynamic modulation* of processing efficiency by arousal states and the underlying neural mechanisms necessitates considering complementary theories, such as Neural Gain Theory.

1.2.2 Neural Gain Theory

While Resource Competition theory describes performance decrements when tasks compete, Neural Gain Theory (NGT) offers a mechanistic framework for *why* the aging brain often struggles with competing demands from physical and cognitive effort. NGT posits that the locus coeruleus-norepinephrine (LC-NE) arousal system dynamically adjusts neural "gain", optimizing attention, information processing, and cognitive function (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024). The LC, a brainstem nucleus and the forebrain's principal NE source, regulates alertness, attention, arousal states, and cognitive control (Huang & Clewett, 2024; Ross & Van Bockstaele, 2021). This system's effective gain modulation enhances the signal-to-noise ratio in neural processing by amplifying task-relevant information and suppressing noise (Huang & Clewett, 2024; Joshi & Gold, 2020; Mather et al., 2016).

Neural gain modulation, detailed by models like Adaptive Gain Theory (AGT; Figure 1), alters neural ensemble sensitivity and responsiveness to inputs (Aston-Jones & Cohen, 2005). AGT notably distinguishes two modes of

LC-NE activity: slower baseline *tonic* activity (reflecting overall arousal and setting global gain) and rapid, transient *phasic* bursts (crucial for event-related processing and adaptive gain) (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024). Higher overall gain, for instance, increases contrast between strongly and weakly activated neural representations, sharpening information processing and improving target discriminability (Eldar et al., 2013). This proposal conceptualizes physical and cognitive effort as modulators of LC-NE system activity. This modulation is critical because, according to AGT, LC-NE activity dictates both the baseline (tonic) arousal state and the brain's capacity for event-related (phasic) neural responses, which together determine the effective neural gain. Optimal gain—moderate tonic arousal supporting robust phasic LC responsivity—promotes efficient cognitive processing (e.g., better accuracy, faster reaction times) (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024; McGinley et al., 2015). Conversely, suboptimal gain—whether too low (due to insufficient tonic arousal/effort, leading to poor phasic LC responsivity) or too high and dysregulated (due to excessive tonic arousal from effort/stress, which can also impair phasic responsivity and prefrontal cortex function, especially in older adults with compromised LC-NE systems)—degrades performance by inadequately distinguishing relevant signals from noise (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024; Mather & Harley, 2016).

This arousal-performance relationship typically follows an *inverted-U pattern* (Yerkes-Dodson law; Hanoch & Vitouch, 2004; Huang & Clewett, 2024; Yerkes & Dodson, 1908). Low arousal yields suboptimal performance due to insufficient neural activation, attentional engagement, and reduced phasic LC responsivity. Moderate arousal optimizes performance, as the LC-NE system effectively modulates gain to prioritize relevant information and facilitate focused task engagement (Aston-Jones & Cohen, 2005; Mather & Harley, 2016). At very high arousal, however, excessive or dysregulated neural activation often impairs performance through overwhelmed systems, increased distractibility, reduced cognitive flexibility, and impaired filtering of irrelevant stimuli (Aston-Jones & Cohen, 2005; Eldar et al., 2013; Hanoch & Vitouch, 2004; Huang & Clewett, 2024).

Aging is hypothesized to alter this inverted-U curve, often manifesting as a leftward shift or compression; this implies older adults may achieve optimal performance at lower arousal/effort levels and are more susceptible to performance decrements at higher demand levels that younger adults might find beneficial or manageable (Mather & Harley, 2016; Mikneviciute et al., 2022). This alteration in the arousal-performance relationship is thought to stem from age-related changes in the integrity and adaptability of the underlying neuromodulatory systems, such as the LC-NE system (David & Malhotra, 2022; Huang & Clewett, 2024). Indeed, older adults often respond differently to arousing conditions compared to younger adults, showing fewer cognitive benefits or even experiencing impairments (Jennings et al., 1988; Nashiro & Mather, 2010). For example, levels of emotional arousal or task-induced stress that enhance cognition in younger adults can surpass an older adult's optimal threshold, potentially impairing memory binding, increasing attentional deficits, or fostering suboptimal decision strategies (Eisdorfer, 1968; Huang & Clewett, 2024; Mather & Harley, 2016; Mikneviciute et al., 2022; Sullivan et al., 2021). These findings suggest a narrower optimal performance window in older adults, highlighting the importance of considering their age-related arousal sensitivity.

In young adults, adaptive neural gain modulation generally functions effectively; when faced with demanding conditions, their arousal systems can support the amplification of task-relevant neural activity and suppression of noise, thereby maintaining performance (Huang & Clewett, 2024). In many older adults, however, the capacity for efficient gain modulation and arousal regulation appears compromised due to age-related neurodegeneration, including at the level of key neuromodulatory nuclei like the LC (Huang & Clewett, 2024; Manaye et al., 1995; Mather & Harley, 2016; Mouton et al., 1994). This reduced efficiency is thought to impair the aging brain's ability to boost neural signals as selectively or powerfully. Consequently, older adults may experience a blunting or dysregulation of effective neural gain, which can be indexed by altered pupillary dynamics (Huang & Clewett, 2024; Van Gerven et al., 2004). Such changes can make it harder for them to filter distractions and maintain focused attention, especially under high cognitive or physiological load.

The non-linear, inverted-U arousal-performance relationship, central to NGT, offers a robust framework for predicting main effects of performance of increasing physical or cognitive effort, particularly in older adults with potentially altered arousal regulation (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024; Mather & Harley, 2016). An effort manipulation's behavioral outcome depends on an individual's operating point on this curve relative to task demands (Huang & Clewett, 2024). For instance, if baseline conditions place an older adult on the *ascending limb* (suboptimal arousal, low neural gain), moderately increased effort could enhance performance by shifting them towards optimal arousal, thereby improving neural gain modulation (Aston-Jones & Cohen, 2005; McGinley et al., 2015). Conversely, if baseline arousal is near peak, the same increased effort might induce supra-optimal arousal (*descending limb*), likely impairing performance via reduced signal selectivity or increased processing noise from an overdriven/dysregulated LC-NE system (Eldar et al., 2013; Huang & Clewett, 2024; Mather & Harley, 2016). Given that aging involves LC-NE system changes that can shift/compress the optimal arousal point (Mather & Harley, 2016; Mikneviciute et al., 2022), detrimental effort effects may emerge at lower demand levels in older versus younger adults (Hanoch & Vitouch, 2004). NGT also accommodates *null main effects* if an effort manipulation induces arousal changes confined to a flat portion of the inverted-U (e.g., at floor/ceiling performance), or if severely blunted arousal modulation capacity, as in some older adults (Van Gerven et al., 2004), prevents effective neural gain changes (Aston-Jones & Cohen, 2005).

NGT principles also allow for hypothesizing interaction effects between physical and cognitive effort, as both demand types presumably contribute to an individual's overall arousal state and position on the arousal-performance curve (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024). A detrimental synergistic interaction is a key hypothesis, especially for older adults with potentially altered arousal-performance curves (Huang & Clewett, 2024; Mikneviciute et al., 2022). Specifically, if combined high physical and cognitive effort propel arousal substantially further onto the descending limb than either high-effort dimension alone, the resultant performance decrement could be supra-additive. Such synergy would theoretically reflect gain modulation systems becoming overwhelmed or dysregulated by excessive LC-NE activity, impairing processing selectivity or efficiency (Eldar et al., 2013; Huang & Clewett, 2024; Mather et al., 2016). Alternatively, NGT's framework supports conceptualizing *crossover interactions*: physical effort might prove beneficial at low cognitive loads (optimizing arousal) but detrimental at high cognitive loads (pushing arousal into supra-optimal territory where PFC-dependent executive functions are impaired) (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024). A *null interaction*, despite significant main effects, is also conceivable within NGT if, for instance, high cognitive load already induces profound supra-optimal arousal and minimal performance, such that additional high physical effort yields no further decline as the system operates at a floor imposed by severe gain dysregulation. Similarly, profound arousal modulation failure under extreme combined demands could uniformly depress performance, obscuring distinct interactive effects (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024). Therefore, dissecting observed main and interaction effects is critical for inferring the arousal modulation system's operating range and efficiency under combined physical and cognitive challenges.

1.2.3 Interpreting Dual-Task Costs: Considering Global and Domain-Specific Influences

A key question arising from theories like NGT and RC is whether older adults' dual-task costs under combined physical and cognitive effort manifest as **domain-general impairments** (i.e., observed across diverse cognitive functions) or as more **domain-specific deficits** (disproportionately impacting certain cognitive tasks over others). Understanding this distinction is crucial for elucidating underlying bottlenecks in older adults' dual-tasking abilities (Murphy et al., 2014). This study's examination of performance across multiple cognitive domains (working memory, long-term memory, auditory perception, visual perception) provides the necessary breadth to explore this question.

Neural Gain Theory (NGT), with its emphasis on the global influence of the LC-NE arousal system, suggests that age-related blunting of neural gain could lead to widespread, relatively domain-general performance impairments under high concurrent demands, as the ability to selectively amplify neural signals might be compromised across various systems (Huang & Clewett, 2024). In contrast, while Resource Competition (RC) theory can also account for domain-general effects (e.g., if a central processing capacity is broadly exceeded), it more readily accommodates domain-specific effects if physical effort directly competes for resources crucial to particular cognitive tasks but not others (Wickens, 2008). Given these theoretical perspectives, the present study's multi-domain approach (H1a, H1b, H2a, H2b) is designed not to statistically equate or contrast effect magnitudes across these potentially disparate tasks, but rather to allow for a comprehensive characterization and subsequent holistic interpretation of the overall *pattern* of dual-task effects.

1.3 Physical Effort Effects on Cognitive Performance in Aging

1.3.1 Theoretical Basis and Mechanisms of Physical Effort

Physical effort—the exertion required to sustain muscle contraction—impacts cognitive performance differently across age groups. In experimental settings, physical effort is operationalized through **isometric handgrip exercise (IHE)**, which involves sustained muscle contraction without changing muscle length. IHE offers several advantages over aerobic or mobility-based paradigms: it allows precise control of effort levels, minimizes movement artifacts, and produces localized fatigue effects with more predictable and controllable cardiovascular responses compared to whole-body exercise (Zénon et al., 2014). Additionally, IHE reliably increases sympathetic nervous system activity through measurable changes in heart rate and blood pressure (Freyschuss, 1970; Seals et al., 2001), triggering norepinephrine release critical for arousal and attention regulation (Sara & Bouret, 2012). These physiological effects make IHE an ideal tool for studying how physical effort modulates cognition through arousal mechanisms mediated by the LC-NE system (as per Neural Gain Theory, Sec. 1.2.2). We quantify physical effort as a percentage of **maximum voluntary contraction (MVC)**, defined as the greatest force an individual can produce in a single muscle contraction. Different MVC levels are expected to place differential demands on cognitive resources (as per Resource Competition theory, Sec. 1.2.1) and arousal modulation systems.

1.3.2 Empirical Evidence and Implications for the Present Study

Physical Effort Effects in Younger Adults. Studies using IHE reveal complex, intensity-dependent effects of physical effort on cognition in younger adults. Moderate physical effort, typically ranging from 20% to 50% MVC, can *enhance* certain aspects of cognition. For example, acute interval IHE (25% MVC) has been shown to improve processing speed during an executive function task (Go/No-Go reaction time) without affecting accuracy (Washio et al., 2021). Other studies using moderate-to-high intensity IHE (30-50% MVC) found enhanced attentional performance (e.g., Stroop task accuracy) (Mather et al., 2020). Similarly, Zénon et al. (2014) observed improved reaction times during a concurrent visual discrimination task when young adults exerted moderate grip force (specifically 23-37% MVC); notably, this performance improvement correlated with proportional increases in pupil dilation up to the 37% MVC level. However, the effects are not uniformly beneficial; another study found that while visual search was faster under high physical effort (40% MVC) compared to low effort (5% MVC), this condition also led to increased vulnerability to salient distractors, suggesting impaired inhibitory control (Park et al., 2021). Furthermore, very high or exhaustive IHE (e.g., $> 70\%$ MVC) can impair working memory and reaction times, even in younger adults (Brown & Bray, 2015). Taken together, the evidence in younger adults suggests a nuanced pattern: moderate physical effort can facilitate some cognitive operations (particularly processing speed) and may reflect optimal arousal and neural gain (Neural Gain Theory, Sec. 1.2.2; Aston-Jones & Cohen, 2005), leveraging their typically ample processing capacity (Resource Competition theory, Sec. 1.2.1). Conversely, higher or exhaustive effort tends to be detrimental, potentially by pushing arousal beyond optimal levels (Neural Gain Theory) or depleting processing resources (Resource Competition theory), especially for functions like inhibitory control. The correlation between pupil dilation and performance improvements at moderate effort (Zénon et al., 2014) further supports arousal-related neuromodulation in this population.

Physical Effort Effects in Older Adults and Rationale for 40% MVC. Compared to younger adults, the cognitive impact of acute IHE in older adults appears more complex, with sparse literature showing mixed results often dependent on task type and the timing of exertion relative to cognitive assessment. Notably, increased vulnerability has been observed during *concurrent* exertion. For instance, Azer et al. (2023) found that moderate concurrent IHE (30% MVC) significantly impaired older adults' working memory accuracy, but only under high cognitive load, suggesting a detrimental effect under combined high demands. This is consistent with moderate physical effort potentially pushing older adults into supra-optimal arousal (due to age-altered inverted-U curves; Neural Gain Theory, Sec. 1.2.2; Mather & Harley, 2016; Van Gerven et al., 2004) or taxing their already diminished processing capacity (Resource Competition theory, Sec. 1.2.1; Van Gerven et al., 2004). In contrast, studies assessing cognition shortly *after* PE bouts have reported potential processing speed benefits (Bachman et al., 2023; Mather et al., 2020), possibly reflecting temporary post-exercise arousal optimization.

This highlights a critical gap concerning the effects of *concurrent* PE across diverse cognitive domains in older adults, which the present proposal aims to address. Understanding the conditions leading to costs versus benefits requires systematic investigation of interaction effects (Aims 1 & 2) and individual differences (Aim 3). Based on prior work indicating cognitive effects of IHE emerge between 20-40% MVC in younger adults (Park et al., 2021; Zénon et al., 2014) and detrimental concurrent effects in older adults around 30% MVC (Azer et al., 2023), this study will contrast a minimal (5% MVC) with a moderately high (40% MVC) physical effort level. While 30% MVC has shown impairments (Azer et al., 2023), our selection of 40% MVC is specifically driven by the theoretical goal of robustly testing Neural Gain Theory predictions regarding performance on the descending limb of older adults' potentially altered arousal-performance curve. This higher level is chosen to ensure a sufficient physiological challenge to observe such NGT-predicted supra-optimal arousal effects and performance declines across diverse tasks and individual capacities, and to simultaneously probe significant resource depletion (Resource Competition theory), while still allowing for comparison with existing findings.

1.4 Cognitive Effort Across Memory and Perceptual Domains: Resource and Neuromodulatory Demands

1.4.1 Defining Cognitive Effort in Experimental Contexts

Cognitive effort refers to the mental exertion required to perform a task. In experimental research relevant to this proposal, cognitive effort is typically operationalized by systematically adjusting task difficulty, for example, by increasing stimulus similarity or memory load. Such manipulations intensify demands on specific cognitive processes like perceptual discrimination, working memory maintenance, or memory retrieval. As Westbrook and Braver (2015) highlight, the cognitive effort elicited by a given task reflects not only its objective demands (e.g., similarity level) but also the engagement of cognitive control processes required to meet those demands, which can vary based on factors like individual capabilities and motivation. Importantly, the impact of increasing cognitive effort on task performance often differs across cognitive domains and age groups, likely reflecting differential demands on underlying processing systems. The following sections review empirical evidence regarding these effects in memory and perceptual domains, considering age differences.

1.4.2 Empirical Evidence: Cognitive Load Effects

Memory Domain Findings: Research examining cognitive load effects on memory reveals significant age differences, highlighting the suitability of the memory tasks selected in Aim 1 for studying effort effects in older adults. *In working memory (WM)*, cognitive load is often manipulated experimentally by increasing the number of items to be maintained (set size) or by requiring participants to ignore distraction during maintenance. While younger adults typically maintain good WM performance even as load increases, showing only modest accuracy decreases at the highest loads, older adults often exhibit greater performance decrements (Gazzaley et al., 2005; Van Gerven et al., 2004). Specifically, studies using increasing memory set sizes have found that older adults show more pronounced reaction time delays and steeper declines in accuracy compared to younger adults (Van Gerven et al., 2004), reflecting potential reductions in effective WM capacity or processing efficiency. Similarly, older adults demonstrate greater difficulty suppressing task-irrelevant distractors during WM tasks (Gazzaley et al., 2005). This body of evidence justifies the use of tasks like the **Change Detection Task (CDT)**, where manipulating set size directly probes WM capacity limits known to be particularly taxed in older adults. *In long-term memory (LTM)*, particularly tasks requiring fine-grained discrimination between memories, cognitive difficulty is often manipulated via the perceptual similarity between previously studied items and novel test items (lures). Seminal work using such paradigms, often termed the **Mnemonic Similarity Task (MST)**, consistently finds that while younger adults maintain high accuracy in discriminating highly similar lures from repeated items ('pattern separation'), older adults exhibit specific and substantial deficits, often misidentifying lures as repetitions (Stark et al., 2013; Yassa et al., 2011). This age-related impairment in pattern separation is linked to functional changes in hippocampal circuits (Yassa et al., 2011). Therefore, employing the MST allows for assessment of LTM discrimination processes that are notably challenged by mnemonic similarity in older adults.

Perceptual Domain Findings: Cognitive load manipulations in perceptual tasks also reveal age-related differences, informing our selection of tasks for Aim 2 suitable for assessing effort's impact on perceptual processing in older adults. *In the auditory domain,* increasing processing difficulty, for example by presenting speech in noisy environments (i.e., reducing the signal-to-noise ratio), significantly impacts performance, particularly in older adults. Studies consistently show that older adults experience greater difficulty understanding speech in noise compared to younger adults, and these deficits are often linked to age-related declines in precise neural timing or synchronization crucial for parsing complex auditory scenes (Anderson & Kraus, 2010; Anderson et al., 2012). Such findings support the use of an **Auditory Discrimination Task (ADT)**, where difficulty can be systematically varied (e.g., by manipulating acoustic similarity of tones), to examine how auditory processing in older adults is affected by increasing cognitive demands. *In the visual domain,* increasing task difficulty (e.g., by reducing stimulus contrast, duration, or by increasing stimulus similarity or visual crowding) can also unmask age-related performance differences. While younger adults may maintain high accuracy across a range of visual discrimination challenges, older adults often exhibit performance declines. For instance, age-related declines in fundamental visual capacities like contrast sensitivity are well-documented (Owsley, 2003, 2016.) Although direct evidence linking cognitive load manipulations to contrast sensitivity changes is less common, it is understood that tasks requiring fine visual discriminations under challenging conditions (e.g., low contrast, brief exposure) will disproportionately affect older adults due to vulnerabilities in specific visual pathways, such as the magnocellular stream (Power et al., 2021; Zhuang et al., 2021). Therefore, employing a **Visual Discrimination Task (VDT)**, where difficulty is varied (e.g., by altering stimulus similarity, duration, or adding visual noise/masking), is crucial for assessing visual processing under cognitive challenge known to be demanding for older adults. This review indicates that increasing cognitive load often reveals distinct performance patterns in older adults, who typically show greater vulnerability to such demands compared to younger adults. These domain-specific sensitivities to cognitive demand set the stage for understanding how such effects might be further modulated by the concurrent imposition of physical effort, which we will explore next.

Based on this consistent evidence of older adults' heightened susceptibility to increased cognitive load across both memory and perceptual domains, the present study hypothesizes that high cognitive effort (i.e., high stimulus similarity) will lead to significantly reduced accuracy and slower reaction times compared to low cognitive effort conditions in all four experimental tasks: the Change Detection Task (H1a), the Mnemonic Similarity Task (H1b), the Visual Discrimination Task (H2a), and the Auditory Discrimination Task (H2b). Establishing these baseline cognitive effort effects is crucial before examining their interaction with physical effort.

1.5 Physical-Cognitive Effort Interactions in Aging: Testing Theoretical Models

Understanding the *interaction* between physical and cognitive effort is crucial. Does the combined effect of these demands simply add up, or does it amplify to disproportionately affect performance? The pattern of interaction observed provides critical clues about underlying mechanisms, framed by Resource Competition and Neural Gain theories.

1.5.1 Empirical Evidence for Physical-Cognitive Interaction Effects

Prior research investigating how concurrent physical and cognitive demands interact to affect performance has yielded important insights, though direct examination across multiple cognitive domains in older adults remains limited. *In younger adults,* studies have sometimes shown a capacity to manage moderate combined loads. For example, Zénon et al. (2014) found that moderate physical effort (23-37% MVC) *improved* reaction times on a concurrent visual discrimination task, an effect correlated with pupil dilation, suggesting optimized arousal. However, their study did not systematically vary cognitive load to test for a statistical interaction, nor did it include older adults.

In older adults, the picture is more complex and often points to increased vulnerability under combined demands. Azer et al. (2023) directly investigated the interaction between isometric handgrip effort (5% vs. 30% MVC) and cognitive load (in a visual working memory task) in both younger and older adults. They found a significant physical × cognitive effort interaction for working memory accuracy specifically in the older adult group: the 30% MVC physical effort impaired accuracy only when combined with high cognitive load. Younger adults did not show this detrimental synergistic interaction. Other research highlights the importance of task timing; for instance, Bachman et al. (2023) found that IHE performed *prior to* (not concurrently with) a working memory task speeded subsequent reaction times in older adults, suggesting beneficial carry-over effects rather than detrimental concurrent interactions in that paradigm.

The existing literature thus indicates that older adults may be particularly susceptible to detrimental interactions when physical and cognitive effort are concurrent and demanding, especially in working memory (Azer et al., 2023). However, there is a scarcity of studies systematically comparing such interaction effects across diverse cognitive domains (e.g., working memory, long-term memory, auditory perception, visual perception) using identical concurrent load manipulations within the same older adult sample. This gap limits our understanding of whether interaction effects are domain-general (affecting all tasks similarly) or domain-specific. The present study, by employing a consistent 2 (physical effort) × 2 (cognitive effort) design across four distinct cognitive domains, directly addresses this gap.

1.5.2 Theoretical Implications of Interaction Patterns

The pattern of interaction observed between physical and cognitive effort provides critical clues for understanding the underlying mechanisms of dual-task costs in older adults, particularly in relation to Resource Competition and Neural Gain theories.

We distinguish between two primary patterns. **Additive effects**, where physical and cognitive effort influence performance independently (no statistical interaction), would suggest that combined demands linearly consume available processing resources up to a fixed capacity limit, consistent with RC models. In contrast, **interactive effects**, where the effect of one factor depends on the level of the other (a significant interaction term), are also anticipated. Detrimental synergistic interactions (performance deteriorating more than the sum of individual main effects) are particularly relevant for older adults under high combined load. Such interactions could reflect NGT mechanisms malfunctioning when the system is overwhelmed (e.g., excessive arousal impairing processing selectivity; Mather & Harley, 2016), especially given potential age-related declines in LC-NE function.

The pervasiveness of these interaction patterns across the memory and perceptual domains examined in Aims 1 and 2 is theoretically informative. Widespread, similar interactions (or additive effects consistent across domains) might suggest global limiting factors, such as central resource depletion (RC) or systemic neuromodulatory failure (NGT). Conversely, interactions that are clearly evident and consistently directional in some domains but weak, absent, or operating differently in others, would point to mechanisms more specific to the affected domains. These could include competition for specialized processing resources (a facet of RC) or non-uniform impacts of arousal dysregulation across distinct cognitive systems (compatible with NGT). Furthermore, NGT specifically posits individual differences in LC-NE integrity and arousal modulation, predicting that variability in interaction effects might correlate with physiological indices of arousal (a focus of Aim 3). Thus, examining the overall pattern of interactions offers a pathway to potentially disentangle the contributions of these underlying mechanisms.

1.6 Cognitive Reserve: Buffering Against Dual-Task Costs in Aging

1.6.1 The Construct and Operationalization of Cognitive Reserve

Cognitive reserve (CR) refers to the brain's capacity to optimize or maintain cognitive performance despite age-related neural changes or neuropathology (Stern, 2009). It is conceptualized not merely as a passive store of neural resources (i.e., brain reserve), but as an active process reflecting the efficiency and flexibility with which brain networks are utilized or reorganized to cope with disruption (Stern, 2009; Valenzuela & Sachdev, 2006). CR is thought to develop through intellectually enriching lifetime experiences, such as formal education, occupational complexity, and engagement in cognitive and social leisure activities, which may foster more efficient neural processing or compensatory strategies (Fratiglioni et al., 2004; Pettigrew & Soldan, 2019; Scarmeas & Stern, 2003; Stern, 2009).

As a latent construct, CR cannot be measured directly; consequently, research relies on various operationalizations, with no single "gold standard" yet established (Nogueira et al., 2022; Wei et al., 2024). A primary approach uses *sociobehavioral proxies* capturing lifetime intellectual enrichment, including formal education, occupational complexity, and cognitively stimulating leisure activities (Scarmeas & Stern, 2003; Stern, 2009). To synthesize these varied experiences, validated questionnaires have been developed. For studies focusing on older adults and the cumulative impact of life experiences, the **Lifetime of Experiences Questionnaire (LEQ)** (Valenzuela & Sachdev, 2007) is a particularly strong instrument. Its detailed assessment of complex mental activities across young adulthood, mid-life, and late life allows for a comprehensive estimation of lifelong cognitive enrichment, which is foundational to CR. This lifespan approach, coupled with the LEQ's documented associations with preserved executive function and memory in aging populations (Karsazi et al., 2022; Nogueira et al., 2022), makes it well-suited for investigating how such accumulated reserve may buffer against dual-task costs in the present study. While other instruments like the Cognitive Reserve Index questionnaire (CRIq) (Kartschmit et al., 2019; Nucci et al., 2012) offer greater brevity, the LEQ's depth in capturing lifespan engagement aligns strongly with the aims of understanding CR's role in older adults. Additionally, estimates of premorbid intelligence (e.g., via the National Adult Reading Test; NART, Nelson & Willison, 1991; Olaithe et al., 2020; van der Linde & Bright, 2024) can supplement CR estimation. In this study, consistent with established research practices emphasizing comprehensive life-course assessment for CR in older adults (Nogueira et al., 2022; Valenzuela & Sachdev, 2007), CR will be primarily estimated using a composite score derived from the LEQ. This proxy-based approach yields an estimate of CR reflecting accumulated resilience from lifelong experiences. CR, as estimated by LEQ, is hypothesized to moderate performance on our *experimental dual-task measures* (accuracy and RT on the CDT, MST, ADT, and VDT) as outlined in Aim 3.

1.6.2 Theoretical Mechanisms of Cognitive Reserve's Protective Effects

Higher CR consistently predicts better maintenance of cognitive function in aging and a reduced risk or delayed onset of dementia, particularly by buffering against performance decrements during demanding dual-task conditions (Lojo-Seoane et al., 2014; Stern, 2009). The mechanisms through which CR (as estimated by the LEQ) might confer this resilience are thought to involve both enhanced processing efficiency (aligning with Resource Competition theory) and greater neural adaptability (aligning with Neural Gain Theory).

From a Resource Competition (RC) perspective, higher LEQ scores, reflecting greater lifelong cognitive engagement, are associated with more effective or efficient use of limited processing resources (Barulli & Stern, 2013; Stern, 2009). Specifically, higher CR (often indexed by proxies like education or occupational complexity, key components of the LEQ) has been linked to greater effective working memory capacity—a core processing resource—which in turn helps mediate CR's protective effects (Sandry et al., 2015). For instance, higher occupational complexity predicts preserved working memory and processing speed in older adults, potentially by fostering sustained attentional allocation and enhancing baseline resource capacity (Smart et al., 2014). Furthermore, individuals with higher CR demonstrate improved strategic resource deployment under competing demands, resulting in smaller dual-task costs (Piche et al., 2024), and exhibit more efficient task prioritization, partly through enhanced executive functions like cognitive flexibility and interference management (Contemori et al., 2024). Such enhanced resource management capabilities could enable individuals to better cope with the combined load of physical and cognitive effort before performance declines.

Beyond these cognitive-level resource advantages, a compelling hypothesis, particularly relevant to Neural Gain Theory (NGT), is that higher CR (estimated via LEQ) is associated with, or contributes to, a more robust, efficient, or adaptable LC-NE system. This hypothesized link is supported by converging evidence suggesting that CR proxies correlate with markers of preserved LC structural integrity and more optimized LC-NE function in older adults (as indicated by studies using, for example, neuromelanin-sensitive MRI or fMRI, though these specific imaging techniques are not part of the current proposal; Clewett et al., 2016; Dahl et al., 2019; Plini et al., 2021; Vockert et al., 2024; Wilson et al., 2013). Furthermore, the proposition that lifelong cognitive stimulation, integral to building CR, enhances LC-mediated neuroprotective and adaptive neural processing capacities is well-supported (Arenaza-Urquijo et al., 2015; Robertson, 2013). A healthier and more adaptable LC-NE system in high-CR individuals could thus manifest as the ability to maintain more optimal arousal modulation and sustain effective neural gain for task-relevant processing, even when challenged by combined stressors, thereby preserving cognitive performance. The integrity and adaptability of such arousal modulation, indexed by pupillometry, will be examined as a direct moderator of dual-task performance in H3b of Aim 3; understanding its potential relationship with CR (which will be explored correlationally as part of Aim 3's exploratory analyses) may offer insights into the NGT-related mechanisms of cognitive reserve. These interpretations, linking CR to both enhanced resource management (RC) and more efficient neuromodulation (NGT), strongly suggest CR could bolster resilience against high-effort dual-task costs, setting the stage for the specific hypotheses regarding its moderating role.

1.6.3 Cognitive Reserve as a Moderator: Hypotheses for Aim 3

These theoretical considerations—CR enhancing resource management (aligning with RC) and potentially bolstering LC-NE adaptability (aligning with NGT, as explored via pupillometry in Aim 3)—directly inform hypotheses for Aim 3 (e.g., H3a). H3a posits that higher CR (estimated via the LEQ) will buffer older adults against performance declines on the study's experimental tasks (CDT, MST, ADT, VDT) under concurrent physical-cognitive effort. Specifically, individuals with higher LEQ scores are expected to show smaller detrimental effects (i.e., smaller accuracy losses and/or reaction time costs) on these experimental tasks when concurrently managing high physical and cognitive efforts. Mechanistically, and aligning with NGT, higher CR may reflect or foster enhanced LC-NE system flexibility and efficiency. This could allow older adults with greater reserve to maintain more optimal neural gain and effectively modulate arousal even under high combined load, thereby preserving performance within their (potentially narrowed) arousal-performance window (Huang & Clewett, 2024). This will be partly explored via pupillometry in Aim 3, examining if LEQ scores relate to more adaptive arousal responses (e.g., more robust task-evoked pupil responses indicative of effective phasic LC engagement, or baseline pupil measures reflecting optimal tonic arousal) under varying effort conditions. By clarifying how CR moderates effort effects, this work identifies potential avenues for interventions aimed at preserving independence in aging populations.

1.7 Arousal Dynamics and LC-NE Responsivity: Tracking Neural Gain in Real-Time

Arousal, the brain's state of heightened neural readiness, is pivotal in modulating cognitive performance under concurrent physical and cognitive demands. Through the locus coeruleus-norepinephrine (LC-NE) system, arousal influences both resource allocation (Resource Competition) and signal enhancement (Neural Gain) mechanisms, operating via the distinct tonic and phasic activity modes previously introduced under Neural Gain Theory. Pupillometry, the measurement of changes in pupil diameter, provides a non-invasive biomarker of these modes—baseline pupil size correlates with tonic LC-NE activity, while task-evoked pupil dilation reflects phasic norepinephrine release during effortful processing (Aston-Jones & Cohen, 2005; Huang & Clewett, 2024; Joshi & Gold, 2020). These pupillary metrics offer a real-time window into arousal dynamics, revealing how neural resources are mobilized and modulated during challenging dual-task performance.

1.7.1 Pupillometry as a Proxy for Arousal Modulation and Neural Gain

Pupil diameter tracks LC-NE dynamics with millisecond precision, providing detailed insights into neural gain—a mechanism that enhances signal-to-noise ratios in task-critical circuits (Aston-Jones & Cohen, 2005). Dilation peaks align with LC-NE-mediated enhancement of task-relevant signals and suppression of distractors (Gilzenrat et al., 2010), allowing researchers to observe neural gain in action. During working memory tasks, phasic dilation correlates with reduced distractor interference (Unsworth & Robison, 2017), while in perceptual tasks, steeper dilation slopes predict faster reaction times (Sörensen et al., 2022). Although aging reduces baseline pupil diameter due to senile miosis (age-related pupil shrinkage), task-evoked dilation normalized to baseline remains a reliable index of LC-NE engagement in older adults (Van Gerven et al., 2004). These measures allow researchers to quantify both resource allocation efficiency and neural signal modulation during cognitive processing across age groups.

1.7.2 Linking Pupillary Responses to Performance: Evidence for Neural Gain Effects

Empirical studies demonstrate that pupillary metrics predict dual-task outcomes in ways that illuminate both theoretical frameworks. In younger adults, larger phasic dilations during high physical effort correlate with stable working memory accuracy, while smaller responses precede lapses in inhibitory control (Zénon et al., 2014). Older adults show more variable patterns: those with preserved dilation slopes maintain performance stability across cognitive domains, whereas flattened responses predict accelerated accuracy losses (Van Gerven et al., 2004). These individual differences align with the *adaptive gain theory*, which posits that optimal LC-NE engagement maximizes neural resource allocation during effortful processing. Crucially, pupillometry disentangles central arousal mechanisms from peripheral motor effects—older adults with equivalent grip force but stronger dilation responses show smaller accuracy declines in visual discrimination tasks compared to peers with weaker pupillary modulation. This approach helps determine whether cognitive effort costs stem from domain-general resource depletion or domain-specific processing limitations.

1.7.3 Basis for H3b Predictions: Arousal as a Modulator of Effort Effects

These findings directly inform H3b, which posits that stronger phasic arousal responses (larger task-evoked pupil dilations) will buffer against performance declines under concurrent physical-cognitive effort. Mechanistically, this hypothesis builds on evidence that preserved LC-NE dynamic range enables older adults to (1) **Amplify task-relevant signals**: Sharper dilation slopes during high-effort trials correlate with enhanced hippocampal pattern separation and occipital contrast sensitivity (Clewett et al., 2018) and (2) **Suppress cortical noise**: Steeper pupillary responses predict reduced frontoparietal conflict during dual-task coordination, minimizing interference (Alnæs et al., 2014).

By contrast, blunted dilation—a hallmark of LC-NE depletion—leaves older adults vulnerable to both resource competition and impaired signal modulation, manifesting as uniform accuracy losses across domains. Pupillometry thus provides critical insights into whether individual differences in arousal capacity explain variability in dual-task resilience, bridging Resource Competition and Neural Gain perspectives to identify potential targets for interventions aimed at optimizing cognitive function in aging.

Impact Statement. Successfully achieving the aims of this proposal will yield significant advancements. By systematically examining concurrent stationary physical effort and cognitive load across memory and perceptual domains, this research will: (1) Provide critical evidence to differentiate between Resource Competition and Neural Gain theories, clarifying whether age-related dual-task impairments stem primarily from global processing limits/neuromodulatory decline or from domain-specific interference; (2) Characterize the specific patterns and conditions (effort levels, cognitive loads, cognitive domains) under which combined physical-cognitive demands most significantly impair performance in older adults; and (3) Identify key individual factors (cognitive reserve, arousal system responsivity) that buffer against these dual-task costs. Ultimately, this knowledge will advance fundamental models of cognitive aging and provide a crucial neuroscientific basis for developing targeted assessments and interventions aimed at preserving functional independence, safety, and quality of life in aging populations.

2 Innovation

1. **Comprehensive Mapping of Physical-Cognitive Effort Interactions Across Domains:** This study introduces a unified protocol to systematically investigate physical-cognitive effort interactions across four distinct cognitive domains (working memory, long-term memory, auditory perception, visual perception) in older adults. Unlike prior work often focused on isolated tasks or single effort dimensions, this design allows for a comprehensive characterization of the *pattern* of dual-task costs. By standardizing effort levels (5% vs. 40% MVC) and cognitive load parameters, we aim to provide clearer insights into whether age-related dual-task costs manifest more as domain-general phenomena (potentially reflecting shared LC-NE limits or central resource depletion) or as domain-specific vulnerabilities (suggesting localized neural bottlenecks or resource conflicts), a distinction critical for understanding the underlying mechanisms and informing targeted interventions.
2. **Probing Effort Thresholds in Older Adults Using Theoretically-Grounded Levels:** We employ specific isometric handgrip levels (5% vs. 40% MVC), chosen to probe predicted age-related limits on performance as conceptualized by both Resource Competition and Neural Gain frameworks. By relating performance under these ecologically relevant effort loads to individual differences in cognitive reserve (estimated via LEQ) and pupillometry-indexed arousal, this study tests mechanistic models of older adults' vulnerability to dual-task costs.
3. **Advancing Mechanistic Understanding via Pupillometry-Indexed Arousal Dynamics:** This study integrates pupillometry with dual-task protocols, moving beyond behavioral metrics to assess central arousal dynamics linked to LC-NE function and neural gain. Task-evoked and baseline pupil measures will offer real-time indices of arousal regulation and LC-NE engagement during concurrent demands, providing insights into central processing largely independent of overt motor execution. This approach allows for the identification of individual differences in neural gain adaptability, which may serve as a valuable biomarker for understanding vulnerability to dual-task costs and could inform future personalized interventions.
4. **Testing Cognitive Reserve as a Modifiable Protective Factor:** By employing the Lifetime of Experiences Questionnaire (LEQ) to estimate cognitive reserve, this study investigates how accumulated lifelong intellectual and experiential enrichment moderates dual-task performance in older adults. We test the hypothesis that higher CR buffers against the detrimental effects of concurrent physical and cognitive effort on memory and executive functions. Understanding this protective role of CR, potentially mediated by enhanced resource management or more adaptable neuromodulatory systems (e.g., LC-NE function), provides a foundation for developing interventions (such as promoting cognitively engaging lifestyles) aimed at bolstering resilience and preserving cognitive health in aging.

3 Approach

3.1 Participants

Fifty healthy older adults will be recruited for this study. Power and sample size justifications are detailed in Section 3.8.

3.1.1 Inclusion & Exclusion Criteria

To be eligible for participation, individuals must be healthy older adults aged 60–90 years. Inclusion further requires fluency in English, right-handedness, normal or corrected-to-normal vision (20/40 or better via ETDRS chart; Group et al., 1991) and hearing (defined as a threshold of 40 dB or better at 1 kHz; Association et al., 2005), and a score greater than 17 (Lai et al., 2022) on the telephone Montreal Cognitive Assessment (T-MoCA; the 22-point validated by Pendlebury et al., 2013). All participants must self-report the absence of major health conditions (e.g., stroke, current dementia diagnosis, diabetes requiring insulin) and be willing to complete all behavioral testing sessions and provide informed consent.

Individuals will be excluded if they report a history of significant neurological disorders (e.g., dementia, multiple sclerosis, traumatic brain injury), current or recent (past two years) psychiatric diagnoses (e.g., schizophrenia, bipolar disorder) or substance use disorders, or current use of psychotropic medications known to significantly affect cognition (e.g., antidepressants with strong sedative or anticholinergic effects, benzodiazepines). Additional exclusion criteria include conditions that would likely impair task performance, such as severe arthritis affecting handgrip, uncontrolled hypertension, or thyroid disease, as well as pregnancy or current institutionalized status.

3.1.2 Baseline Cognitive Characterization

To provide a comprehensive characterization of the enrolled sample's baseline cognitive functioning, all participants who meet the inclusion criteria will also complete standardized neuropsychological tests during an initial baseline session. These data will primarily serve for sample description and will be considered as potential covariates or for exploratory analyses in Aim 3 (see Section 3.7).

3.1.3 Recruitment

Participants will be recruited from Riverside and San Bernardino counties, aiming for a broad variability in socioeconomic status (SES) and ethnic diversity. Recruitment methods will include neighborhood fliers, bulletin boards, and telephone mailers.

3.2 Overall Experimental Design and Procedure

Participants will attend a total of four sessions. The initial session will commence with baseline procedures, including obtaining informed consent, administration of questionnaires (e.g., LEQ), neuropsychological characterization, and the initial Maximum Voluntary Contraction (MVC) measurement for the isometric handgrip task (detailed in Section 3.3.1). Following these baseline activities, the first of the four experimental cognitive tasks will be administered.

The subsequent three sessions, along with the experimental portion of the first session, will each be dedicated to one of these four distinct cognitive tasks. Each of these four task-focused sessions is expected to last approximately 75 minutes and will include task-specific instructions, practice trials, and the main experimental blocks. To minimize carryover and fatigue effects, the order of the four cognitive tasks across these sessions will be counterbalanced using a modified Williams design (Bate & Jones, 2008; Wang et al., 2009; Williams, 1949), which also alternates between memory (CDT, MST) and perceptual (ADT, VDT) task domains (see Figure 2).

Subject #	Actual	sequence			Session			
					1	2	3	4
1	A	B	C	D	ADT	CDT	VDT	MST
2	B	D	A	C	CDT	MST	ADT	VDT
3	C	A	D	B	VDT	ADT	MST	CDT
4	D	C	B	A	MST	VDT	CDT	ADT

Figure 2. Example of a Williams design used to counterbalance task order across participants. Each row represents a unique sequence of task sessions (ADT, VDT, CDT, MST), ensuring balanced exposure to tasks across sessions while controlling for practice and fatigue effects.

The experimental sessions will adhere to a core dual-task protocol that systematically combines concurrent physical effort and cognitive effort manipulations, with continuous pupillometry used to track arousal dynamics throughout. The specific details of these manipulations and the task battery are described in Section 3.3 (Protocols were previously validated in young adults (N=38, SYP) and adapted for older adults, for instance, by adjusting trial numbers where appropriate to minimize fatigue and ensure task feasibility).

3.3 Experimental Manipulations and Task Battery

This section details the experimental manipulations of physical effort and cognitive effort applied across the tasks, followed by descriptions of the four cognitive tasks that constitute the experimental battery. All tasks employ a dual-task design requiring concurrent physical and cognitive exertion.

3.3.1 Physical Effort Manipulation

Physical effort will be operationalized using isometric handgrip exercise (IHE). Participants will exert a specific level of isometric muscle contraction—either 5% MVC (*low physical effort*) or 40% MVC *(high physical effort)*—on a hand dynamometer (Vernier Software & Technology, Beaverton, OR), proportional to their individual Maximum Voluntary Contraction (MVC). MVC will be measured at the start of the baseline session by taking the average of three maximal contractions, and will be briefly re-assessed at the beginning of each experimental session to confirm stability and adjust target forces if necessary.

For each trial requiring physical effort, participants will perform the handgrip at the target percentage of their MVC for 4.45 seconds prior to the cognitive stimulus, guided by immediate visual feedback of their exerted force. They will then be cued to maintain this force level throughout the cognitive component of the trial without ongoing visual feedback of their force.

3.3.2 Cognitive Effort Manipulation

Across all tasks, cognitive effort (CE) will be manipulated by systematically varying stimulus similarity to create a *low cognitive effort* and a *high cognitive effort* condition. High similarity conditions are designed to increase objective task difficulty by placing greater demands on specific cognitive processes (e.g., perceptual discrimination, working memory maintenance, or memory retrieval) and challenging the efficiency of neural gain modulation, compared to low similarity conditions. The precise operationalization of low and high cognitive effort via stimulus similarity parameters is specific to each task and detailed below.

3.3.3 Cognitive Task Battery

Participants will typically respond using a standard button box (e.g., "Same"/"Different" for CDT/ADT/VDT and "New"/"Similar"/"Old" for MST). Common trial structures (e.g., cueing, stimulus presentation, response window) are used where appropriate, with specifics provided for each task. The following four tasks will be administered:

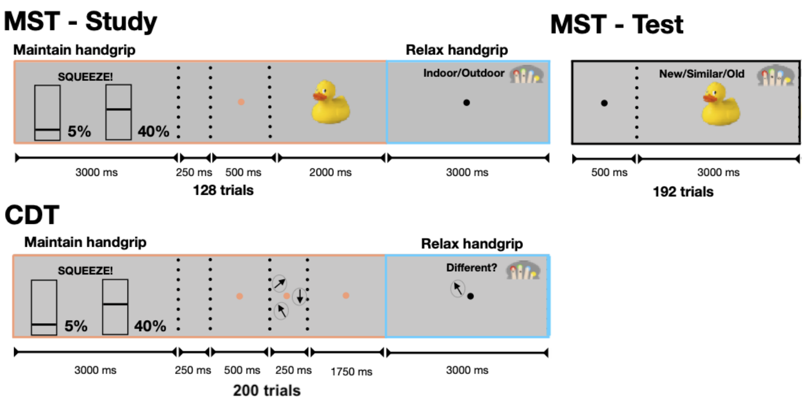

Figure 3. The overall schematics of visual working memory and long-term memory tasks for Aim 1. The MST consists of two phases: a study phase where participants classify objects as indoor or outdoor while maintaining handgrip at 5% or 40% MVC, followed by a test phase where they categorize images as ‘New’, ‘Similar’, or ‘Old’. The CDT involves memorizing the orientation of three arrows under 5% or 40% MVC handgrip conditions and determining whether a probe arrow has changed direction. While the MST assesses long-term memory through object similarity judgments, the CDT evaluates working memory through spatial orientation changes.

Visual Working Memory: Change Detection Task (CDT) The CDT assesses short-term visual working memory using oriented arrows (Cappiello et al., 2018). During each trial, while maintaining the specified handgrip force (5% or 40% MVC), participants memorize a study array of three black arrows (0.5° width, 2° length, grey background) presented for 250ms. After a 1750ms delay, a single probe arrow appears. Participants indicate via button press whether this probe arrow matches its original orientation or has changed direction (rotated 5°, 20°, 45°, or 90° clockwise/counterclockwise; see Figure 3 bottom). Cognitive effort is manipulated by rotation angle: smaller rotations (5°, 20°) constitute high cognitive effort, demanding greater mnemonic precision, while larger rotations (45°, 90°) constitute low cognitive effort. Each of the 2 (physical effort) × 4 (rotation angle) conditions will be presented equally across 200 trials.

Visual Long-Term Memory: Mnemonic Similarity Task (MST) The MST evaluates object discrimination in long-term memory across study and test phases (Kirwan & Stark, 2007; Stark et al., 2019; Yassa et al., 2011). *Study Phase (128 trials):* While maintaining handgrip (5% or 40% MVC, initiated 3s prior to stimulus and held throughout), participants classify objects (from answer set C, publicly available at https://github.com/celstark/MST) as "indoor" or "outdoor" (2000ms presentation). *Test Phase (192 trials, no concurrent handgrip):* Participants categorize images as "Old" (identical to studied objects, 64 trials), "Similar" (lures visually similar to studied objects, varying across four similarity levels, 64 trials), or "New" (novel foils, 64 trials) using a three-button response box (see Figure 3 top). Cognitive effort during encoding (study phase) is manipulated by the handgrip, while cognitive effort during retrieval (test phase) is manipulated by lure similarity: distinguishing highly similar lures (Levels 1-2) represents high cognitive effort, demanding greater hippocampal pattern separation, compared to less similar lures (Levels 3-4; low cognitive effort).

Auditory Perception: Auditory Discrimination Task (ADT) Adapted from established paradigms (Murphy et al., 2011; Näätänen, 1990), the ADT investigates auditory frequency discrimination under concurrent physical effort. While maintaining handgrip (5% or 40% MVC, initiated 3.75s prior and sustained), participants experience a two-interval forced-choice paradigm (Figure 4 top). A standard tone (1000 Hz, 100ms) is followed by a target tone (100ms) differing in frequency by +4, +8, +32, or +128 Hz, separated by a 700ms ISI. Participants indicate if the target differs from the standard. Cognitive effort is manipulated by frequency offset: smaller offsets (+4/+8 Hz) represent high cognitive effort, requiring higher perceptual precision, while larger offsets (+32/+128 Hz) represent low cognitive effort. Each of the 2 (physical effort) × 4 (frequency offset) conditions will appear equally across 200 trials.

Visual Perception: Visual Discrimination Task (VDT) The VDT employs a paradigm similar to the ADT, using visual Gabor patches (6 cycles/degree, 4° diameter, 100ms duration; Figure 4 bottom). While maintaining handgrip, two Gabors are presented sequentially. The standard stimulus has 0.5 contrast; the target's contrast is offset by +0.04, +0.08, +0.16, or +0.32. Procedures mirror the ADT. Cognitive effort is manipulated by contrast offset: smaller offsets (0.04, 0.08) represent high cognitive effort, demanding greater visual discrimination precision, while larger offsets (0.16, 0.32) represent low cognitive effort.

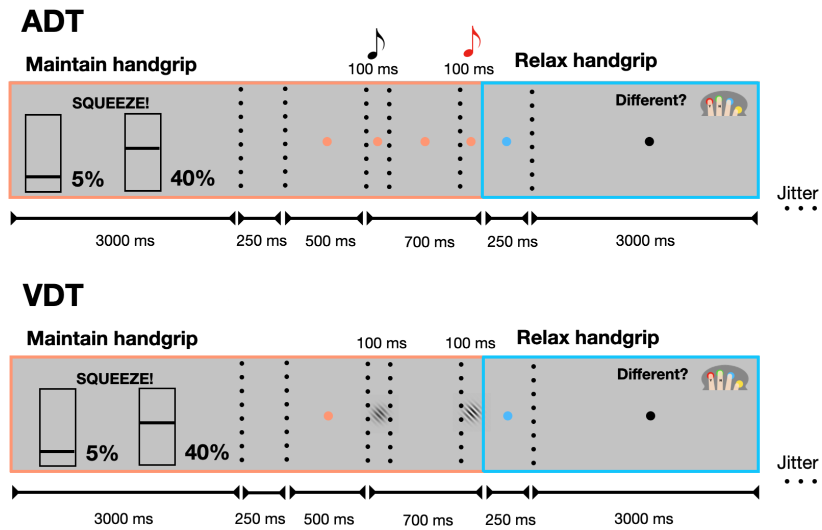

Figure 4. The overall schematics of auditory and visual tasks for Aim 2. Participants maintain a hand grip at either 5% or 40% of their MVC. Two sequential stimuli (100 ms each) are presented with a 700 ms ISI. After the stimuli, participants relax their hand grip, indicate whether the second stimulus is the same or different from the first.

3.4 Key Outcome and Moderator Measures

3.4.1 Primary Performance Metrics

For all experimental tasks (CDT, MST, ADT, VDT), the primary dependent variables for Aims 1 and 2 will be accuracy (e.g., percent correct, P("Old"|Target) for MST) and reaction time (RT) for correct responses.

3.4.2 Moderator Variable: Cognitive Reserve (LEQ)

Cognitive reserve (CR) in this study will be primarily estimated using the Lifetime of Experiences Questionnaire (LEQ) (Valenzuela & Sachdev, 2007). The LEQ is a self-administered instrument (appx. 30 minutes) specifically designed to quantify engagement in complex mental activities across three distinct life stages: young adulthood (13-30 years), mid-life (30-65 years), and late life (65+ years). It comprehensively assesses educational attainment, complexity of primary and secondary occupations, and engagement in a variety of cognitive leisure (e.g., reading, learning languages, playing musical instruments) and social activities (Valenzuela & Sachdev, 2007). Following established procedures, responses from each life stage (which contribute equally) will be used to calculate a total composite LEQ score, with higher scores indicating greater estimated CR (Karsazi et al., 2022; Valenzuela & Sachdev, 2007). The composite LEQ score will thus provide the primary individual difference variable for estimating CR to test its moderating role in Aim 3.

3.4.3 Moderator Variable: Arousal Responsivity (Pupillometry)

Pupil size will be measured using the tower mount 1000 Hz binocular eye-tracker (Eyelink - SR Research Ltd., ON, Canada). Pupil dilation data will be processed to remove blinks and artifacts (e.g., using established algorithms; Kret & Sjak-Shie, 2019; Mathôt & Vilotijević, 2023) and analyzed to assess task-evoked changes in pupil size, considered a proxy for phasic LC-NE activity and neural gain modulation (Aston-Jones & Cohen, 2005; Joshi & Gold, 2020). To measure pupil dilations relative to baseline, the dataset will be normalized for each trial by dividing the pupil trace by the mean pupil size during a 500ms pre-stimulus window, accounting for individual differences in tonic arousal and senile miosis (Bitsios et al., 1996; Winn et al., 2018). Aggregated measures of task-evoked pupil dilation (e.g., mean dilation during relevant trial epochs) will serve as the primary index of arousal responsivity for Aim 3.

3.5 Aim 1: Determine how concurrent physical and cognitive effort affects working and long-term memory performance in older adults

3.5.1 Analytical Framework

Statistical Approach: Separate Mixed-effects ANOVAs will assess physical effort (5% vs. 40% MVC) and cognitive effort (low vs. high similarity) effects on accuracy and reaction time (RT) for each task (CDT and MST). Performance measures (accuracy and RT) for the specific levels of similarity within the low cognitive effort (CDT:

45°/90° rotation; MST: Levels 3-4 lure similarity) and high cognitive effort (CDT: 5°/20° rotation; MST: Levels 1-2 lure similarity) conditions will be averaged to represent the two levels of this factor in the ANOVAs.

$$\text{Accuracy}_{ijk} = \beta_0 + \beta_1 \text{PE}_j + \beta_2 \text{CE}_k + \beta_3 (\text{PE} \times \text{CE})_{jk} + (1|\text{Subject}_i)$$

$$\text{RT}_{ijk} = \beta_0 + \beta_1 \text{PE}_j + \beta_2 \text{CE}_k + \beta_3 (\text{PE} \times \text{CE})_{jk} + (1|\text{Subject}_i)$$

3.5.2 H1a: Working Memory (CDT)

Predictions:

- **Main effect of Physical Effort**: We expect worse performance (lower accuracy and slower reaction times) for high (40% MVC) vs. low (5% MVC) physical effort. This prediction aligns with previous findings (Azer et al., 2023) and is consistent with higher physical effort either exceeding older adults' resource capacity (Resource Competition theory; see Sec. 1.2.1) or inducing supra-optimal arousal (Neural Gain theory failure; see Sec. 1.2.2).
  Alternative Outcomes: A null main effect of Physical Effort on CDT performance might suggest that the 40% MVC level did not sufficiently tax older adults' processing capacity (Resource Competition) or push them beyond their optimal arousal range (Neural Gain) for this working memory task.
- **Main effect of Cognitive Effort**: We predict worse CDT performance (lower accuracy, slower RTs) under high cognitive effort (5°/20° rotation) compared to low cognitive effort (45°/90° rotation), consistent with prior cognitive load effects in older adults' WM (Gazzaley et al., 2005; Van Gerven et al., 2004). Such a decline is anticipated under Resource Competition theory, as greater stimulus similarity may exceed available WM capacity (see Sec. 1.2.1), and under Neural Gain theory, as discriminating highly similar stimuli requires finer, potentially compromised, gain modulation in older adults (see Sec. 1.2.2; Aston-Jones & Cohen, 2005). The interaction analysis (below) and Aim 3 moderation analyses will provide further insight into the interplay between these mechanisms.
  Alternative Outcomes: Null effects for the main effect of Cognitive Effort on CDT performance could indicate that the similarity manipulation was not sufficiently challenging for this sample, or that participants successfully mitigated the increased load, possibly via compensatory strategies (Reuter-Lorenz & Cappell, 2008).
- **Interaction (PE × CE)**: We predict a significant interaction where the negative effect of high physical effort on CDT performance is largest under high cognitive effort, based on previous findings (Azer et al., 2023). This outcome would support the hypothesis that combined high demands disproportionately impair performance due to either breached resource ceilings (Resource Competition) or exacerbated gain modulation failure (Neural Gain). Aim 3 analyses will help differentiate these possibilities.
  Alternative Outcomes: (1) A **null PE × CE interaction** on CDT performance would suggest that limitations are primarily driven by fixed resource ceilings (Resource Competition), dominating over dynamic arousal modulation effects (Neural Gain). (2) **Divergent RT/Accuracy patterns** (e.g., faster RTs with lower accuracy under high physical effort) would be interpreted within the Neural Gain framework as potentially indicating strategic shifts (speed-accuracy tradeoff) due to inefficient gain modulation under high load.

3.5.3 H1b: Long-Term Memory (MST)

Predictions:

- **Main effect of Physical Effort**: Consistent with H1a, we predict worse LTM performance (lower accuracy, slower RTs in the MST) under high (40% MVC) vs. low (5% MVC) physical effort. The general theoretical interpretations (Resource Competition/Neural Gain theories) align with those detailed for H1a (see also Sec. 1.2.1 1.2.2).
  Alternative Outcomes: A null effect of PE on MST performance could share interpretations with H1a (insufficient challenge). However, a unique alternative for LTM is that its underlying processes may be inherently less susceptible to concurrent PE than WM, potentially due to reliance on different or less overlapping neural resources (Wickens, 2008).
- **Main effect of Cognitive Effort**: We predict worse LTM performance with high vs. low lure similarity in the MST, reflecting increased demands on hippocampal pattern separation and retrieval (Stark et al., 2019). While general Resource Competition/Neural Gain interpretations apply (see H1a; Sec. 1.2.1 1.2.2), the mechanisms here specifically involve LTM discrimination challenges.

Alternative Outcomes: A null cognitive effort effect in the MST could suggest robustness of LTM discrimination to this manipulation in older adults or task insensitivity. Alternatively, as in H1a, it might reflect successful mitigation of cognitive load (Reuter-Lorenz & Cappell, 2008).

- **Interaction (PE × CE)**: We predict a PE × CE interaction paralleling H1a, where high PE most negatively impacts LTM performance under high CE (high lure similarity). Such a finding would again be interpretable via general Resource Competition or Neural Gain frameworks (see Sec. 1.2.1 1.2.2), potentially indicating domain-general limitations. The involvement of Aim 3 remains key for differentiating these.
  Alternative Outcomes: Distinct from WM, for the MST: (1) An *improvement* in accuracy under high PE might suggest that arousal specifically optimizes hippocampal pattern separation via Neural Gain mechanisms. (2) MST-specific RT delays under high PE without accuracy decrements could indicate RC specific to LTM motor-retrieval pathways (Stark et al., 2019), rather than global limitations. A null interaction would again suggest fixed resource ceilings (RC) as the primary driver.

3.5.4 Interpreting Interaction Patterns Across Memory Domains

The primary analyses for Aim 1, as detailed in H1a and H1b, will focus on identifying the main effects of physical effort, cognitive effort, and their interaction on performance metrics (accuracy and reaction time) *within* CDT and *within* MST separately.

Following these within-domain analyses, the overall *pattern* of findings from the CDT and MST will be considered holistically to inform a qualitative interpretation regarding the potential consistency of dual-task costs across these two memory domains. This interpretive step will focus on the consistency and direction of any observed physical and cognitive effort interaction effects. Such patterns will be discussed in the context of Resource Competition and Neural Gain theories (as introduced in Significance, Sec. 1.2) and interpreted according to the framework detailed in Approach, Sec. 3.6.5, to explore whether they suggest predominantly domain-general limiting factors or mechanisms more specific to each memory domain.

It is important to note that this study will not involve direct statistical comparisons of the *magnitude* of interaction effects (e.g., comparing η_p^2 values or beta coefficients of interaction terms) between the CDT and MST to make claims about domain generality or specificity. Instead, the concordance and directionality of effects across the two memory tasks will provide the basis for subsequent theoretical interpretation. Further mechanistic insights will be drawn from Aim 3.

3.6 Aim 2: <u>Test whether the effects of concurrent physical and cognitive effort extend to perceptual performance in older adults</u>

3.6.1 Analytical Framework

Statistical Approach: The analytical approach for Aim 2 will mirror that of Aim 1 (see Sec. 3.5.1), employing separate 2 (Physical Effort: 5% vs. 40% MVC) × 2 (Cognitive Effort: Low vs. High Similarity) mixed-effects ANOVAs on accuracy and reaction time (RT) for each perceptual task (ADT and VDT). For these ANOVAs, performance measures will be averaged across the specific levels defining low cognitive effort (ADT: 32Hz/128Hz offset; VDT: 0.16/0.32 contrast offset) and high cognitive effort (ADT: 4Hz/8Hz offset; VDT: 0.04/0.08 contrast offset).

3.6.2 H2a: Auditory Perception (ADT)

Predictions:

- **Main effect of Physical Effort**: Based on principles of Resource Competition (see Sec. 1.2.1) and potential Neural Gain disruptions (see Sec. 1.2.2; Aston-Jones & Cohen, 2005; Mather & Harley, 2016), we predict worse ADT performance for high vs. low physical effort. If observed, this could reflect either domain-general RC or widespread NG disruption. Aim 3 will further probe these possibilities.
  Alternative Outcomes: A null PE effect for the ADT could suggest insufficient challenge for this auditory task, or that auditory processing relies on different neural resources (Wickens, 2008).
- **Main effect of Cognitive Effort**: We expect worse ADT performance for high (4Hz/8Hz offset) vs. low (32Hz/128Hz offset) similarity, due to increased demands on perceptual precision (Chiu et al., 2019). This aligns with RC theory (exceeding perceptual/attentional resources; Sec. 1.2.1) and NG theory (requiring finer, potentially compromised, gain modulation; Sec. 1.2.2; Aston-Jones & Cohen, 2005; Zekveld et al., 2018). Aim 3 analyses will

provide further context.

Alternative Outcomes: Null CE effects could indicate insufficient manipulation challenge (Chiu et al., 2019) or successful load mitigation (Reuter-Lorenz & Cappell, 2008).

- **Interaction (PE × CE)**: Extending patterns from WM (Azer et al., 2023), we predict a significant interaction where high PE most impairs ADT performance under high CE. This is consistent with combined load exceeding processing capacity (RC; Wickens, 2008) or disrupting optimal gain for auditory discrimination (NG failure; Aston-Jones & Cohen, 2005; Mather & Harley, 2016). Aim 3 will help differentiate these.

  Alternative Outcomes: A **null interaction** would suggest auditory processing limitations primarily reflect RC. **Reversed effects** (e.g., faster RTs at 40% MVC) could indicate an NG benefit (Mather & Harley, 2016), though less likely.

3.6.3 H2b: Visual Perception (VDT)

Predictions:

- **Main effect of Physical Effort**: Consistent with H2a, we predict worse VDT performance under high vs. low physical effort. General RC/NGT interpretations align with H2a (see also Sec. 1.2.1 1.2.2). A VDT-specific RC consideration involves vulnerable visual pathways (e.g., dorsal stream overload; Pestilli et al., 2011) if accuracy particularly declines under high CE.

  Alternative Outcomes: A null PE effect on VDT performance could share interpretations with H2a (insufficient challenge). Alternatively, if effects are absent only in VDT, it may suggest reliance on distinct visual processing resources (Wickens, 2008).

- **Main effect of Cognitive Effort**: We predict worse VDT performance with high (0.04/0.08 contrast offset) vs. low (0.16/0.32 offset) similarity, reflecting demands on visual discrimination precision. General RC/NGT interpretations apply (see H2a; Sec. 1.2.1 1.2.2), with mechanisms here specific to fine visual contrast discrimination.

  Alternative Outcomes: A null CE effect in the VDT could indicate insufficient manipulation demand or robust visual discrimination. Alternatively, as in H2a, it might reflect successful load mitigation (Reuter-Lorenz & Cappell, 2008).

- **Interaction (PE × CE)**: We predict a PE × CE interaction paralleling H2a, where high PE disproportionately impairs VDT performance under high CE. This is anticipated due to potential taxation of limited domain-specific visual pathway resources (RC; e.g., magnocellular stream vulnerabilities Power et al., 2021) and/or NG impairment affecting difficult visual discriminations. General RC/NGT interpretations are detailed in H2a (see also Sec. 1.2.1 1.2.2). Aim 3 remains key.

  Alternative Outcomes: Distinct from ADT, for the VDT: (1) **Speed-Accuracy tradeoffs** might indicate strategic resource reallocation. (2) An *improvement* in accuracy at 40% MVC could suggest NG-driven enhancement of occipital gain (Zénon et al., 2014). A null interaction would again point to RC.

3.6.4 Interpreting Interaction Patterns Across Perceptual Tasks

The primary analyses for Aim 2 (H2a and H2b) will identify the main effects of physical effort, cognitive effort, and their interaction on performance *within* ADT and *within* the VDT separately.

Adopting a similar interpretive strategy to that detailed for the memory tasks (Approach, Sec. 3.5.4), the overall *pattern* of findings from the ADT and VDT will then be considered holistically. This qualitative interpretation will focus on the consistency and direction of any observed PE × CE interaction effects. Such patterns, discussed in the context of Resource Competition and Neural Gain theories (as introduced in Significance, Sec. 1.2), will be interpreted following the framework in Approach, Sec. 3.6.5, to inform discussions on whether these influences appear predominantly supramodal or modality-specific within perception.

Consistent with the overall approach for this study, this will **not** involve direct statistical comparisons of the *magnitude* of interaction effects between the ADT and VDT. Instead, the concordance and directionality of effects across these two perceptual tasks will provide the basis for subsequent theoretical interpretation, further informed by Aim 3.

3.6.5 Overall Interpretive Framework for Domain Generality of Effort Interactions

The overall pattern of findings from the primary within-domain analyses conducted for Aim 1 and Aim 2 will subsequently inform a qualitative, holistic interpretation regarding the potential pervasiveness of dual-task costs across cognitive domains. For instance, a pattern where the effects of concurrent effort (e.g., detrimental impacts on performance) are consistently observed across most or all tested memory and perceptual domains—irrespective of the precise magnitude of these effects within each individual domain—would be consistent with theoretical accounts emphasizing global limiting factors such as systemic neuromodulatory failure (NGT) or central resource depletion (RC theory). Conversely, a pattern where such effects are clearly evident and consistently directional in some domains but weak, absent, or opposing in others, would suggest that mechanisms specific to the affected domains play a more prominent role, such as competition for specialized processing resources (RC theory) or non-uniform impacts of arousal dysregulation (NGT). This interpretive approach, focusing on concordance and directionality over direct magnitude comparisons, aligns with the understanding that these diverse tasks involve distinct processes and metrics. Aim 3 insights will further aid in disambiguating these contributions.

3.7 Aim 3: Test whether Cognitive Reserve and Arousal Responsivity moderate the impact of concurrent physical and cognitive effort on memory and perceptual performance in older adults

3.7.1 Analytical Framework

Primary Statistical Approach: Linear Mixed-Effects Models (LMEMs) To test our primary hypotheses regarding moderation by cognitive reserve (H3a) and arousal responsivity (H3b), our main approach will utilize LMEMs analyzing trial-level performance (accuracy or RT) from the experimental tasks (CDT, MST, ADT, VDT). Using trial-level performance as the outcome, even when a moderator such as Cognitive Reserve (LEQ) is at the participant-level, is chosen to maximize statistical power by utilizing all available data points and to consistently model within-subject variance across all Aim 3 analyses. Participant will be included as a random effect (minimally with a random intercept, potentially with random slopes for within-subject factors like PE and CE if supported by model fit). All models will include Physical Effort (PE: 5% vs. 40% MVC) and Cognitive Effort (CE: Low vs. High stimulus similarity) as fixed effects, along with their interaction term (PE*CE). Control covariates (e.g., age) will be included as appropriate.

A conceptual representation of the full fixed-effects structure for these LMEMs (where M represents the specific moderator, LEQ or Pupil) is:

$$
\begin{aligned}
\text{Performance}_{it} = \beta_0 &+ \beta_1 \text{PE}_{it} + \beta_2 \text{CE}_{it} + \beta_3 \text{M}_{i(t)} \\
&+ \beta_4 \text{PE}_{it}\text{CE}_{it} + \beta_5 \text{PE}_{it}\text{M}_{i(t)} + \beta_6 \text{CE}_{it}\text{M}_{i(t)} \\
&+ \beta_7 \text{PE}_{it}\text{CE}_{it}\text{M}_{i(t)} + (\text{Other Covariates like age}) + u_{0i} + (\text{random slopes if applicable}) + \epsilon_{it}
\end{aligned}
$$

where Performance_{it} is the outcome on an experimental task for participant i on trial t, β_0 is the intercept, $\beta_1 - \beta_7$ are fixed effect coefficients, $\text{M}_{i(t)}$ is the participant-level (e.g., LEQ) or trial-level (e.g., mean task-evoked pupil dilation, Phasic_Pupil_{it}) moderator, u_{0i} is the random intercept for participant i ($u_{0i} \sim N(0, \sigma^2_{u0})$), and ϵ_{it} is the residual error ($\epsilon_{it} \sim N(0, \sigma^2_{\epsilon})$).

Hypotheses and Interpretation of LMEMs: Based on the rationale provided in the Significance section (Sec 1.6 & 1.7):

- **H3a (Cognitive Reserve Moderation)**: We hypothesize that higher CR, as measured by the LEQ composite score (LEQ_Score_i), will buffer older adults against the detrimental performance impact of concurrent high physical and high cognitive effort. In the LMEMs, we specifically predict a significant three-way interaction (e.g., PE × CE × LEQ_Score_i) indicating that the negative effect of combined high PE and high CE on accuracy and RT is attenuated for individuals with higher LEQ scores. This would be consistent with CR reflecting more efficient resource management or enhanced neural adaptability (Stern, 2009).
- **H3b (Arousal Moderation)**: Consistent with Neural Gain Theory (Aston-Jones & Cohen, 2005; Joshi & Gold, 2020), we hypothesize that individuals demonstrating more effective phasic arousal responses (e.g., larger aggregated task-evoked pupil dilations, $\text{Phasic\_Pupil\_Agg}_i$) will be less affected by concurrent high effort demands. In the LMEMs, we predict significant interactions (e.g., PE × CE × $\text{Phasic\_Pupil\_Agg}_i$) such that the

performance decrement typically observed under combined high PE and high CE is smaller for individuals with larger task-evoked pupil dilations. This would suggest more successful neural gain modulation and processing efficiency under demanding conditions (Murphy et al., 2014).

Exploratory Analyses To further understand the interplay of CR, arousal, and baseline cognitive functioning, a few focused exploratory analyses will be considered:

1. The collected baseline neuropsychological data will be used for sample description. Their relationship with LEQ-estimated CR scores may also be exploratorily examined to provide further context on individual differences within the sample.
2. To specifically probe the impact of physical effort under high cognitive challenge, we will compute a difference score for each participant and task: $\Delta\text{Performance}_{\text{HighCog},i,\text{task}}$ (performance at 40%MVC *minus* performance at 5%MVC from high CE trials). We will explore its relationship with LEQ scores and a participant-level aggregate of phasic pupil responses (e.g., mean task-evoked dilation during the relevant high CE trials, ($\text{Phasic\_Pupil\_Agg}_i$) using linear regression, potentially including essential covariates (e.g., age). The model would be:

$$\begin{aligned}\Delta\text{Performance}_{\text{HighCog},i,\text{task}} = &\\ &\beta_0 + \\ &\beta_1 \text{LEQ\_Score}_i + \beta_2 \text{Phasic\_Pupil\_Agg}_i + (\text{Essential Covariates}_i) + \\ &\epsilon_i.\end{aligned}$$

Alternative Outcomes and Cross-Domain Consistency Null findings for moderation from our primary LMEM analyses (H3a, H3b) might suggest that effort effects are primarily driven by resource ceilings not strongly ameliorated by LEQ-estimated CR or by the aspects of arousal responsivity captured by pupillometry in this sample. The patterns of significant moderation by LEQ and pupillometry across memory and perceptual tasks will be qualitatively compared to inform the discussion on whether these moderating roles appear domain-general or domain-specific, following the interpretive framework in the Significance section.

3.8 Power and Sample Size

Power Analyses and Sample Size Determination Power analyses were conducted to determine the sample size required to detect hypothesized effects with adequate statistical power (typically 0.80 at $\alpha = 0.05$).

For Aims 1 and 2, which examine 2 (Physical Effort: PE) × 2 (Cognitive Effort: CE) interactions on performance within each task, power analysis using G*Power 3.1 for within-subject repeated measures ANOVAs indicated that 38 participants are required. This calculation was based on an expected medium effect size ($\eta_p^2 = 0.12$) for the PE × CE interaction, derived from comparable dual-task studies in older adults (Azer et al., 2023), assuming a correlation among repeated measures of 0.5.

For Aim 3, which tests whether Cognitive Reserve (CR via LEQ; H3a) and arousal responsivity (task-evoked pupil dilation; H3b) moderate the impact of PE and CE, our primary analyses involve Linear Mixed-Effects Models (LMEMs) focusing on PE × CE × Moderator three-way interactions. To ensure our design can detect these moderation effects, power simulations were conducted using the R package 'simr' (Green & MacLeod, 2016). These simulations for LMEMs indicated that a sample size of approximately **N = 45–50** older adults provides about **80% power** to detect a **medium-sized three-way interaction effect** (quantified as an effect explaining variance comparable to an $f^2 \approx 0.15$) at the $\alpha = 0.05$ significance level.

Final Sample Size We will recruit **50 older adults** (60–90 years). This sample size accounts for potential attrition (estimated at $\sim$10-15%) and exclusion of participants with excessive motion artifacts in pupillometry data (anticipated < 5% loss; Hansen & Holmqvist, 2021), ensuring we retain sufficient participants ($N \geq 45$) for robust analyses. This N provides > 80% power for the medium interaction effects targeted in Aims 1 & 2, and approximately 80% power for detecting the medium-sized three-way moderation effects in the primary LMEMs for Aim 3.

Justification of Anticipated Effect Sizes The targeted effect sizes are informed by prior literature and theoretical considerations:

- **Dual-task interactions (Aims 1 & 2)**: We expect medium effect sizes ($\eta_p^2 \approx 0.12$) for the PE × CE interactions, based on directly comparable findings in older adults performing concurrent physical and working memory tasks (Azer et al., 2023).
- **Cognitive Reserve Moderation (H3a)**: We anticipate a medium effect size ($f^2 \approx 0.15$) for CR (LEQ-estimated) moderating dual-task costs. This is supported by studies showing that CR proxies account for a significant portion of variance in dual-task performance in older adults (e.g., Vallesi, 2016, reporting effects consistent with $f^2 \approx 0.1 - 0.2$) and by findings of CR × task difficulty interactions on cognitive performance (Balart-Sánchez et al., 2024). While some studies show smaller direct correlations between LEQ and global cognitive measures (Gonzales, 2012), the expectation of a medium effect for *moderation* in a demanding dual-task context is plausible given CR's theoretical role in enhancing resilience under challenge (Stern, 2009).
- **Pupillometry (Arousal) Moderation (H3b)**: We also expect a medium effect size ($f^2 \approx 0.15$) for task-evoked pupil dilation moderating dual-task performance. This is grounded in findings that: (1) Older adults can exhibit robust pupillary responses to cognitive load (El Haj et al., 2023). (2) In tasks requiring significant cognitive effort, larger task-evoked pupil dilations are strongly correlated with better performance outcomes (e.g., $r \approx -0.5$ between pupil size and error rate, explaining 25% of variance; Rondeel et al., 2015; Van der Wel & Van Steenbergen, 2018). If arousal responsivity explains a substantial portion of performance variance under load, it is reasonable to expect it to also significantly modulate (i.e., interact with) the effects of other manipulated load factors (PE and CE). Thus, an $f^2 \approx 0.15$ for the three-way PE × CE × Pupil interaction is a justifiable target, reflecting a scenario where individual differences in arousal capacity significantly alter how combined physical and cognitive demands impact performance.

3.9 Pitfalls and Strategies

- *What if muscle fatigue induced by 40% MVC confounds the interpretation of effort effects?* We will implement several strategies:
  1. Measure MVC at the beginning of each session to account for day-to-day variability.
  2. Continuously monitor grip force during trials for significant declines or increased variability within and across blocks, indicative of fatigue.
  3. Include block number as a factor in statistical analyses to test for performance decrements over time that might signal fatigue.
  4. Exclude trials or participants showing excessive force decline (e.g., >15% drop from target sustained over multiple trials).
- *What if task order or practice effects confound effort comparisons across memory and perceptual tasks?* We address this through:
  1. **Williams Design Counterbalancing**: Each participant completes tasks in a unique Latin square order (Figure 2), minimizing practice/fatigue biases.
  2. **Practice Trials**: 10 trials/task before data collection to stabilize performance.
  3. **Order Sensitivity Analysis**: Include task sequence as a covariate in mixed models to quantify carryover effects.
- *What if the LEQ scores do not show the expected moderation effects, or if there are concerns about its comprehensiveness in this specific context?* Mitigation strategies include:
  1. **Examine LEQ Subscales**: If the LEQ composite score does not yield significant moderation, we will exploratorily examine its subscales (e.g., education, occupational complexity, different life-stage activities) for differential predictive power, as certain facets of CR might be more relevant than others (Valenzuela & Sachdev, 2007).
  2. **Consider Established Proxies as Covariates/Exploratory Predictors**: While LEQ is primary, we will have data on education years and can derive an estimate of premorbid IQ (e.g., from demographics or a brief vocabulary test if added). These can be used in exploratory models or as covariates to understand their relationship with LEQ and the outcomes.
  3. **Alternative Questionnaire (CRIq)**: As a contingency, if widespread issues with LEQ completion or validity arise, the more time-efficient CRIq (Nucci et al., 2012) could be considered for future related work or if a

subset of data allows for its administration, though this is not the primary plan.

4. **Control Variables**: Include hearing/vision thresholds in regression models to isolate reserve effects.

- *What if task difficulty levels (low/high similarity) induce ceiling or floor effects in older adults?* We will:
  1. **Pilot Testing**: Adjust similarity levels based on older adults' performance (e.g., reduce MST lure similarity if accuracy >90% at Level 4).
  2. **Adaptive Staircasing**: Consider using adaptive procedures if pilot data show extreme effects, though the current design uses fixed levels to facilitate comparison across effort conditions.
  3. **Exclusion Criteria**: Remove participants with >90% accuracy at hardest levels or <55% at easiest across conditions, as this may indicate misunderstanding or inability to perform the task..
- *What if pupillometry fails to capture individual differences in LC-NE function due to age-related miosis or medication effects?* Contingency plans include:
  1. **Baseline Normalization**: Express dilation as % change from pre-trial baseline to account for tonic differences and miosis.
  2. **Medication Covariates**: Track beta-blockers/anticholinergics and include as covariates.
  3. **Convergent Measures**: Collect heart rate variability (HRV) during tasks to cross-validate arousal indices (Shaffer et al., 2014).
- *What if individual differences in LC-NE system integrity overshadow effort effects in Aim 3?* To address this:
  1. **Focus on Moderation**: Aim 3 specifically tests *moderation* - how reserve/arousal influence the *impact* of effort, rather than just main effects of reserve/arousal.
  2. **Stratified Sampling (Consideration)**: The primary analysis will use LEQ scores as a continuous moderator. If indicated by distributional properties or initial findings, exploratory *post-hoc* analyses might examine effects by stratifying the sample based on LEQ scores (e.g., median split), though this is not the primary analytical approach.
  3. **Statistical Controls**: Covariates (age, baseline pupil) will be used.
  4. **Bootstrapping**: Validate regression models with 1,000 resamples to ensure robustness to outliers.

By addressing these potential pitfalls and implementing the suggested strategies, the study will be better equipped to produce reliable and generalizable findings on how concurrent physical and cognitive demands interact in older adults, interpreted through the lenses of Resource Competition, Neural Gain, and Cognitive Reserve theories.

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