Lifestyle and Personality Factors that Contribute to Cognitive Reserve across the Lifespan

by

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Abstract

Declines due to cognitive aging can significantly impact day to day living, and those who have higher levels of cognitive persistence can potentially mitigate some of that decline (Li et al., 2024). An example of this could be shown by observing the relationship between cognitive persistence and discerning difficult to hear speech. The theory of cognitive reserve (CR) proposes that individual differences in life experiences such as education, occupation, and mentally or socially stimulating activities, can prevent dementia/brain damage from having as strong as an effect on an individual compared to someone with different experiences (Harrison, Sajjad, Bramer, Ikram, Tiemeier, & Stephan, 2015). It has been suggested by several studies that grit is a predictor of CR (Rhodes & Giovannetitti, 2021, Rhodes, et. al, 2017). Persistence, which involves engaging effort to overcome difficulty during cognitive tasks, is conceptually similar to grit but can be measured using cognitive assessments, rather than self-report. Chapter 1 provides an overview of the literature on cognitive aging and factors that might contribute to CR to offset age-related declines in cognition. The first project, discussed in Chapter 2, was designed to investigate the relationship between age, levels of persistence, and accuracy of discerning speech that has been time compressed at three different rates. Older adults showed steeper declines in accuracy with increased time-compression, despite higher cognitive persistence improving accuracy overall. This resulted in poorer speech recognition for fast speech in older compared to younger adults. Pupillometry indicated older adults had larger initial changes in pupil diameter across compression conditions than younger adults, suggesting high baseline effort regardless of task difficulty. Older adults also showed a delayed pupil response to rapid speech, suggesting age-related declines in recruitment of effort in response to challenging

listening conditions. The second project, discussed in Chapter 3, investigated the relationships between persistence, grit, and CR to evaluate whether grit builds CR directly, or indirectly by increasing persistence. The hypothesized structural model linking grit to persistence to CR was not supported. However, project 2 established that grit was correlated with persistence on the Anagram Persistence Task (APT), and there was a trend toward a correlation between persistence on the Wisconsin Card Sorting-64 task (WCST-64) and CR. As the APT and WCST-64 measures of persistence were not correlated with each other, these results suggest independent time- and effort-based persistence components. These separate persistence components merit further investigation to determine if they differentially support grit and CR in healthy aging. Finally, Chapter 4 concludes that persistence may act as a compensatory mechanism to benefit performance in challenging task conditions. However, its effectiveness in aging may be limited by age-related constraints on the timely deployment of cognitive resources.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this dissertation, the following Artificial Intelligence (AI) tools were used: Google Colab. This tool was used primarily to assist in the development of appropriate R code for analysis. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain scholarly integrity of this research.

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List of Abbreviations

AD	Alzheimer's Disease
APOE	Apolipoprotein E
APT	Anagram Persistence Task
ΔPD	Change in Pupil Dilation
CR	Cognitive Reserve
CRI	CR index
CRIq	CR index questionnaire
ACC	dorsal anterior cingulate cortex
HD	Huntington's Disease
K-MMSE	Korean version of the Mini-Mental State Exam
MMSE	Mini-Mental State Exam
MoCA	Montreal Cognitive Assessment
MS	Multiple Sclerosis
PD	Parkinson's Disease
PET	positron emission tomography
PiB	Pittsburgh Compound B
PRMQ	Prospective and Retrospective Memory Questionnaire
PSWQ	Penn State Worry Questionnaire
RSpan	Reading Span task
SES	Socio-economic status
TBI	Traumatic Brain Injury

WCST-64 Wisconsin Card Sorting Task

Chapter 1: An Overview of CR and the Role of Persistence in Cognitive Aging

As individuals age, they can experience declines in cognitive functions, including processing speed, memory, language, visuospatial abilities, and executive function (Ticha et al., 2023, Salthouse, 2010). Age-related cognitive decline impacts performance in everyday life as well as clinical assessments. When faced with cognitive decline, routine tasks such as driving and managing personal finances can become very difficult (Ticha et al., 2023). By investigating factors that impact age-related cognitive changes, individuals at higher risk can be identified and preventative strategies can be developed (Salthouse, 2010). The present dissertation examines how persistence, which is the application of effort to overcome a mental challenge (Teubner-Rhodes et al., 2017), relates to CR and accompanying performance on challenging cognitive tasks during healthy aging. Chapter 1 gives an overview of changes in cognitive processes that occur with age, the role that persistence may play in mitigating decline, and background about the theory of cognitive reserve. Chapter 2 presents a study examining the role of persistence in understanding time-compressed speech, a task requiring increased listening effort, in younger and older adults. Chapter 3 presents a study examining the relationship between grit, persistence, and CR across the adult lifespan to assess the hypotheses that grit is related to CR due to its effects on persistence, which directly builds CR to reduce age-related declines in cognitive performance. Finally, Chapter 4 discusses how the results of this dissertation shape our understanding of the role of persistence in age-related cognitive decline. The present studies investigated the role of persistence in mitigating age-related cognitive decline. We examined the relationship between persistence and understanding time-compressed speech in younger and older adults and the link between grit, persistence, and cognitive reserve. By understanding these factors, we may be able identify those at risk for cognitive decline and develop interventions to enhance cognitive function during healthy aging.

Age-related cognitive decline does not impact all individuals in the same way or to the same degree; some people are able to maintain high levels of cognitive function during aging. A proposed reason for this unexpected level of functioning is the development of CR (Stern, 2002). By investigating the factors that influence cognitive decline and CR, we will be better able to mitigate the challenges of old age, identify those at high risk for cognitive decline, and create interventions and strategies to prevent the progression.

Cognitive aging refers to the decline of cognitive abilities, like memory, executive function, processing speed, and attention as an individual gets older (Salthouse, 2010). Processing speed, the rate that an individual can intake, process, and respond to information, declines with age (Ticha et al., 2023). Processing speed is one of the strongest predictors of performance for older adults on different cognitive tasks. Decline in processing speed has been linked to an overall cognitive decline as well as the increased need for assistance for routine living activities (Ticha et al., 2023).

Working memory, the short-term maintenance and manipulation of information, also shows a decline with age. This decline in working memory affects thinking speed and attention (Daselaar & Cabeza, 2013). Executive function, which includes abilities such as problem-solving, planning, and multitasking, is another cognitive domain that experiences decline with age. Executive function decline is a notable characteristic of neuropathological impairment from dementia (Daselaar & Cabeza, 2013). In conclusion, normal aging is associated with declines in processing speed, working memory, and executive function.

Individuals with higher persistence show smaller age-related declines in performance due to increased application of effort in response to task difficulty (Teubner-Rhodes, 2020). A systematic review and meta-analysis explored the impacts of engagement, persistence, and adherence on cognitive training outcomes for older individuals with and without cognitive decline or impairment (Li et al., 2024). Engagement, persistence, and adherence significantly influenced the outcomes of cognitive training, with higher levels of engagement and persistence associated with better cognitive training outcomes. This effect applied to older adults with normal cognition and those with cognitive impairment. The effects of engagement and persistence on cognitive training outcomes were more pronounced in older adults with normal cognition compared to those with cognitive impairment. These findings suggest that factors such as persistence can positively influence the effectiveness of cognitive training.

Defining CR

It has been observed that individuals with similar levels of neuropathology or brain damage sometimes exhibit different levels of cognitive impairment, which creates a mismatch in expected outcomes based on disease progression and observed outcomes (Stern, 2002). For example, a practitioner could notice that two patients with similar lesions as a result of Alzheimer's disease (AD) do not display the same level of cognitive impairment, with one patient seemingly unaffected. Stern (2002) proposed the theory of CR to explain the observed differences exhibited in levels of cognitive impairment of individuals with similar levels of neuropathology or brain damage. Stern suggested that the function of CR is to maintain normal or better than expected cognitive functioning despite the expected trajectory of cognitive decline due to the presence of neuropathology or brain damage. The mechanism by which CR is able to maintain a better-than-expected level of performance is by utilizing cognitive strategies or alternative neural networks. Stern suggested that the brain could use CR to adapt and compensate in the face of functional or structural damage by falling back on alternative neural resources that had been built over a lifetime of experiences (Stern, 2002).

Stern (2002; Stern et al., 2023) specifically defines CR as a construct that refers to the capacity of an adult brain to sustain pathological damage while still maintaining normal functioning, allowing some individuals to cope better than others with age-related changes and neurodegenerative pathologies by the development and utilization of alternative cognitive strategies or neural networks that compensate for age- or disease-related brain changes. Stern's definition adds to the parameters outlined by Satz (1993), that CR is the individual differences in the flexibility and efficiency of cognitive functioning that are associated with variations in brain structure and function and that confer some degree of protection against the adverse effects of brain aging and/or brain disease.

Research surrounding CR often is entangled with research on several other similar concepts. Stern et al. (2023) introduces the overarching term resilience to refer to three related age-protective factors: CR, brain reserve, and brain maintenance. Stern (2013) first made the distinction between brain reserve and CR, stating that brain reserve depends on brain size or neuronal count and should be considered a passive model of reserve. In contrast, CR is defined as the efficient use of neuronal networks and use of strategies and is thus an active model. Stern further explains the difference between active and passive models, with passive models revolving around the amount of damage that can occur prior to reaching a threshold for clinically observable changes and active models focusing on differences in how a task is processed in the brain using different accumulated resources and strategies (Stern, 2002; Stern et al., 2023). CR is the brain's capacity to compensate for neuropathological or other brain damage and age-related cognitive decline by utilizing alternative neural networks and cognitive strategies in order to maintain functioning and prevent noticeable cognitive decline. Individuals with higher CR can seemingly delay the onset of cognitive decline while those with less reserve will perform at noticeably lower levels (Stern 2002). The key elements of CR are that individual differences in brain function, structure, and connectivity are impacted by lifetime differences in education, occupational complexity, and intellectual stimulation, which can protect an individual's cognitive abilities (Stern, 2002). For example, when attempting to study something, a person with high CR might form an association between the new information and things they know, look for and recognize patterns, and utilize context instead of relying on simple memorization of content.

Similarly, brain reserve can serve as protection against neuropathological or other brain damage; however, brain reserve is a more anatomically focused theory. Brain reserve specifically refers to the physical structures that could aid in adding to reserve (Stern et al., 2023). Specifically, factors such as brain size, neuronal density, synaptic connectivity, and neural plasticity determine the brain's capacity to maintain functioning. Individuals with a greater overall brain size have a greater number of synaptic connections and neurons, which theoretically compensate for the damaged or lost brain cells. Like CR, brain reserve could stave off cognitive impairment or decline (Stern, 2009).

Brain maintenance also shares traits with CR and brain reserve but differs in that it is the study of actions taken that support the preservation and optimization of the aforementioned structures, functions, and cognitive strategies involved in cognitive and brain reserve. The factors involved in brain maintenance promote overall brain health, such as healthy diet, social interaction, physical exercise, and intellectual pursuits (Valenzuela & Sachdev, 2006). In summary, CR focuses on individual differences in brain functioning or brain resilience, brain reserve focuses on the structural characteristics that influence brain resilience, and brain maintenance focuses on the lifestyle factors that influence brain resilience.

While distinctions between CR, brain reserve, and brain maintenance have been established, the distinction between them has not been strictly followed within existing literature on these topics. At times, the terms have been used interchangeably. For the purposes of this paper, the theory of CR is that "individual differences in the cognitive processes or neural networks underlying task performance allow some people to cope better than others with brain damage" (Stern, 2009). For studies that do not make a distinction between the types, researchers should consider using the umbrella term, "reserve".

Neurological Basis for Reserve Theories

Neuroimaging research has allowed investigators to show that individuals with higher CR also exhibit higher grey matter density, increased brain volume, and more connectivity (Stern et al., 2005). In a study of 17 older adults and 20 younger adults, positron emission tomography (PET) was used to explore how CR is mediated by brain networks by investigating the relationship between network expression and performance on a memory assessment and a measurement of CR (Scarmeas et. al, 2003). The memory assessment was a serial recognition task where participants needed to recognize nonsense shapes in a low demand condition as well as a titrated demand condition. To measure CR, a combined score of years of education, the National Adult Reading test, and the revised Wechsler Adult Intelligence Scale was created. A sub-profile model identified functionally connected regions that changed activation in the lower and higher demand conditions and were differentially expressed in both age groups. Regions identified in this topography were the right hippocampus, posterior insula, thalamus, and right and left operculum. Analysis showed that younger subjects with higher CR displayed increased expression of the identified topography, while older participants with higher CR displayed decreased expression. The authors found that the topography was differentially expressed as a function of levels of reserve and concluded that it could physically represent reserve. The difference in topography between the age groups suggested that older adults were using a functionally reorganized network to accomplish the task, giving evidence of a compensatory network that older adults use to keep functioning in light of age-related changes. This compensatory recruitment of additional networks has been found by other researchers as well, with studies of healthy populations showing that those with higher CR recruited additional brain regions and activated more task-relevant existing networks as forms of compensation against normal age-related cognitive changes (Barulli, et al., 2013, Steffener et al., 2011). As individuals acquire the lifetime of experiences that build CR, they are also influencing their brain physically.

CR can potentially mitigate the negative effects of amyloid deposits on neuropsychological performance in older adults. A study was conducted to determine if amyloid deposits impaired neuropsychological performance in older adults and if CR could modify the relationship (Rentz et al., 2010). The study utilized PET imaging to record the retention of Pittsburgh Compound B (PiB) in the brain, which is used to measure amyloid deposit volume. The study recruited 66 controls and 17 patients with Alzheimer's disease (AD) and compared their recorded PiB retention with their performance on a series of neuropsychological tests and then analyzed the effect a CR proxy had on their relationship. The proxy used was a combined score of education and performance on the National Adult Reading test. Results indicated that PiB retention was inversely related to performance on the neuropsychological assessments, which included the Mini-Mental State Exam (MMSE); the Digit Span Forward and Backward;

Trails A and B; Controlled Oral Word Fluency; Category Generation to animals, vegetables, and fruit, the Free and Cued Selective Reminding Test, Free Recall and Cued Recall subtests; the Boston Naming Test; the Visual Form Discrimination Test; and the Memory Capacity Test. For the participants with AD, CR was found to modify the relationship between amyloid deposits and neuropsychological performance. For those with higher levels of CR, increased amyloid deposits were not associated with poorer performance on the cognitive assessments. Because amyloid deposits were associated with lower neuropsychological performance and the association was modified by CR, CR may offer some protection against cognitive impairment from amyloid deposits that accumulate in AD (Rentz et al., 2010).

Imaging studies have also highlighted the association between CR and specific brain regions. For example, individuals with higher CR have been shown to have increased activation and thickness in the prefrontal cortex (Stern, 2002). Higher CR has also been associated with greater hippocampal volume (Valenzuela et al., 2008), as well as increased connectivity and activation in response to a memory task in the posterior cingulate cortex (Pudas et al., 2013). These examples provide a physical link to the "reserves" in reserve theories.

Clinical Applications of CR

CR may be a key factor contributing to patient outcomes in a variety of clinical conditions affecting the brain. Patients with higher levels of CR could maintain higher levels of functioning in the face of a condition that was expected to create deficits. The ability to build reserves to actively fight against these possible declines could offer some hope to patients facing diagnoses with no other clinical interventions available. Notably, CR is built by a lifetime of experiences, so it cannot function as a quick intervention in light of a diagnosis, and it is most effective when seen as an ongoing preemptive effort.

Traumatic brain injuries (TBIs) are among the brain changes where CR can potentially determine the outcome for the patient. In a study of adults with TBIs of varying severity, pre-TBI IQ was used as a CR proxy (Steward et al., 2018). Patients' processing speed, verbal fluency, and memory were assessed during recovery. Analysis showed that those with higher reserve had faster processing speeds, higher verbal fluency, and performed better on memory tasks, compared to those with lower levels, which the authors suggested was evidence of the neuroprotective quality of CR (Steward et al., 2018). In fact, CR, measured with the proxy of pre-injury IQ, has been established as predictor of recovery outcomes in several longitudinal studies (Fraser et al., 2019; Nunnari et al., 2014; Levi et al., 2013; Kesler et al., 2003). The most commonly used proxies for CR are those that measure the buildup of lifetime experiences that contribute to the development of the cognitive resources that comprise CR (Stern, 2006). IQ is not used as frequently as a proxy, as it is often considered an innate quality. The education, occupation, and lifestyle of an individual directly build reserve, while innate intelligence does not (Stern, 2006). IQ can be a successful proxy for CR in some cases because of the relationship between higher IQ and higher educational and occupational attainment. While not a perfect proxy for CR, IQ can be a useful tool in situations where other approximations of reserve are not available.

Stroke, a cerebrovascular incident that blocks blood flow to the brain, is one of the leading causes of death and disability worldwide (Rosenich et al., 2020). Survivors of stroke are impacted by the structural damage done to their brain, which can lead to impairments in sensation, movement, language, and/or cognition, depending on the location and extent of the resulting brain damage (Rosenich et al., 2020). CR has the potential to explain why some stroke patients are seemingly less affected than others. A study that analyzed 7459 stroke patients showed that a CR proxy, derived from both level of education and occupational complexity, moderated stroke recovery speed (Shin et al., 2020). In this longitudinal study, patients were administered the Korean version of the MMSE (K-MMSE) at eight different time points after their stroke: baseline, discharge, 3 months, 6 months, 12 months, 18 months, 24 months, 30 months. The K-MMSE screens for cognitive impairment with items assessing orientation, working memory, short-term memory, and language functioning. Analysis of the slopes of the K-MMSE scores revealed that those with higher CR scores (derived from a composite of education level and occupational attainment) started earning higher K-MMSE scores sooner than their counterparts with lower CR.

Measuring CR could provide insight into even early stroke outcomes. Patients who differ in years of education show differences in alertness, working memory, executive functions, and global cognition during the acute stroke phase, which is the first seven days after a stroke occurs (Umarova et al., 2019). Patients underwent a battery of evaluations including the Montreal Cognitive Assessment (MoCA) (Nasreddine, 2005); a tonic alertness task, which measured reaction time to a target; a digit span task to assess working memory; an executive function task based on word fluency and semantic sorting; spatial neglect assessments; a crystalized intelligence task based on the Multiple-Choice Vocabulary Test; and a motor deficits task. Patients also had an MRI examination that included lesion mapping. Stroke damage was quantified by relative lesion volume for analysis. Using education as a proxy measure for CR, analyses revealed CR was positively correlated with post-stroke alertness, global cognition, working memory, and executive functioning. This finding indicated that CR contributes to the initial severity of disability and cognitive deficits as a result of stroke (Umarova et al., 2019).

Parkinson's Disease (PD) is characterized by tremor, muscular rigidity, and slow, imprecise movement due to degeneration of basal ganglia and a dopamine deficiency. Like many neurodegenerative diseases, it primarily affects middle-aged and older adults. PD can have both motor and cognitive implications, with dementia impacting 80% of PD patients after 20 years. PD patients with dementia show an abnormal number of Lewy Body protein deposits (Perneczky et al., 2008) and demonstrate dementia symptoms including impairments in memory, concentration, and judgement. A systematic review of papers on PD, cognition, and education found that CR, as measured by higher education, positively impacted outcomes for PD patients (Hindle, 2013). Analysis found a significant association with higher education and performance on the MMSE, global cognition, attention, executive function, visuospatial function, and working memory. This review also indicated that CR slowed cognitive decline in PD patients, which adds support to the claim that CR has protective properties.

Research studying other clinical populations, such as Huntington's Disease (HD) and Multiple Sclerosis (MS), provides more evidence of the protective qualities of CR. HD is a genetically inherited neurodegenerative disease that results in chorea and dystonia, issues in coordination, behavioral difficulties, and cognitive decline (Walker, 2007). Those with higher CR as measured by the CRIq, displayed a slower and milder progression of HD, as measured by Unified HD Rating Scale (UHDRS) (Klempír et al., 2006), which includes sections for motor, cognitive, functional and behavioral abilities (Migliore et al., 2022). Analyses indicated a correlation between higher CRIq scores and cognition, with the highest association being found between cognition and CRIq leisure activity sub-scores. Thus, engagement in lifestyle activities believed to build reserve can predict slower progression of HD.

MS is a neurological disease that is characterized by demyelination of neural cells, which most commonly results in symptoms impacting mobility, hand function, vision, fatigue, cognition, bowel/bladder function, sensory, spasticity, pain, depression, and tremor/coordination (Kister, 2013). Researchers observed that some patients with MS do not show cognitive impairment despite high disease burden in the form of cerebral atrophy and lesions in the white matter. A review of MS studies observed that greater vocabulary and early life participation in cognitively stimulating activities decreased cognitive impairment as a result of MS (Sumowski & Leavitt, 2013).

CR has clinical implications across many conditions, including TBIs, stroke, PD, HD, and MS. CR can potentially moderate the impact of neurological conditions, and lead to better patient outcomes. Understanding CR can inform preventative strategies and individualized rehabilitation plans.

Life Experiences that Contribute to CR

Research has identified different behavioral and demographic factors that appear to affect CR. Among these factors are education level (Katzman, 1993; Stern, 2002), occupational complexity (Foubert-Samier et al., 2012; Stern, 2009), socioeconomic status (SES) (Scarmeas et al., 2006), bilingualism (Alladi et al., 2013; Bialystok, Craik, & Luk, 2012), engagement in cognitively stimulating activities (Verghese et al. 2003; Wilson et al., 2019; Gow et al., 2012; Valenzuela et al., 2018), cognitive engagement in early life (Stern et al., 1994), and social engagement (Trejo-Becerra & Reynoso-Alcántara, 2019; Wang et al., 2002).

Education

Education, measured in terms of years of education and/or highest degree earned, is a strong proxy of CR (Katzman, 1993; Stern, 2002). Education provides individuals with opportunities for ongoing intellectual stimulation and development of cognitive resources. Education is a suitable proxy for CR because of the underlying cognitive domains that it influences. Education can increase performance of memory, executive function, language, and visuospatial ability (Opdebeeck et al., 2016). A meta-analysis investigated the most common proxy measures of CR, education level, occupational status, and participation in stimulating leisure activities. Of the 135 studies included, education was used as a measure in 109, occupation was used as a measure 19 times, participation in cognitively stimulating activities was used 31 times, and a combination of the three factors was used 6 times. The measures were all positively associated with cognition, with cognitively stimulating activities and occupation displaying the most variation. These findings indicated that the proxy measures for CR can influence CR independently of each other, but they do have similar underlying processes. Additionally, participants' performance on cognitive screening tasks was found to be significantly associated with education level, with higher performance being associated with more education. Extra years of education are considered to increase CR, and it is important that the education results in an increase in the previously listed cognitive domains.

To investigate the impact education can have on dementia, a meta-analysis of 133 articles analyzed participants' levels of education as well as dementia, AD, and vascular dementia; in total, 437,477 participants were included (Meng & D'Arcy, 2012). Analysis found that those with lower levels of education were more at risk of developing dementia. Investigating the subset of studies that provided physiological data showed that those with higher education maintained cognitive performance despite the presence of brain damage supporting the claim that CR impacts the rate of cognitive decline, with higher levels of education masking the disease pathology.

It seems that the effects of education are not limited to masking neuropathology. A longitudinal study explored the relationship between education, apolipoprotein E (APOE), and dementia (Wang et al., 2012). APOE is a gene that controls the production of apolipoprotein E, and individuals who have the APOE E4 version of the gene are at increased risk for developing late-life onset of AD. The study included 602 dementia-free individuals over the age of 75 from Stockholm Sweden, who were examined 9 years after their initial enrollment to determine if they had developed dementia in that time. Information on education, SES, occupation, and late-life leisure activities were collected. Participants were also classified as carriers or non-carriers of the APOE E4 gene. Analysis indicated that even carriers of the APOE E4 gene benefitted from reserve enhancing factors, with all participants with higher reserve scores having reduced risk for developing dementia. In the face of a genetic predisposition for dementia, the possibility of a CR-based treatment could mean a significant increase in late-life quality for carriers.

A study was conducted to examine the relationship between education and AD using the National Alzheimer's Coordinating Center datasets with a total of 2,372 participants (Roe et al., 2007). The objective of the study was to see if level of education could account for cases where individuals were diagnosed with no dementia but upon their death were revealed to have neuropathological evidence of AD. Analysis showed that, depending on the diagnostic measure used, 12-19% of individuals who met the criteria for AD neuropathology were not diagnosed with dementia. It was shown that individuals with more education were less likely to have been diagnosed with dementia. Despite the differences in neuropathologic criteria reported to the database, education was found to be predictive of dementia status in individuals found to have neuropathologic evidence of AD. This finding supports the claim that those with higher education, and thus higher CR, are less likely to exhibit observable cognitive deficits and can better cope with the brain changes from AD.

Occupation

The second most common proxy of CR is occupational attainment: occupations that have higher complexity and are higher in cognitive demands are associated with increased CR (Stern, 1994; 2002). Occupational attainment is often classed by skilled or non-skilled work, with higher skilled work offering more cognitive stimulation and demanding more cognitive effort, resulting in the development of higher levels of CR.

In development of CR theory, researchers began to investigate occupation as a risk factor or predictor of dementia in tandem with education because investigators noted that lower levels of occupation negatively impacted performance on some diagnostic tests, making it difficult to assert that education was indeed a risk factor at the time (Stern, 1994). In a cohort study, 593 participants without dementia ages 60 years or older who had been placed on a list indicating a risk for developing dementia were assessed 1 to 4 years later and were examined with the neuropsychological measures used to place them on the list. A total of 106 individuals on the list developed dementia between assessments. Low education, low occupational attainment, and a combined low occupational attainment and low education factor were analyzed, and all were found to be significant risk factors for developing dementia, with the combined factor showing the greatest risk. Importantly, this study found that occupational attainment could operate as a stand-alone predictor and proxy for CR.

Occupation can influence CR in a similar way that education does, increasing cognitive stimulation and abilities. Occupation often involves training and on-the-job learning that can be equated to continued education, and complex jobs require employees to engage in demanding cognitive operations on a frequent basis (Baldivia, 2008). Higher complexity of work as measured by mental demand, concentration required, precision required, and time spent working under pressure were all associated with reduced risk of developing cognitive impairments (Bosma et al., 2003). While investigating accelerated cognitive decline in individuals with low education, occupation was suggested as a factor that could help boost CR despite the association between low education and low CR. In a longitudinal study with data from 708 individuals aged 50 to 80 years in the Maastricht Aging Study, the contribution of occupation to the relationship between education level and age-related cognitive decline was investigated (Bosma et al., 2003). The occupation factor was created by labeling jobs based on average responses to the following four questions: "Is your work mentally demanding?", "Do you have to concentrate strongly during work?", "Does your work require great precision?", "Do you regularly work under time pressure?". Participants also underwent a cognitive assessment, the MMSE, which was repeated after three years. Analyses indicated that individuals with lower education levels experienced more cognitive decline than the more educated individuals, but also that 42% of the association was attributed to low mental stimulation and lack of challenge at work. The authors stressed the relevance of this finding to bridging the gap in cognitive decline between education groups. Findings suggested that increasing work-related mental stimulation and challenges for individuals with low levels of education could offer protection against cognitive decline by building CR, and that providing this increase in mental stimulation at work is much more actionable that modifying a person's intellectual abilities in mid-life (Bosma et. al., 2003).

Social/Leisure Activities

An additional contributor to CR is found in social or leisure activities. Routine participation in cognitively stimulating hobbies and interactions can boost CR (Verghese et al., 2003). It's been suggested that lifestyle choices, such as novel social interactions or stimulating hobbies such as reading, allow individuals to practice using alternative brain networks and increase cognitive flexibility (Scarmeas & Stern, 2003).

A cohort study of 469 individuals older than 75 years old investigated the relationship between leisure activities and risk of development of dementia. At the start of the study, none of the participants were diagnosed with dementia. Participation in leisure activities such as reading, playing board games, playing musical instruments, and dancing was scored based on frequency of activity in days per week. Participants were followed up with at a median of 5.1 years after initial assessment. Of the 469 individuals, 124 subjects developed dementia. Analysis indicated that increased activity scores were significantly associated with reduced risk for dementia (Verghese et al., 2003). Beyond providing support for stimulating activities as a proxy for CR, this study provides important information about when CR can be built, as the activity score was derived from the participants' current lifestyles. Education and occupation have traditional time courses that begin in early life and taper at retirement age, while engagement in stimulating activities is not limited to any particular time of life, increasing an individual's chances to build their CR.

Social engagement is one stimulating activity that has been shown to play a large role in cognitive health (Stern, 2002; Saczynski et. al., 2006). The Honolulu Heart Program and the Honolulu-Asia Aging study followed 2513 Japanese American men and examined how low levels of social engagement in mid- and late-life impacted the participants' risk of developing dementia (Saczynski et al., 2006). Findings indicated that social engagement in mid-life was not associated with the risk of dementia, and that those who have the least social engagement in late life had the most risk of developing dementia.

Social activities were found to decrease risk of developing dementia in a longitudinal study conducted using data from the Kungsholmen Project, which was active from 1987 to 1996 (Wang et al., 2002). Researchers hypothesized that social networks could provide a protective effect from dementia because they provided social interaction and intellectual stimulation. Using the Kungholmen Project data, the relationship between engagement in different activities and dementia diagnoses was analyzed. It was found that frequent engagement (defined as daily to weekly engagement) in social activities was associated with decreased risk of dementia.

Bilingualism

Another possible contributor to CR is bilingualism, which refers to proficiency in or frequent use of two languages. People who are bilingual may have a "bilingual advantage" that has been described as better cognitive control than their monolingual counterparts (Bialystok, Craik, & Luk, 2012). Bilingualism may lead to better performance on tasks of inhibition, anticipation, monitoring, task switching, and attention, and it is suggested that this more efficient use of brain resources allows bilingual individuals to maintain higher levels of cognitive functioning in the face of neuropathology (Guzmán-Vélez & Tranel, 2015). Bilingualism gives people more neural resources to rely on throughout their lives, suggesting that it is a factor that increases CR.

In a study investigating the role of bilingualism in CR, researchers analyzed brain atrophy in 40 individuals who received a diagnosis of probable AD (Schweizer et al., 2012). It was expected that bilingual individuals would show higher levels of brain atrophy than the monolingual individuals, as they would be able to operate at a higher level than would be expected based on the progression of the disease. In analysis, bilingual and monolingual individuals were matched on level of cognitive performance and years of education. Of the pairs, bilingual individuals exhibited substantially greater brain atrophy than the monolingual individuals, especially in the radial width of the temporal horn and the temporal horn ratio. The authors concluded that bilingualism contributes to increasing CR (Schweizer et al., 2012). Aging related changes in cognitive abilities can have a negative impact on those affected. Investigating factors that could prevent cognitive decline would serve our aging population well. One proposed topic for inquiry is persistence and how it may allow individuals to persevere though difficult tasks. This author proposes that persistence should be investigated in relationship to CR, as individuals use *cognitive strategies* and alternative neural networks to maintain better than expected cognitive abilities. Education, occupational complexity, SES, bilingualism, and engagement in cognitively stimulating activities are well established in the literature as contributors to building CR (Stern, 2010). Exploring the relationship of CR to other factors such as persistence may help establish a more detailed understanding of what type of person may be more likely to have higher CR. In the next chapter, a project is presented to investigate the impact persistence has in older and younger adults when faced with a difficult to recognize auditory task. It will be followed by a project focused on the relationship between grit, persistence, and CR. Lastly, Chapter 4 will discuss general conclusions.

Chapter 2: Persistence and Understanding of Time-Compressed Speech in Younger and Older Adults

Older listeners who face hearing loss and cognitive decline also complain of temporal difficulties in understanding speech, particularly when the rate of speech is increased. These may be attributed to slower processing times in the aging auditory system (Chisolm et al., 2003). However, another possible reason for the decline of intelligibility of rapid speech may be related to top-down control of processes. One such process is persistence, or the application of extra effort to overcome difficulties encountered in mentally challenging tasks (Teubner-Rhodes et al., 2017). Persistence may become more important for maintaining understanding of fast-rate speech in healthy aging, as top-down control of attention begins to fail or as declines in processing speed make it more effortful to track fast-rate speech.

Persistence has been shown to recruit cingulo-opercular regions of the brain (Teubner-Rhodes et al., 2017). These neural resources are also recruited to enhance task performance in degraded listening conditions by older listeners (Eckert et al., 2008; 2016).

Listening effort has been defined as "the attention and cognitive resources required to understand speech" (Picou, Ricketts & Hornsby, 2013). Listening can become effortful due to a degraded speech signal, interference by noise, or listener limitations (Pichora-Fuller et al., 2016). Effortful listening combines bottom-up and top-down processing (Zekveld et al., 2006). Bottom-up processes allow auditory information to travel efficiently from the ear to higher-level processing structures of the brain. Top-down processing occurs when the brain exerts greater attention towards listening (especially in high cognitive load conditions; Zekveld et al., 2006). In conditions when bottom-up processing is compromised (e.g., time-compressed speech, speech-in-noise), top-down processing strategies become necessary (Pichora-Fuller, 2008). Listening effort may explain why some people with hearing loss indicate that they have a harder time understanding speech in the absence of no change in listening performance. If individuals engage resources or increase effort they may be able to retain better listening performance even with conditions that make listening more difficult (Eckert et al., 2016).

Individuals facing effortful listening during time-compressed speech may resort to persistence as a top-down processing strategy. As speech becomes degraded, listeners may experience processing difficulty that can reduce performance and result in fatigue. Thus, listeners who are more persistent, that is, who are willing and able to increase their effort in degraded speech conditions, are expected to have better performance than listeners who are less persistent. Persistence has been shown to predict neural activity in the dorsal anterior cingulate cortex (dACC) that detects and mitigates errors when discerning speech from background noise (Teubner-Rhodes et al., 2017). Specifically, older adult listeners with higher persistence show greater activity in the dACC in response to errors in speech recognition. They also demonstrate a greater boost in performance following increased activity in the dACC (Teubner-Rhodes et al., 2017), indicating a stronger link between dACC function and real-time performance enhancements in response to task difficulty.

Recent findings also show that greater persistence is associated with better recognition of words in sentences presented in background noise (Teubner-Rhodes et al., in prep). Importantly, this result controlled for effects of hearing loss, such that individuals with better persistence had better word recognition than expected by what they could hear, whereas individuals with worse persistence had worse word recognition than expected. Additionally, the effect of persistence on recognizing speech in noise became stronger with increasing age: persistence was a better predictor of word recognition in older adults than in younger adults (Teubner-Rhodes et al., in prep). This is consistent with evidence that older adults report greater listening effort than younger adults (Anderson Gosselin & Gangé, 2011; Piquado, Isaacowitz, & Wingfield, 2010). If the task is more challenging, then more persistence will be required in order to succeed.

Persistence may influence the experience of cognitive load during listening via the dACC. As described above, greater persistence is associated with larger increases in dACC activity in response to degraded speech (Teubner-Rhodes et al., 2017). Increased activity in cingulo-opercular brain regions, including the dACC, is associated with increased pupil dilation (Kuchinsky et al., 2016), a physiological index of cognitive load. Pupil dilation is an objective measure that can track the listening effort and cognitive stress associated with speech intelligibility for young, middle-aged, and older adults (Kuchinsky et al., 2013; Wingfield, 2016). Because the pupillary response is controlled in part by the attention system, increases in pupil dilation provide a valid, objective measure of cognitive stress and increasing task demands (Zekveld et al., 2011). Increased pupil diameter can be taken as a signal that the listener is willing to engage with the task (Winn et al., 2018), with studies showing that increased pupil diameter was associated with increased accuracy (Ohenforst et al., 2017; Wendt et al., 2018) The proposed research uses task-related pupil dilation to characterize listening effort associated with time-compressed speech in younger and older individuals.

Understanding time-compressed speech becomes more difficult with age (Letowski, 1996), leading to increased listening effort and comprehension failures. These effects are partly due to hearing loss, but older adults exhibit difficulties in speech intelligibility for rapid speech, even after controlling for reduced audibility of the speech signal (Gordon-Salant, 2007). Because hearing loss only partially explains older adults' temporal processing deficits, hearing aids cannot fully restore speech recognition. Hearing aids provide some relief for rapid speech by increasing audibility, but older adults who have been fitted for hearing aids often report dissatisfaction with their devices, reducing compliance and adherence (Singhal & Kapoor, 2019). Persistence may predict benefit from hearing aid use, and who is most likely to continue using their aids. The present research will inform the development of interventions to improve cognitive persistence in order to aid speech recognition in challenging conditions.

Recent research shows the value of pupillometry, or the measurement of pupil dilation over time, as an index of effortful listening and word selection difficulties. If an individual remains engaged in a task, as the task demands increase, so will the individual's pupil size. (Granholm et al., 1996). It is unclear how persistence abilities will impact this physiological measure. Research examining the role of persistence in understanding degraded speech is sparse. The current study is one of the first to look at resource allocations for processing rapid speech, persistence abilities, and their relationships to listening effort (pupil dilation) and reduction in speech intelligibility. Aging effects on time-compressed speech have been studied previously, but it is largely unknown how younger versus older listeners will apply persistence for speech processing in rapid (30% compression) and very rapid (60% compression) conditions.

Teubner-Rhodes et al. (2017) have developed a novel measure of persistence from the Wisconsin Card Sorting Task (WCST-64), which assesses the extent to which participants exceed performance expectations when the task becomes challenging. Most existing measures of persistence rely on self-report measures that are subjective and domain-specific (Choi et al., 2010; Cloninger et el., 1994; Doherty-Bigara & Gilmore, 2016; Onatsu-Arvilommi & Nurmi, 2000; Pintrich et al., 1991; 1993; Steinberg et al., 2007; Zhang et al., 2011). This new measure revolutionizes the way that researchers assess persistence by using a behavioral task that taps the application of effort to improve performance and is completely independent of task ability. Thus, the WCST-64 measure isolates task-related persistence more successfully than previous measures.

Older adults report greater listening effort than younger adults, especially for degraded speech (Anderson Gosselin, & Gangé, 2011). Individuals facing effortful listening during time-compressed (i.e., rapid) speech may resort to persistence, the ability to exert effort to overcome difficulty, as a top-down processing strategy. Indeed, persistence predicts neural activity in the dACC that detects and overcomes errors when recognizing speech in background noise (Kolling et al., 2016). Pupil dilation is an objective measure that can track the listening effort associated with speech intelligibility for young, middle-aged, and older adults (Kuchinsky et al., 2013; Teubner-Rhodes & Kuchinsky, 2020). Because the pupil response reflects cortical inputs to the autonomic nervous system, increases in pupil dilation indirectly measure the attention system's response to increasing task demands (Wingfield, 2016).

The purpose of this project is to understand how persistence affects recognition of time-compressed speech in younger and older adults. Aim 1 assesses the extent to which individual differences in persistence predict speech recognition, assessed by word repetition accuracy, under different time-compression conditions. We hypothesize that greater time-compression will predict lower speech recognition accuracy. Additionally, increased persistence will predict better speech recognition accuracy, especially as time-compression increases. That is, speech recognition will decline at faster speech rates to a greater extent in low persistence individuals than in high persistence individuals.

Aim 2 examines the extent to which individual differences in persistence predict cognitive load, measured by pupil diameter, under different time-compression conditions. We hypothesize that greater time-compression will increase pupil diameter; however, there may also be a negative, quadratic effect of time-compression, with pupil diameter increasing from 0 to 30% compression rates and decreasing from 30 to 60% compression rates, consistent with evidence that effort increases until tasks become too challenging and then drops off. We predict that persistence will interact with time-compression effects, such that individuals with higher persistence will have larger increases in pupil diameter as speech rate becomes more rapid than those with lower persistence. This pattern would be consistent with the notion that more persistent individuals apply more effort as task difficulty increases.

Aim 3 assesses how age moderates the effects of persistence and time-compression on speech recognition accuracy and pupil diameter. We hypothesize that older adults will have poorer word repetition accuracy than younger adults, especially at faster compression rates. The interaction between persistence and time-compression will be stronger for older adults than younger adults because time-compression is less effortful for younger adults who typically have faster processing speed and greater working memory capacity. With regards to pupil results, we predict that quadratic effects of time compression will be more negative in older adults than in younger adults, indicating that time compression has a larger effect on physiological effort in older adults and that older adults are more likely to decrease effort at the fastest speech rate. Again, the interaction between persistence and time-compression will be stronger for older adults due to the increased importance of applying effort to understand fast speech in this age group.

Method

Participants

Participants for this study included thirty healthy younger adults from the ages of 18 to 35 and ten healthy older adults from the ages of 65 to 85. Participation from older adults was reduced due to the COVID-19 pandemic. Participants were required to be monolingual native speakers of American English and have normal or corrected-to-normal vision. Participants were excluded if they had greater than 55 dB hearing loss, a history of head trauma or seizures, a neurological disorder, or colorblindness. We allowed participants with mild-to-moderate hearing loss, as some degree of hearing loss is typical of older adults, and speech stimuli were presented at levels loud enough to be discriminable with mild-to-moderate loss. Participants were recruited in the Auburn-Opelika area through flyers and emails at Auburn University and in the surrounding community. An advertisement was placed through *auburn.sona-systems.com* as well as at organizations in the local community. Participants were compensated for their time and received $10 per hour or $20 for the completion of the study.

All procedures were administered in accordance with the Auburn University-approved IRB protocol #19-187 and the Declaration of Helsinki.

Materials

MoCA

The MoCA (Nasreddine, 2005) is a screening tool for detecting cognitive impairment. The MoCA is used to detect mild cognitive decline and early signs of dementia. It assesses different cognitive domains: attention and concentration, executive functions, memory, language, visuo-constructional skills, conceptual thinking, calculations, and orientation. Example items include saying as many words beginning with the letter “F” in 60 seconds as possible, delayed recall of 5 words, and copying an ambiguous image. Each item is assigned a point value, and participants earn points for correct responses. The final score is out of 30 possible points. Participants’ scores are compared to the expected score based on age and years of education to determine if they are exhibiting signs of cognitive dysfunction (Rossetti et al., 2011). Participants must meet the score minimum derived from the median score for their age and education level to be included in the study.

Connections Test

The Connections test (Salthouse, 2000) is a pen-and-paper measure of visual attention and task switching. Each of 6 trials presents 49 circles labeled with letters or numbers positioned pseudo-randomly across a page, such that sequential targets are near to each other. Two trials have letters only, two trials have numbers only, and four have both letters and numbers. It is a trail-making task involving connecting as many targets in a sequence as possible within 20 seconds. Participants complete four conditions: connecting letters alphabetically, connecting numbers in ascending order, alternating connections between ascending letters and numbers, and alternating connections between ascending numbers and letters. The letters and numbers conditions scores reflect simple processing speed, while the letters to numbers and numbers to letters conditions scores reflect complex processing speed, or the speed at which a person is able to make decisions or problem solve in response to information. The number of connections made in the letters and numbers conditions make up the connections simple score, while the number of connections made in the letters to numbers and numbers to letters conditions reflects the participant's connections complex score.

Reading Span (RSpan) Short (Oswald et al., 2015)

RSpan Short is a computerized task to assess working memory. Participants were shown a set of sentences and were asked to judge if the sentence made sense or not. Once they read and judged a sentence, the participant was shown a letter to recall at the end of the set. In total 6 sets were presented with ascending list lengths, by twos, from 2 to 6 (i.e. 2, 2, 4, 4, 6, 6). At the end of the set, participants viewed an array of 9 letters and selected the letters they had seen in each sentence, in sequential order. The RSpan score is derived from the sum of the numbers of letters recalled from each perfectly recalled set and has a maximum score of 30.

WCST-64: Computer Version 2 (Kongs et al., 2000)

The WCST-64: Computer Version 2 (Kongs et al., 2000) is a measure of abstract rule learning and set-shifting ability, which with modified scoring also measures levels of cognitive persistence (Teubner-Rhodes et al., 2017). This task involves viewing a series of 64 cards depicting different numbers of colored shapes and sorting them to one of 4 example cards. Each card can be categorized based on the color of its symbols, the shape of its symbols, or the number of symbols it has. Participants are naïve to the sorting rule expected of them. Once ten correct categorizations have been made in a row, the sorting rule changes, and the participant must adapt their strategy. Abstract rule learning is measured by the number of trials it takes for the participant to reach the first rule change (range: 10 – 64 trials), with fewer trials indicating faster learning (Kongs et al., 2000). Set-shifting ability is measured by the number of efficient switches, which occur when the participant immediately switches to the new rule following a rule change. Set-shifting scores range from -1 (efficient switches were not possible) to 4 (Teubner-Rhodes et al., 2017). A persistence score is derived by subtracting observed total accuracy from the accuracy expected based on the participants' number of efficient switches (Teubner-Rhodes et al., 2017).

Dynamic Range Task

Participants were presented with a pretest to measure the dynamic range of the pupil in order to ensure their pupils responded appropriately to light. Participants began by being asked to focus on the middle of a light shade of grey in a solid color visual field measuring 240 mm x 169.5 mm x 7.5 mm. The participant was then presented with two varying light intensities of grey; the first was a dark shade of grey (light intensity: 464646) presented for 8 seconds and the second was a light shade of grey (light intensity: D2D2D2) presented for 8 seconds (Winn et al., 2018; Piquado et al., 2010). Participants were presented with this task a total of five times.

Time-Compressed Speech Recognition Task

The time-compressed speech recognition task was used to assess participants' recognition for words presented at time compression rates of 0% (normal speech), 30% (rapid speech), and 60% (very rapid speech).

Monosyllabic words from the NU-6-word list by Auditec (Hurley & Sells, 2003), which is used by audiologists during hearing assessments, were presented to participants via E-Prime 3.0 (Psychology Software Tools, 2016). The word lists consisted of words at 0%-compression, 30%-compression, and 60%-compression. The task was to listen to four words presented at the same compression rate and to say the words aloud after presentation as accurately as possible. There were 12 trials in each condition. Each track from the original NU-6 word lists contained 50 words, which were each presented with the carrier phrase, "say the word." Stimuli were edited using Adobe Audition in the following manner: Each track was split into individual wav files that contained only the carrier phrase and the word stimulus. The wav files were then individually edited to contain only the word and silence. Wav files in the 0%-compression condition were clipped to 2 seconds long (8 seconds for the trial). Wav files in the 30%- and 60%-compression conditions were edited to lengths of 1.2 seconds (4.8 seconds for the trial) and 0.8 seconds (3.2 seconds for the trial), respectively, to be consistent with their compression rates. The integrity of the stimuli was maintained throughout the editing process. The sample rate was 44100 Hz, and the Bit Depth 32.

Pupillometry was used to measure participants' pupil response during speech recognition, which is thought to reflect cognitive load. Micromedical Videonystagmography (VNG) goggles and headphones were used for measuring the pupils binocularly and administering the time-compressed speech recognition task. The pupil recording for each trial was 8 seconds long, which encompassed listening time in the 0%-compression condition and both listening time and participant response in the 30%- and 60%-compression conditions. To obtain the pupil diameter, we divided the pupil recording into five time windows that were each one second long. Pupil diameter at the beginning of the window was subtracted from the end to examine its relative change. We did not examine data after five seconds, which would have compared listening in 0%-compression to responding in the other conditions. When using pupillometry, it is common to remove outliers that can be created from blinks, longer periods of closed eyes, or other artifacts (Kret & Sjak-Shie, 2019). Any value over 50 was removed, as values higher represent an impossible change in pupil dilation. A total of 406 entries were removed out of 7485 (5% of data). The change in pupil diameter was calculated for each eye and the value used in analysis was an average for both eyes.

Procedure

Prior to the COVID-19 pandemic, all procedures were conducted in-person over the course of 2 visits. Each participant began by completing informed consent and background questionnaires. Participants were screened for cognitive/memory impairments with the MoCA. After eligibility in the study was confirmed, participants completed the Connections task, the Automated Short RSpan task, and the WCST-64.

During the second visit of the experiment, vision and hearing screenings were conducted in the Auburn University Speech and Hearing Clinic. A Snellen's chart was used for vision screening with subjects with normal or corrected-to-normal (20/20) vision qualifying for the study. The audiologic screening consisted of a) otoscopic examination to ensure normal outer ear structure, b) tympanometry to confirm normal middle ear function, and c) hearing sensitivity determination at frequencies 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz in both ears.

After screening, participants completed the pupil dynamic range task and the time-compressed speech recognition task while their pupil diameter was measured using pupillometry. The time-compressed speech test was administered at a comfortable listening level through headphones. Pupil diameter and dilation was measured using non-invasive Micromedical Videonystagmography (VNG) goggles. Initial pupil diameter and final pupil diameter for each 1 second time period were obtained. Pupil diameter was calculated by subtracting the initial from final pupil diameter for the various conditions.

Following the onset of the COVID-19 pandemic, procedures were adapted to reduce the amount of in-person contact. The consent procedure, questionnaires, MoCA, and RSpan were completed online on video conferencing. The WCST and connections test were administered in person in the beginning of Visit 2, which remained in person. PPE was worn and the lab was sanitized before and after each participant's visit. A total of 21 participants, some who were later excluded for incomplete data, were run in person before the COVID-19 changes went into effect.

Statistical Analyses

To verify that our sample demonstrated typical age-related declines in performance on cognitive tasks, we conducted one-tailed independent-samples *t*-tests to compare younger and older adults on MoCA total score, Connections Simple number of connections, Connections Complex number of connections, RSpan score, and WCST-64 number of trials before the rule change. If assumptions of equal variance were not met, then the Welch's *t*-test was used. The

Mann-Whitney U test was used to compare younger and older adults on number of efficient switches, which is an ordinal variable (participants who cannot achieve an efficient switch are given a score of -1).

To examine word repetition accuracy (ACC) when listening to time-compressed speech, a logistic mixed effects model was created using the glmer function in the lme4 package (Bates et al., 2015) in R. The model included fixed effects of age group (AG), persistence (PERSIST), the level of time-compression (COMP), and their interactions as well as a by-subjects (SUBJ) random intercept term with a random slope of time-compression. The by-items random intercept term was not included because the words were presented in a fixed order to minimize individual differences. We therefore used the maximal random effects structure justified by the design as recommended by Barr et al. (2013). The model for word repetition accuracy was conducted using the following: ACC = AG + PERSIST + COMP + AG × PERSIST + AG × COMP + PERSIST × COMP + AG × PERSIST × COMP + (1 + COMP | SUBJ).

To examine change in pupil dilation (ΔPD) when listening to time-compressed speech, we conducted linear mixed effects models using lmer separately for each time window. This approach is useful for eye data that have considerable individual variability, missing data, or unbalanced designs when the precise time-course of the signal is not of interest (Ito & Knoeferle, 2022). To determine whether changes in pupil dilation are non-linear as time-compression increases, we compared models with and without the quadratic effect of time-compression at each time window (specified below with only the interaction terms for simplicity). Linear and quadratic time-compression terms were added using the R function poly, which creates orthogonal polynomial variables to prevent collinearity. To enable direct model comparison via likelihood ratio tests, models were fit by maximum likelihood and include by-subjects random intercepts but not slopes. The best-fitting model was re-fit using REML to obtain unbiased estimates of variance components and fixed effects and minimize the likelihood of type I error (Luke, 2017).

Model 1: $\Delta PD = AG \times PERSIST \times COMP + (1 \mid SUBJ)$

Model 2: $\Delta PD = AG \times PERSIST \times COMP \times COMP^2 + (1 \mid SUBJ)$

The model with the significantly better fit, with a p-value < 0.05 from the likelihood ratio test, was selected as the best-fitting model for that time window. If the comparison was not statistically significant ($p \geq 0.05$), Model 1 was considered the best-fitting model.

In all regression models, age group was dummy coded with younger adults as the reference level, while persistence and compression were both scaled to z-scores. All analyses were conducted using a significance level of 0.05.

Results

An independent samples t-test on MoCA scores and age group showed no significant difference between the younger (M = 27.82, SE = 0.39) and older (M = 26.56, SE = 0.69) groups ($t(35) = 1.60$, $p = .06$, one-tailed). However, the younger group demonstrated significantly better performance on the Connections Simple task (M = 129.58, SE = 4.48) compared to the older group (M = 94.86, SE = 12.70; $t(31) = 3.23$, $p = .001$, one-tailed), and on the Connections Complex task (M = 70.15, SE = 3.04) compared to the Older group (M = 54.57, SE = 5.41; t(31) = 2.40, $p = .01$, one-tailed). Performance on the RSpan task was also significantly higher in the younger group (M = 23.91, SE = 0.90) compared to the older group (M = 19.43, SE = 2.28; $t(28) = 2.19$, $p = .02$, one-tailed). Analysis of WCST trials to learn using Welch's *t* for one-tailed hypothesis revealed no significant group differences (Younger: M = 12.29, SE = 0.22; Older: M = 16.11, SE = 2.27; $t(8.15) = -1.68$, $p = .93$). The Mann-Whitney U found no significant differences found between younger (*M* = 2.36, *SE* = 0.28) and older adults (*M* = 1.90, *SE* = 0.57) for the number of efficient switches on the WCST ($W = 160$, $p = .25$).

Word Repetition Accuracy

The initial logistic mixed-effects model of word repetition accuracy converged but had a singular fit. Thus a simpler model was fitted, which had the same fixed effects of age group, persistence, compression, and their interactions, but included only a by-subject random intercept term. The results of this simplified logistic mixed-effects model are presented in Table 1.

Table 1

Summary of Fixed Effects from the Model of Word Repetition Accuracy

Fixed Effect	*B*	*SE*	*z*	*p*
Intercept	1.98	0.11	18.03	<.001
Age Group: Older	-0.15	0.23	-0.63	0.531
Persistence	0.33	0.15	2.18	0.029*
Compression	-0.32	0.05	-6.26	<.001*
Age Group: Older × Persistence	-0.28	0.19	-1.45	0.146
Age Group: Older × Compression	-0.24	0.11	-2.23	0.026*
Persistence × Compression	-0.01	0.06	-0.14	0.886
Age Group: Older × Persistence × Compression	-0.11	0.08	-1.32	0.186

Note: * p < .05. The intercept reflects log-odds of a correct response in younger adults with mean levels of persistence at 30%-compression.

The simplified model revealed a statistically significant effect of persistence (z = 2.18, p = .03), indicating that as persistence increases, accurate responding increases at 30% compression in younger adults. Also, a significant effect of compression was found (z = -6.26, p < .001), suggesting that higher levels of compression are associated with decreased accurate responding.

There was a statistically significant two-way interaction between age group and compression (z = -2.23, p = .03). This indicates that the effect of compression on the predicted probability of accuracy differs between the age groups. The negative relationship between scaled compression and accuracy is stronger for the older group compared to the younger group. Whereas the predicted probability of correct word recognition declines from 0.91 (*SE* = 0.01) at 0%-compression to 0.83 (*SE* = 0.02) at 60%-compression for a younger adult with average persistence, it declines from 0.93 (*SE* = 0.02) at 0%-compression to 0.76 (*SE* = 0.04) at 60%-compression for an older adult (see Figure 1).

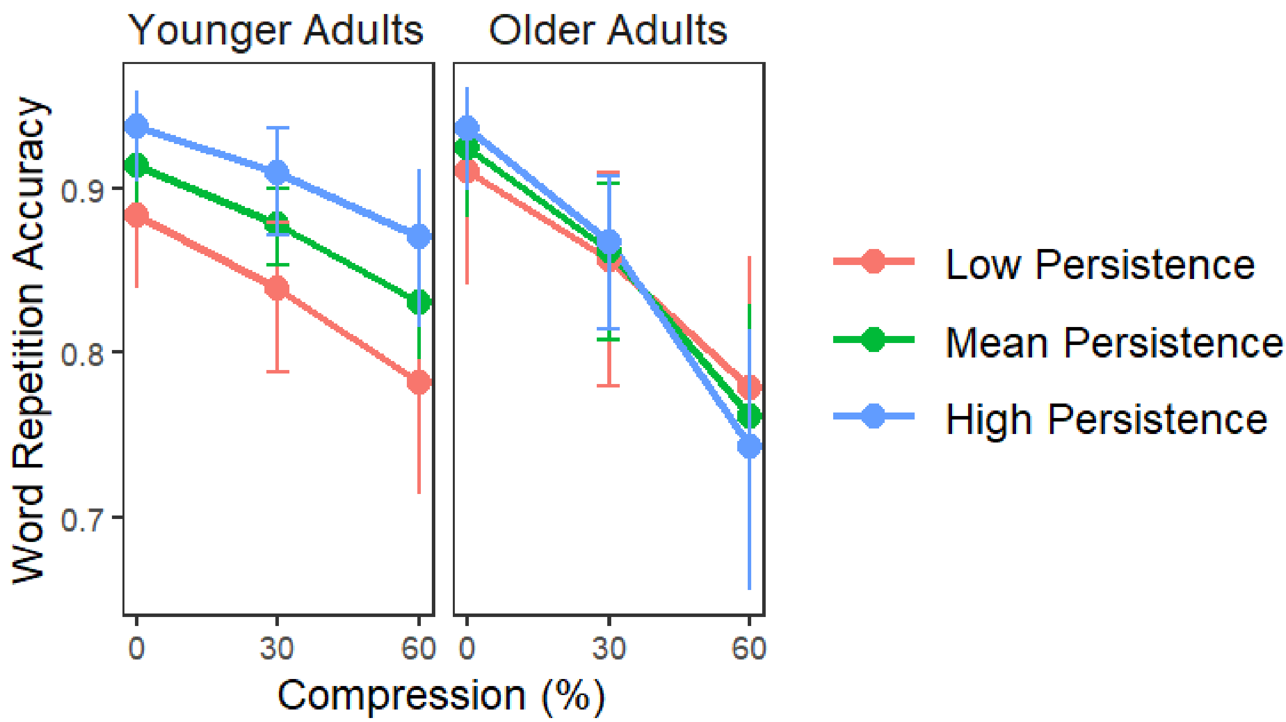

Figure 1. Predicted probability of word repetition accuracy by age group, compression, and persistence. Lines represent persistence at the mean ± 1SD. Error bars indicate 95% confidence intervals.

Pupillometry

The complete results for linear mixed-effects models of ΔPD in each time window are reported in the Appendix (Table A1). Key results are summarized below.

Time Window 1

Analysis of ΔPD during the first time window indicated that the inclusion of the quadratic term marginally improved the model fit ($\chi^2(4) = 8.89$, $p = .06$). Therefore, Model 2 was selected as the best-fitting model for time window 1 and re-fitted using REML.

Results from the REML-fitted linear mixed-effects model for ΔPD time window 1 revealed two statistically significant fixed effects. A significant effect of age group was observed ($\beta = 0.80$, $SE = 0.41$; $t(1281) = 1.96$, $p = .0499$), indicating that ΔPD in time window 1 was significantly different between the two age groups, with older adults exhibiting higher estimated ΔPD compared to younger adults at 30% compression. Additionally, the quadratic term of speech compression was a significant predictor of ΔPD time window 1 ($\beta = 18.36$, $SE = 7.40$; $t(1281) = 2.48$, $p = .01$). This finding suggests a significant non-linear, quadratic relationship between speech compression and ΔPD in younger adults in this time window, such that ΔPD decreased from 0%- to 30%-compression, and increased again at 60%-compression (see Figure 2).

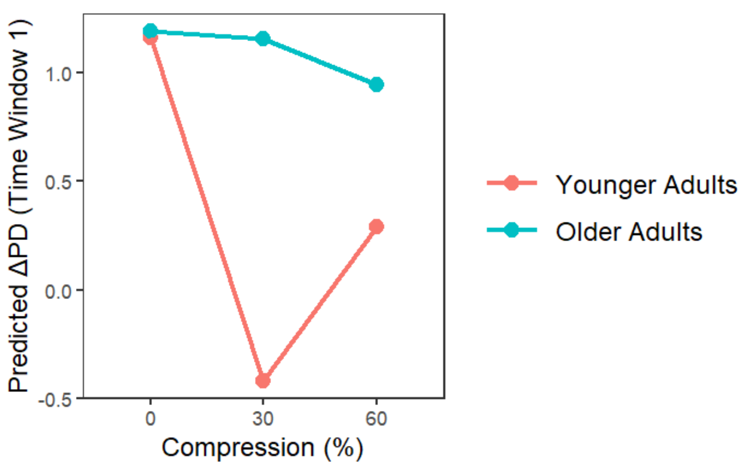

Figure 2. ΔPD in time window 1 as predicted by compression and age group, displayed at the mean level of persistence.

Time Window 2

For the second time window, including the quadratic term for time-compression did not significantly improve the model fit ($\chi^2(4) = 0.71$, $p = .95$). Model 1 was selected as the best-fitting model and subsequently re-fitted using REML. Analysis of ΔPD in time window 2 revealed several significant fixed effects in the REML-fitted linear mixed-effects model. A significant effect of persistence was observed (β = 1.23, *SE* = 0.41; $t(23.11) = 3.00$, $p = .01$), indicating that ΔPD increased significantly with higher levels of persistence in younger adults at 30% compression. A significant effect of compression was also found (β = 0.52, *SE* = 0.19; $t(1233.27) = 2.70$, $p = .01$), suggesting that higher speech compression rates were associated with increased ΔPD in younger adults with mean levels of persistence. Furthermore, a significant two-way interaction between persistence and compression was present (β = 0.82, *SE* = 0.28; $t(1242.19) = 2.89$, $p = .004$). This indicates that the relationship between the speech compression score and ΔPD in this time window is moderated by persistence. Finally, a significant three-way interaction among age group, persistence, and compression was observed (β = -1.40, *SE* = 0.35; $t(1236.06) = -3.99$, $p < .001$). This complex interaction suggests that the combined effects of persistence and speech compression on ΔPD vary significantly across the two age groups (see Figure 3). Specifically, whereas younger adults with different levels of persistence began with similar ΔPDs at 0%-compression, those with higher persistence showed larger increases in pupil diameter as speech compression increased. In contrast, older adults with higher persistence began with larger ΔPDs at 0%-compression than those with lower persistence, and this difference across persistence levels diminished as compression increased.

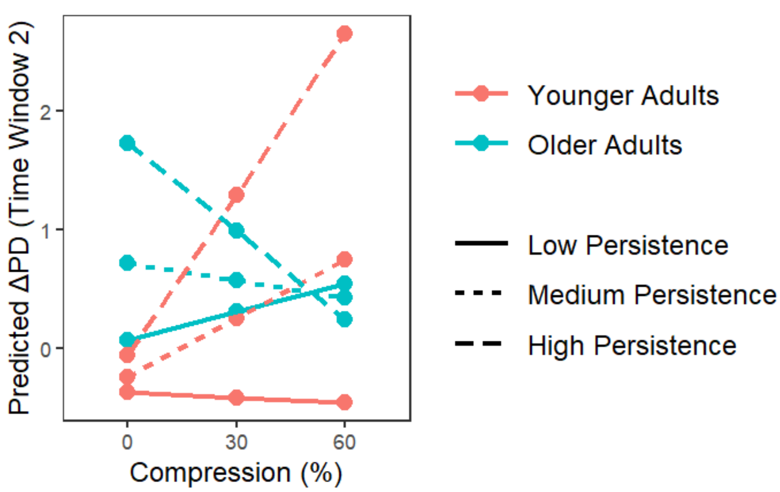

Figure 3. ΔPD in time window 2 as predicted by compression and age group, displayed at the 10th, 50th, and 90th percentiles of persistence.

Time Window 3

For the third time window, the likelihood ratio test did not indicate a significantly better fit for Model 2 compared to Model 1 ($\chi^2(4) = 6.80$, $p = .15$). Therefore, Model 1 was selected as the best-fitting model of ΔPD and subsequently re-fitted using REML.

For ΔPD in time window 3, the REML-fitted linear mixed-effects model revealed a marginal effect of persistence ($\beta = 0.55$, $SE = 0.29$; $t(1280) = 1.86$, $p = .06$), such that those with higher persistence tended to have larger ΔPDs in time window 3. There was also a significant two-way interaction between older age and compression ($\beta = 0.879$, $SE = 0.391$; $t(1280) = 2.25$, $p = 0.03$). This indicates that the linear relationship between speech compression and ΔPD in time window 3 is significantly different for older compared to younger adults (see Figure 4), with ΔPDs significantly increasing with compression in older adults ($\beta = 0.75$, $SE = 0.34$; $t(1249) = 2.23$, $p = .03$), compared to the non-significant decrease with compression in younger adults at mean persistence levels ($\beta = -0.12$, $SE = 0.20$; $t(1259) = -0.63$, $p = .53$).

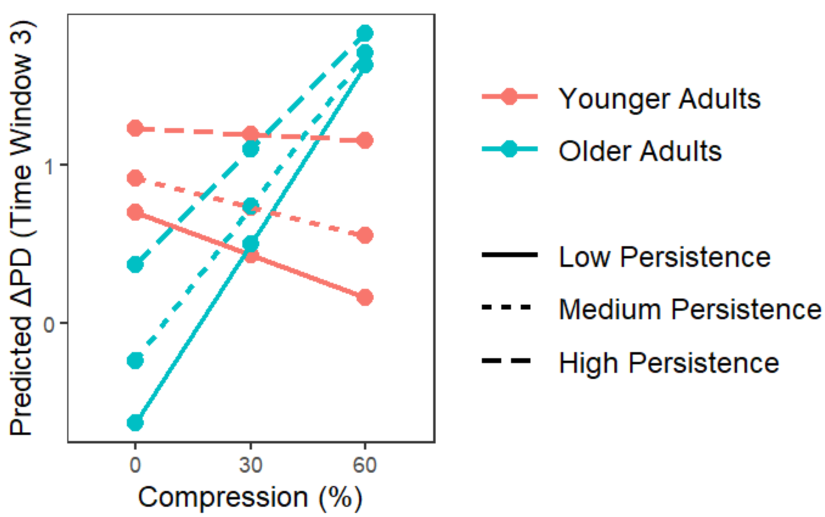

Figure 4. ΔPD in time window 3 as predicted by compression and age group, displayed at the 10^{th}, 50^{th}, and 90^{th} percentiles of persistence.

Time Window 4

For the fourth time window, the likelihood ratio test revealed a statistically significant improvement in model fit when the quadratic term for time-compression and its interactions were included (Model 2; $\chi^2(4) = 20.05$, $p < .001$). Therefore, Model 2, incorporating both the linear and quadratic effects of time-compression, was selected as the best-fitting model of ΔPD and subsequently re-fitted using REML.

Analysis of ΔPD in time window 4 using the REML-fitted linear mixed-effects model revealed a significant fixed effect for the quadratic speech compression term ($\beta = -28.05$, $SE = 7.59$, $t(1237.91) = -3.69$, $p < .001$). This finding indicates a significant non-linear, quadratic relationship between speech compression and ΔPD in younger adults in this time window (see Figure 9), where ΔPD was significantly higher at 30%-compression ($M = 1.74$, $SE = 0.45$) than at 0%-compression ($M = -0.07$, $SE = 0.45$; $t(1240) = 3.55$, $p < .001$) or at 60%-compression ($M = 0.26$, $SE = 0.46$; $t(1244) = 2.84$, $p = .005$) at mean levels of persistence. In older adults, ΔPD was not significantly higher at 30%-compression ($M = 0.19$, $SE = 0.76$) than 0%- ($M = -0.33$, $SE = 0.77$; $t(1241) = 0.59$, $p = .56$) or 60%-compression ($M = 0.04$, $SE = 0.75$, $t(1240) = 0.18$, $p = .86$) at mean levels of persistence (see Figure 5).

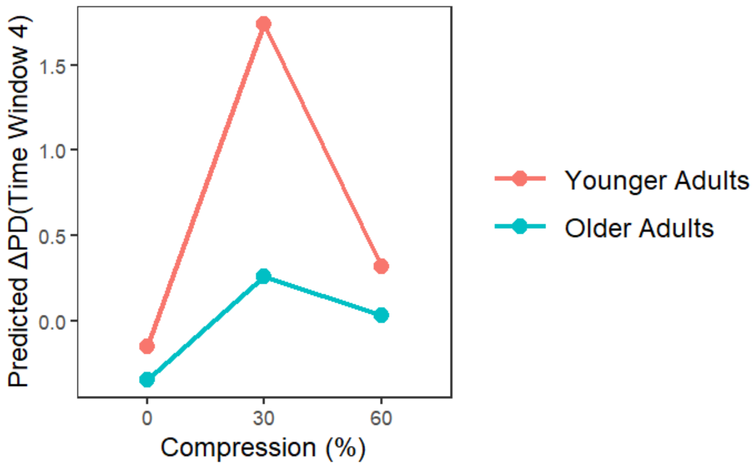

Figure 5. ΔPD in time window 4 as predicted by compression and age group, displayed at the mean level of persistence.

Time Window 5

In time window 5, Model 1 demonstrated a better fit to the data compared to Model 2, which did not significantly improve model fit ($\chi^2(4) = 4.99$, $p = .29$). Therefore, Model 1 was selected as the best-fitting model. For ΔPD in time window 5, the REML-fitted linear mixed-effects model revealed no statistically significant fixed effects at the conventional alpha level of .05.

Discussion

We observed typical effects of time-compressed speech, namely that word recognition decreased as speech rate increased. Interestingly older adults exhibited steeper declines in word repetition accuracy with increased time-compression than younger adults, indicating age-related declines in processing time-compressed speech. Additionally, higher levels of persistence were associated with better word repetition accuracy, suggesting a benefit of applying effort when recognizing speech. The effects of age group, persistence, and time-compression on pupil diameter were complex and depended on the time window analysis, with some indication that the pupil response to fast speech rate was delayed in older adults relative to younger adults. We discuss the implications of these results in detail below.

Older adults' speech recognition was more adversely affected by time-compression than younger adults. This supports the established pattern of age-related declines in cognitive abilities such as processing speed, working memory, and executive functions (Salthouse, 2010; Ziegler, et al., 2013). These cognitive declines may contribute to the increased difficulty older adults experience when processing time-compressed speech, as task demands include rapid processing, working memory demands, and the ability to manage increasing cognitive load (Pichora-Fuller et al., 2016). The findings of this study contribute to the existing literature on cognitive aging and speech perception in challenging listening conditions. The observation that word repetition accuracy decreases with increasing time-compression, and that this effect is more pronounced in older adults, is consistent with previous research demonstrating age-related deficits in processing degraded or rapidly presented speech (Pichora-Fuller et al., 2016). This study provides insights into the factors influencing word repetition accuracy when listening to time-compressed speech, highlighting the amplified difficulty faced by older adults. The significant interaction between age groups and compression highlights the impact of age-related cognitive vulnerabilities on processing rapid speech.

The significant positive effect of persistence on word repetition accuracy suggests that individual differences can modulate performance on this cognitively demanding task. Higher persistence leads to higher accuracy when repeating time-compressed words, potentially by increasing effort or engagement, which could help counteract the negative effects of compression. The positive association between persistence and word repetition accuracy also supports the literature exploring the role of factors such as motivation, effort, or grit, in influencing performance on cognitive tasks (Choi et al., 2010; 2015; Duckworth et al., 2007; Rhodes et al., 2017; Rhodes & Giovannetti, 2022). However, the beneficial effect of persistence was not significantly moderated by time-compression or by age. This may indicate that the ability and willingness to apply effort may help participants of all ages listen to and repeat back a series of words at both normal and fast speech rates.

The analysis of ΔPDs across time windows revealed some effects were consistent across windows, while others were not, highlighting the evolving nature of cognitive load during speech comprehension. A notable age difference emerged in the initial time window, where older adults exhibited significantly larger ΔPDs compared to younger adults. Larger pupil size and pupil dilation response has been connected to better cognitive abilities (Zekveld et al., 2018), which seems to be reflected in our healthy older sample's MoCA scores. Interestingly, results showing larger ΔPDs in older adults than younger adults run counter to the finding that age is related to smaller pupil size and pupil dilation response (Zekveld et al., 2018). The significantly larger ΔPDs exhibited by the older adults suggests a higher baseline or initial engagement of cognitive resources in older adults, regardless of the compression level or their persistence. This could indicate that the initial processing demands of task onset are particularly salient for older adults. Typically, larger pupil diameter at baseline is associated with poorer performance (Zekveld et al., 2018). In later time windows, age group interacted with compression levels: whereas young adults (but not older adults) demonstrated increased ΔPD at faster speech rates in time window 2, older adults (but not young adults) demonstrated increased ΔPD at faster speech rates in time window 3. This perhaps indicates that both young and older adults exert increased effort in response to time-compressed speech, but young adults have a faster physiological response to the increased listening demands.   Increased degradation of stimuli is associated with larger pupil size and pupil dilation response up to resource overload (Zekveld et al., 2018), which may help explain our finding that higher persistence led to larger ΔPDs at 0%-compression for older adults compared to younger adults, but diminished as compression increased.

Speech compression consistently showed a significant impact on ΔPD, although the nature of this effect varied over time. In early (time window 1) and later (time window 4) time windows, a significant quadratic relationship was observed. The middle time windows (2-3) were best described with a linear model. The switches from a quadratic to a linear relationship and back suggests that the response to compression changes as processing unfolds. This may, in part, have to do with how much speech information has been presented at different time windows. For the middle time windows, speech is still being processed in all conditions, with the greatest demands for 60%-condition, which is the fastest speech rate. However, by time window 4, the demands of speech processing are ending for the 60%-compression condition, resulting in a return to baseline, but still ongoing for the 30%-compression condition, resulting in continued elevation in pupil diameter.

Cognitive persistence demonstrated a significant positive effect on ΔPD in time window 2, indicating that individuals with higher persistence generally exhibited greater cognitive effort during this phase. While a marginally significant trend in the same direction was seen in time window 3, the effect was not significant in the earlier or later windows. This could imply that the effect of persistence is most pronounced during the middle of processing the speech content. At time window 2, the effect of persistence interacted with age group and compression. While higher persistence was associated with larger ΔPDs in time window 2 for both age groups, for younger adults this persistence effect was smallest at 0%-compression and became larger as compression and ΔPD increased. In contrast, for older adults, this persistence effect was largest at 0%-compression and became smaller as compression increased – *and ΔPD decreased*. While the increase in persistence effects with compression in younger adults is expected, the opposite trend in older adults is somewhat surprising – why should persistence result in more physiological effort for normal than fast speech rates in older adults? One possibility is that baseline effort even for normal speech is higher in older adults, especially those who are more persistent. Another is that older adults exhibit a delayed response to time-compression, failing to increase their effort with increased compression until time window 3.

Several limitations should be acknowledged. The sample size, while sufficient for the statistical analyses conducted, may limit the generalizability of the findings to broader populations. The study participants were recruited from a community high in academics which may indicate that our sample of older adults had better cognitive health than the general population. Future research should aim for a larger and more diverse sample. Compressed speech represents one form of speech degradation. Future studies could explore the effects of various types and combinations of speech degradation. The reliance on ΔPD within predefined time windows does not capture the entire pupillary response or the peak pupil dilation over the course of listening. Analyzing the entire pupillary response/waveform could provide a more detailed understanding. Due to the change in stimulus rate during our time compressed speech task, different stages of listening or responding happened at different times based on condition during the time windows. Specifically, while speech continued through the end of time window 5 in the 0%-condition, it stopped during time window 4 in the 60%-condition (after 3.2 seconds) and during time window 5 in the 30% condition (after 4.8 seconds). This limits the comparability of effects at each time window, especially after time window 3. The time compressed speech and response windows are not distinctly identified, which may prevent useful comparison.

Additionally, by analyzing each time window separately, we were unable to assess how persistence and age affected pupil dilation over the listening period within each time condition. Including time as a variable in analyses may offer a different picture of the role age and persistence play in physiological effort when listening to time-compressed speech.

We conclude that speech comprehension for time-compressed speech is affected by an interaction between age and persistence. Older adults are more susceptible to the adverse effects of compression, exhibiting a steeper decline in word accuracy. Persistence seems to serve as a generalized compensatory mechanism, predicting better word accuracy across age groups and compression levels. Older adults show a higher initial cognitive load as indicated by ΔPD in Time Window 1 and a delayed increase in ΔPD to increasing speech rates compared to younger adults. In younger adults, high persistence leads to increased effort as the task becomes harder, while older, persistent adults show evidence of a high baseline effort but fail to increase that effort under the most demanding (fastest) conditions. These findings suggest that successful speech comprehension in challenging conditions relies on the timely and strategic deployment of cognitive effort.

Chapter 3: Factors that Contribute to CR across the Lifespan

The theory of CR proposes that individual differences in life experiences such as education, occupation, and mentally or socially stimulating activities, can prevent normal neural declines as well as dementia/brain damage from having as strong as an effect on an individual compared to someone with different experiences by creating a larger "reserve" or store of neural resources for an individual to access when needed (Harrison et al., 2015). While the effect of education, occupation, and engagement in stimulating social activities/hobbies has been studied extensively, the body of work supporting other experiences that may build CR is less established. It has been suggested by several studies that grit, "the passion and perseverance for long-term goals" (Duckworth et al., 2007), which is classified as a personality trait, is a predictor of CR (Rhodes & Giovannetitti, 2022; Rhodes et al., 2017). The most popularly researched factors that contribute to CR are experientially based, while less research has been conducted on stable individual differences such as personality traits. Grit is one such personality trait that could contribute to the development of CR. Persistence, closely related to grit but a cognitive capability, may also contribute to CR. This Chapter will suggest additional factors that may impact the development of CR, specifically grit and persistence, and conduct an experiment to investigate their relationship.

Measurement of CR

Measuring CR is typically done by proxy, resulting in some circular language regarding measurement and building CR. For example, education improves CR, and years of education is often used as an indirect measure of CR. CR is most frequently measured by a proxy derived from lifetime experience. Education, occupational attainment, or complexity and social engagement/leisure activities are often used individually or in combination. Cognitive performance measures, which typically assess processing speed, memory, attention, language, and executive function, can be used to indicate levels of cognitive function. Those with higher levels of CR perform better than those with lower levels of CR, despite age-related changes or expected decline based on pathology (Satz, 1993).

The CR index questionnaire (CRIq) was developed to integrate different proxies of CR into one scale. The CRIq is self-report and is focused on different lifestyle and cognitive factors that have been identified as important to developing CR (Nucci et al., 2012). Example items on the CRIq include years of education, professional occupation, frequency of reading newspapers and magazines, number of children, and management of one's own accounts. The scale is divided into three sections: education, working activities, and leisure time. The sub-scores from each section are averaged to create the total CR index (CRI) score, with a higher CRI score indicating higher levels of CR. The scores are classified into five CRI levels: Low (less than 70), Medium-low (70-84), Medium (85-114), Medium-high (115-130) and High (more than 130) (Nucci, 2012). The CRIq has been found to be a reliable measure of CR within a population of patients with AD with a positive correlation of 0.89 (Garba et al., 2020). The CRIq has also been validated in a sample of 499 participants, using the Brief International Cognitive Assessment for MS and was determined to be valid with a Cronbach alpha coefficient of 0.78 (Ozakbas et al., 2021).

Training for CR

Currently, there are no programs or interventions designed to build CR. While we know that education, occupation, and other lifestyle factors can build CR, we have not yet created an intervention to build CR. Often those who are concerned with their cognitive health are encouraged to pursue activities and make lifestyle changes that reflect some of the proxies of

CR. An example of this would be older adults being told to do crosswords, Sudoku, and other brain teasers to “keep sharp” (Nombela et al., 2011). These strategies may be effective because they require individuals to partake in cognitively stimulating activities, learn strategies, and develop cognitive resources, but it is important that a protocol is established that identifies activities that are more directly proven to increase CR. Proxies for CR such as education level, occupation, occupational complexity, lifestyle, and engagement in social activities can influence CR through the long period of time that the person engages in them. It is likely that no brief training program would be able to have the same impact that these lifelong hobbies would. Education, which is the primary proxy used for CR, is often measured by years of education or identified as ongoing education, indicating that CR is built slowly through the accumulation of experiences. Researchers have suggested that there is no critical period for CR and that CR can begin to be built at any point in life if the individual begins engaging in cognitively stimulating or complex activities (Stern, 2006). It is a commonly held belief that our brains cannot grow and change after we reach a certain age. Although this myth has been debunked, it is true that experiences in early life play an important role in increasing CR, with growing evidence supporting contributions to building CR from mid-life experiences as well (Chan et al., 2018). Utilizing CR to prevent or protect against different sources of cognitive decline is an attractive idea; however, as of yet, there have been no experimental studies that try to build CR through a targeted intervention. Future research will likely focus on the potential of an intervention to boost CR, because, while CR has been shown to help protect and preserve cognitive functioning after the fact, using it intentionally a priori could result in better outcomes for more people. Such an intervention could begin by focusing on participant cognitive engagement and providing/encouraging participants to seek out ongoing stimulating experiences.

Personality and Behavioral Factors that Contribute to CR

Grit

Grit is the ability to sustain effort and interest over an extended period to achieve long-term goals, and a person with high grittiness is described as having a strong work ethic, resilience in the face of challenges, and a steadfast commitment to one's aspirations (Duckworth et al., 2007). Grit is measured via the Grit Scale, which is a self-report measure that tracks perseverance of effort and consistency of interest on a Likert scale (Duckworth et al., 2007). It can also be measured by the Grit-O scale within an academic context (Eskreis-Winkler et al., 2014). Sample items from the Grit Scale include, "I have overcome setbacks to conquer an important challenge," "I have difficulty maintaining my focus on projects that take more than a few months to complete," and "I have been obsessed with a certain idea or project for a short time but later lost interest" (Duckworth et al., 2007).

Grit has proven to be a significant predictor of academic achievement and career attainment. Grit is developed by effortful engagement in activities, deliberate practice, and learning from failures. Supportive environments, a growth mindset, and self-control help to develop grit (Duckworth al., 2012). Grittiness has a strong association with better academic outcomes as well. It was found that grit was significantly correlated with academic achievement (Duckworth, & Quinn, 2009, Eskreis-Winkler et al., 2014). In addition, grit is also associated with cognitive ability, as those with higher cognitive abilities also display higher levels of grit (Rimfeld et al., 2016).

Grit has also been associated with another proxy of CR, namely, occupational attainment. An important element of building CR is ensuring that cognitive stimulation is ongoing. A study of grit and occupational retention found that gritty people are more likely to stay engaged within their occupations (Eskreis-Winkler et al., 2014). Grittiness is a quality that can be increased if so desired, by employing self-regulation strategies, cultivating a growth mindset, and engaging in deliberate practice (Duckworth et al., 2013; Duckworth et al., 2005, Eskreis-Winkler et al., 2014; Duckworth et al., 2011). Perseverance, a main component of grittiness, has been associated with increased cognitive control and attention (Ziegler et al., 2013).

Grit has been suggested as a non-cognitive component to build CR, based on a study of adolescent grit and late life cognition (Rhodes et al., 2017). The Wisconsin Longitudinal Study included a random sample of 10,317 students who graduated from high schools in Wisconsin in 1957 and collected data up to 2011. The study collected educational, career, social, family, health, and psychological variables; IQ scores from state records; and follow-up surveys collecting cognitive information. Grit was measured by class rank controlled by IQ, with an individual's rank reflecting their effort rather than innate intellectual abilities. Late-life cognition was measured via a memory task that included immediate and delayed recall. Performance on the memory task was compared to class rank and IQ together, and class rank and IQ separately. Analysis found that higher class rank and IQ predicted better recall. While both IQ and class rank acted as predictors, class rank was a stronger predictor, providing evidence that grit can act as a factor that contributes to building CR.

Persistence

In many ways, the concepts of grit and persistence have been considered interchangeable and often appear in the literature as such. This author stresses the importance of distinguishing between the two. Grit is passion and perseverance for long-term goals (Duckworth et al., 2007). Persistence is applying effort to overcome a mental challenge in the moment (Teubner-Rhodes et al., 2017). Grit is a personality trait, while persistence is a cognitive ability. Grit is measured via the Grit Scale, which asks individuals to evaluate their own grittiness. More empirical conclusions could be drawn by also administering assessments of persistence, as it is not self-reported and is a cognitive measure rather than a personality measure. This is not to say that grit research is not a valuable contributor to understanding CR, but rather that examining persistence as a factor would provide a specific connection to the cognition functions occurring in those developing higher levels of CR.

Grit and persistence are distinct concepts; however, the essence of their definitions is similar. Grit and persistence both enable individuals to recruit resources. Connections between grit and CR have already been established (Rhodes et al., 2017). Due to connections between the two constructs, it is possible the persistence can be beneficial to building CR in the same way that grit is, by allowing an individual to commit to a long-term course of action (study, occupation, habit) that in turn, allows CR to grow. As closely related concepts, it could be true that those who are considered grittier also display higher levels of cognitive persistence, and that those who have higher measured levels of persistence will show a higher level of CR as well. Nevertheless, because grit and persistence are theoretically distinct constructs that are measured differently, they may make unique contributions to the development of CR.

Task-based measures evaluating the investment of effort on difficult tasks should be considered to assess the relationship between persistence and CR. One task-based measure of persistence derived from the WCST-64 assesses the extent to which participants exceed performance expectations when the task becomes challenging (Teubner-Rhodes et al., 2017). Other measures of persistence rely on self-report measures that are subjective and domain-specific (Choi et al., 2010; Cloninger et el., 1994; Doherty-Bigara & Gilmore, 2016; Onatsu-Arvilommi & Nurmi, 2000; Pintrich et al., 1991; 1993; Steinberg et al., 2007; Zhang et al., 2011). In contrast, the WCST-64 measure uses a behavioral task to measure the application of effort to improve performance and is independent of task ability, making it an isolated measure of persistence.

Implications

Due to its protective potential, CR is important to develop. Those who have attained more education and work in stimulating occupations have a significant advantage in developing CR, and thus may experience increased quality of life and maintain functioning after neurological damages. Often, those who come from higher SES have access to higher education, which opens doors to more skilled occupations. As the advantages of CR can be so critical to well-being, it is important to investigate as many avenues as possible to increase it, especially those that are more readily available to all SES groups. Grit may be one of those factors.

Grit has been associated with academic achievement and occupational attainment; however, grittiness can exist in the absence of those factors. Grit is generally considered a personality trait, and its measurement is not limited to the confines of education or occupational achievement, rather to resilience and perseverance. Grit is perseverance and dedication to the pursuit of long-term goals. In the application of grit, there is potential for continued cognitive stimulation and the need for various cognitive domains such as sustained attention to task-relevant stimuli and inhibition to non-task relevant stimuli, problem solving, and cognitive persistence. In order to grow CR outside of academics or a demanding occupation, an individual must seek out continued participation in intellectually stimulating activities and interactions. Those higher in grit are able to sustain effort and motivation in pursuit of their goals, and thus may find developing lifestyle changes that encourage CR more feasible than their less gritty counterparts.

Hypotheses

CR theory proposes that differences in life experiences such as education, occupation, and mentally or socially stimulating activities, can prevent normal age-related neural declines and dementia/brain damage from having as strong of an effect on an individual compared to someone with different experiences. It has been suggested by several studies that the personality trait of grit, the passion and perseverance for long term goals, is a predictor of CR. Typically, the factors found to be associated with CR (e.g., education, occupation, and IQ) have an overt connection to cognitive health. In the case of grit, it is possible that an underlying cognitive variable is at play, which could explain how grit has a positive effect on CR. Persistence, which engages effort to succeed on difficult cognitive tasks, is conceptually very similar to grit, but can be measured using cognitive assessments, rather than self-report. Based on the research supporting the link between grit and CR, and the conceptual connection between grit and persistence, this researcher proposes that persistence levels could be an additional cognitive predictor of CR, and that persistence mediates the relationship between grit and CR. The theorized relationship between grit, persistence, CR, age, and performance on cognitive assessments is depicted in Figure 6.

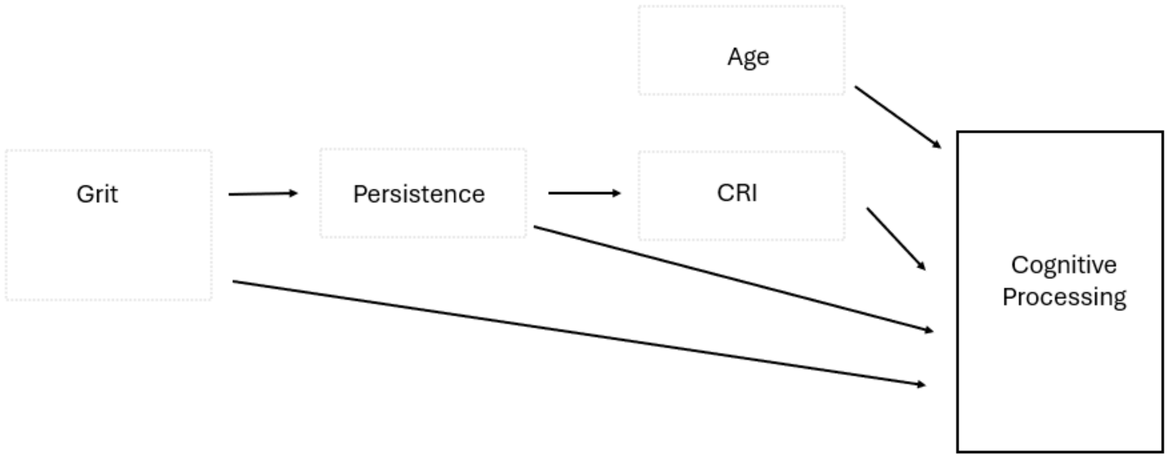

Figure 6. Theorized relationships between grit, persistence, lifetime experiences building cognitive reserve, age, and cognitive processing.

Method

Participants

Participants of this study were 50 adults aged 18 and up. We used stratified random sampling to obtain 25 adults younger than 50 years and 25 older than 50 years. Participants were recruited in the Auburn-Opelika area through flyers and emails at Auburn University and in the surrounding community, and via community outreach efforts. Additionally, the Department of Psychology's SONA research recruitment system was used to recruit student participants and the online Research Participant Screening and Registry, IRB # 23-110 EP 2303, was used to recruit healthy participants from the Auburn community. Informed consent was obtained, and all procedures were administered in accordance with the Auburn University-approved IRB protocol #24 691 EP 2403 and the Declaration of Helsinki.

Materials

Grit Scale (Qualtrics)

The Grit Scale (Duckworth, & Quinn, 2009) is a self-report measure of a participant's level of grit. The Grit Scale is a series of 12 statements and questions that participants respond to using the following scale: not like me at all, not much like me, somewhat like me, mostly like me, very much like me. Example items include: "New ideas and projects sometimes distract me from previous ones" (reverse scored), "Setbacks don't discourage me," "I don't give up easily," and "I have been obsessed with a certain idea or project for a short time but later lost interest" (reverse score). Each response is assigned a point value, and the points are added together, higher scores indicate higher grit.

CRIq (Qualtrics)

The CRIq (Nucci, 2012) measures CR acquired throughout the lifespan. The CRIq estimates a participant's CR through the collection of information related to the entire adult life. The questionnaire is divided into three sections: CRI-Education, CRI-Working Activity, and CRI-Leisure Time. The education section records the highest level of education a person obtained and assigns 1 point per year of schooling. If an individual needed to repeat a year they are given 0.5 points. In the occupation section type and years of work are recorded and sorted into different categories based on cognitive demand and responsibility. The leisure time section refers to activities such as volunteering and socializing.

MoCA

The MoCA (Nasreddine, 2005), as described in Chapter 2, is a standardized assessment for mild cognitive impairment and dementia. Unlike previously, no score minimum need be met to continue participation.

Anagram Persistence Task (APT)

The APT (Eisenberger & Leonard, 1980) is used to measure persistence. It involves solving anagrams, which are formed by rearranging the letters of words. Participants are given a series of 14 anagrams to solve that vary in difficulty: seven were solvable and seven were not. Participants tried to solve each anagram within 120 seconds by typing the solution in a response box and then clicking a button to start the next trial. They were allowed to advance to the next trial at any time. The time taken to solve each anagram or spent trying to solve it before skipping it or timing out at 120 seconds is recorded. Less time before solving the solvable anagrams indicates higher verbal ability, while more time spent trying to solve the unsolvable anagrams indicates higher persistence.

Digit Span Task

The Digit Span task (Wechsler, 1945) is a measure of short-term and working memory. In the Digit Span task, the participant is presented with six lists containing a sequence of numerical digits and is tasked to recall each sequence. The lists start with two-digit sequences and increase by 1 digit if the participant can repeat at least 5 out of 6 sequences correctly. This process continues until the person can no longer repeat the sequences, up to a maximum of 10 digits. The longest number of digits with at least 5 out of 6 sequences recalled is the person's digit span.

Connections Test

As seen in chapter 2, the Connections test (Salthouse, 2000) is a measure of visual attention and task switching. It is a trail-making task involving connecting as many targets in a sequence out of a total of 49 targets as possible within 20 seconds. It includes four conditions: letters, numbers, letters to numbers, and numbers to letters. The letters and numbers conditions scores reflect simple processing speed, while the letters to numbers and numbers to letters conditions scores reflect complex processing speed. The number of connections made in the letters and numbers conditions make up the connections simple score, while the number of connections made in the letters to numbers and numbers to letters conditions reflects the participant's connections complex score.

WCST-64: Computer Version 2

As seen in chapter 2, the WCST-64: Computer Version 2 (Kongs, 2000) is a measure of abstract rule learning and set-shifting ability, which with modified scoring also measures levels of cognitive persistence (Teubner-Rhodes et al., 2017). This task involves viewing a series of 64 cards depicting different numbers of colored shapes and sorting them to one of 4 example cards. Each card can be categorized based on the color of its symbols, the shape of its symbols, or the number of symbols it has. Participants are naïve to the sorting rule expected of them. Once ten correct categorizations have been made in a row, the sorting rule changes, and the participant must adapt their strategy. Abstract rule learning is measured by the number of trials it takes for the participant to reach the first rule change (range: 10 – 64 trials), with fewer trials indicating faster learning. Set-shifting ability is measured by the number of efficient switches, which occur when the participant immediately switches to the new rule following a rule change. Set-shifting scores range from -1 (efficient switches were not possible) to 4. A persistence score is derived by subtracting observed total accuracy from the accuracy expected based on the participants' number of efficient switches (Teubner-Rhodes et al., 2017).

Procedure

Participants were seated in a private testing room with a computer. Each participant began by completing informed consent and providing contact information. Participants who were recruited from the community recruitment pool provided certain data (including some demographics) in the recruitment screener. Participants were asked during consent if they give permission for their research data and their screener data to be linked. If they allowed those data to be linked, the corresponding information was not collected again. Then, the following background questionnaires were administered via a Qualtrics survey: demographic and language background questionnaires; the Edinburgh Handedness Inventory (Oldfield, 1971); a medical history questionnaire, the Penn State Worry Questionnaire (PSWQ) (Startup & Erickson, 2006) to index self-reported trait worry; the Prospective and Retrospective Memory Questionnaire (PRMQ) (Sala, 2020) to index prospective and retrospective memory function; the Grit Scale to assess grit via self-report items; and the CRIq to assess levels of CR by inventory of life experiences. The PSWQ and PRMQ are not the focus of the present study and will be discussed elsewhere.

The remaining measures no longer used Qualtrics. Participants were assessed for cognitive/memory impairments with the MoCA. Participants then completed a computerized APT administered through E-Prime version 3.0 (Psychology Software Tools, Pittsburgh, PA), which asked participants to unscramble letters to make words or advance to the next item without solving. The Digit Span task assessed short-term memory span and attention. The participant listened to a series of digits and were then asked to repeat the digits back in the same order. They also completed the pen-and-paper Connections task, which involved connecting a series of alphanumeric dots in order as quickly as possible, to assess simple and complex processing speed. Participants completed the computerized WCST-64 to assess rule-switching ability and persistence. They were read scripted instructions to teach them how to complete the task without giving away information about the rule switches. Participants used the mouse to drag and drop each test card to one of the 4 example cards.

The total procedure took about 1 to 1.5 hours over 1 in-person session.

Statistical Analyses

Descriptive statistics were calculated for all variables (Grit, CR, persistence from WCST-64 and persistence from APT). Prior to examining our research questions of interest, we conducted a correlation test to evaluate the relationship between persistence scores from the WCST-64 and APT assessments. We expected the persistence scores to be significantly correlated since they putatively measured the same construct; however, they were not ($r = -0.03$, $p = .82$; 95% CI [-0.31, 0.25]). Thus, we conducted analyses separately for each persistence score.

In order to investigate the theorized relationships between grit, persistence, lifetime experiences building cognitive reserve, cognitive processing, and age, path analysis was conducted. To simplify and create one cognitive processing variable, correlations were conducted between all the cognitive scores—the Digit Span Task, the connections simple, the connections complex, solvable APT, the MoCA, WCST Learning, and WCST Switching, and with age—at the $p <.05$ level. The correlation matrix between scores from the cognitive assessments and age should show the expected pattern of decline with age. We planned to simplify the cognitive assessments into one cognitive processing variable, as appropriate, by including all variables in the creation of the residual cognitive processing score. Cognitive variables that were not correlated with the other cognitive variables or with age it were not included in the composite score. To create the composite cognition variable, the cognitive assessments were z-scored and averaged. Of the cognitive assessments, higher scores indicate better performance for all but two tasks. Higher scores on the solvable APT trials and WCST learning tasks both indicate poorer performance; in order to create a composite score, the signs on the z-scores were reversed for these two tasks prior to averaging. Finally, age was regressed out so that the variable reflected cognitive performance controlled for age.

To assess the relationship between grit, persistence, lifetime experiences building cognitive reserve, cognitive processing, and age, two different path models were created and compared. Path analyses were conducted using the lavaan package (Rosseel, 2017) in R. The path analyses reflected the path models outlined in Figures 2 and 3. The first model of interest investigated if grit has a direct effect on cognitive performance. For this model, a sample size of 50 subjects is required based on the number of parameters included (Kline, 1998). In this model it is expected that increased composite cognition scores will be associated with higher CR, higher persistence and higher grit. Higher CR will be associated with higher persistence, while higher persistence will also be associated with higher grit, as depicted in Figure 7.

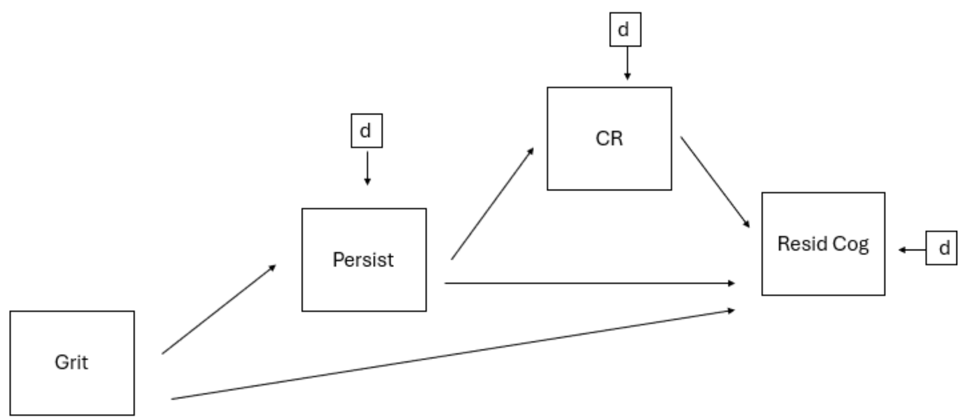

Figure 7. Proposed path model with direct effect from grit. Persist = composite persistence score; Resid Cog = composite cognition score after regressing out age; d = disturbance term.

For comparison, the second model did not include a direct effect from grit on CR. This model included four parameters, thus requiring a sample size of 40 participants. In this model it is expected that increased composite cognition scores will be associated with higher CR and higher persistence. Higher CR will be associated with higher persistence, while higher persistence will also be associated with higher grit, as depicted in Figure 8.

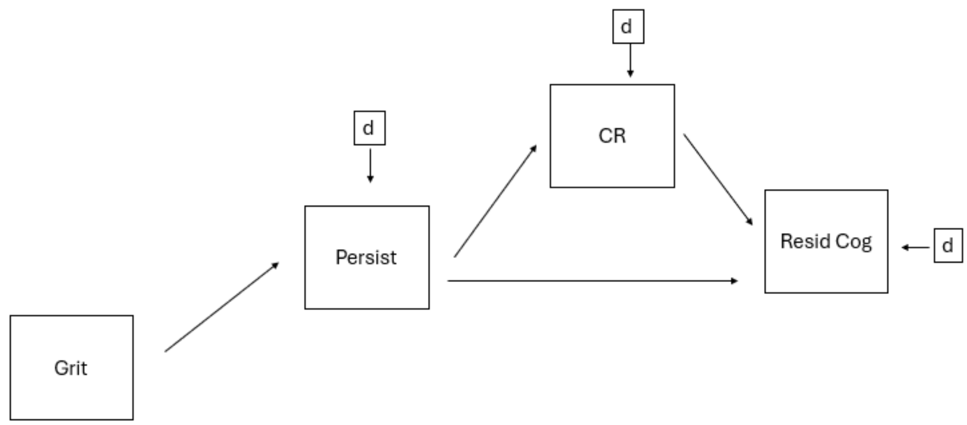

Figure 8. Proposed path model with no direct effect from grit. Persist = composite persistence score; Resid Cog = composite cognition score after regressing out age; d = disturbance term.

Directly comparing these models allowed us to determine if grit builds CR only indirectly through persistence or if it also directly contributes to lifetime experiences that contribute to CR. All analyses will be conducted using a significance level of 0.05. The data from the study is available on the Open Science Framework.

Results

Descriptive statistics for the variables included in the analysis are presented in Table 2. Pearson correlations among the cognitive processing variables (digit span, connections simple, connections complex, APT verbal RT, MOCA, trials to learn on WCST, and number of efficient switches on WCST) and age were examined (see Table 3). These revealed significant positive correlations between several cognitive variables: higher digit span scores, higher MoCA scores, and more efficient switches on WCST were each associated with completing more connections on both the simple and complex connections trials, which were also strongly correlated with each other. As longer verbal RTs on the APT indicate slower verbal processing speed, these were negatively correlated with simple and complex connections, MoCA, and number of efficient switches. This shows that, to some extent, digit span, simple and complex connections, APT verbal RT, MoCA, and number of efficient switches on WCST reflect a common index of cognitive ability. With older age, individuals made fewer simple connections, were slower to solve anagrams, and had fewer efficient shifts, with a trend toward fewer complex connections as well. This supports age-related decline of these abilities.

Table 2

Means and standard deviations for measured variables

Variable	*M*	*SD*
1. Digit Span	5.54	1.15
2. Connections Simple Score	109.02	25.07
3. Connections Complex Score	52.40	17.87
4. APT Verbal RT	10500.94	4044.06
5. MOCA	26.86	2.29
6. WCST TTL	14.71	8.60
7. WCST ES	1.31	1.33
8. Age	44.74	18.14

9. Grit Total Score	42.80	6.96
10. CRIQ Total Score	113.14	20.40
11. WCST Persist	0.01	0.10
12. APT Persist RT	54015.53	24411.66

Note. M and *SD* are used to represent mean and standard deviation, respectively. WCST TTL = WCST Trials to Learn; WCST ES = WCST Efficient Shifts.

Table 3

Correlations (with confidence intervals) between cognitive variables and age

Variable	1	2	3	4	5	6	7
1. Digit Span							
2. Connections Simple Score	.30* [.02, .53]						
3. Connections Complex Score	.42** [.16, .62]	.71** [.54, .82]					
4. APT Verbal RT	-.04 [-.32, .24]	-.52** [-.70, -.28]	-.48** [-.67, -.23]				
5. MOCA	.15 [-.14, .41]	.32* [.05, .55]	.45** [.20, .65]	-.45** [-.65, -.20]			
6. WCST TTL	-.09 [-.36, .19]	-.10 [-.37, .19]	.04 [-.24, .32]	-.06 [-.33, .23]	.15 [-.13, .42]		

7. WCST ES	.20	.31*	.29*	-.30*	.11	-.19	
	[-.09, .46]	[.03, .55]	[.01, .53]	[-.53, -.02]	[-.18, .38]	[-.45, .10]	
8. Age	-.10	-.42**	-.27	.29*	.09	.05	-.33*
	[-.36, .19]	[-.63, -.17]	[-.51, .01]	[.02, .53]	[-.20, .36]	[-.24, .33]	[-.56, -.05]

Note. Values in square brackets indicate the 95% confidence interval for each correlation. The confidence interval is a plausible range of population correlations that could have caused the sample correlation (Cumming, 2014). WCST TTL = WCST Trials to Learn; WCST ES = WCST Efficient Shifts. * indicates $p < .05$. ** indicates $p < .01$.

We note a couple of deviations from expected relationships: First, the number of trials to learn the sorting rule on the WCST was not significantly related with any of the other cognitive assessments or with age. Second, although the relationship was not significant, the correlation coefficient between MoCA and age was positive, indicating that MoCA scores numerically *increased* with age in this healthy lifespan sample, rather than demonstrating age-related decline. As a result, we opted to exclude trials to learn on WCST and MoCA scores from our composite measure of cognition. The composite cognitive processing variable was created by averaging the standardized scores from digit span, simple score, complex score, reverse-scored APT verbal RT, and number of efficient shifts on the WCST. We then took the residual composite score after regressing out age, which had a significant negative association with composite cognition (b = -0.02, SE = 0.005; t = -3.07 (48), p = .004).

Results of Planned Path Analyses

Path analysis was used to examine the relationships between grit (Total Score), CR (CRIQ Total Score), measures of persistence from both WCST and APT tasks, and the age-residualized cognitive processing composite. Two sets of models were tested, one for each persistence measure.

First, the models with persistence from WCST as the mediator were evaluated. A model including a direct path from grit to the cognitive processing composite (Model 1) and a model without the direct path (Model 2) were compared. The chi-square test of Model 1 was significant ($\chi^2(1) = 8.46$, $p = .004$; AIC = 437.84, BIC = 458.87), indicating poor fit. Model 2 also showed a significant chi-square test ($\chi^2(2) = 9.18$, $p = .01$; AIC = 436.56, BIC = 455.68), indicating poor fit. An ANOVA comparing the two models was not significant ($\Delta\chi^2(1) = 0.72$, $p = 0.40$), suggesting that removing the direct path from grit to the cognitive processing composite did not significantly worsen model fit. Given the non-significant difference and lower AIC and BIC values, Model 2, the more parsimonious model, was selected as the preferred model. In this model, the path from persistence to CRIQ total score was marginally significant ($b = 0.25$, $SE = 0.14$; $z = 1.78$, $p = .08$) and the path from CRIq total score to the cognitive processing composite score was not significant ($b = .001$, $SE = 0.15$; $z = 0.01$, $p = .995$). The path from persistence to the cognitive processing composite score was also not significant ($b = -0.06$, $SE = 0.15$; $z = -0.40$, $p = .69$). The path from grit to persistence was not significant ($b = -0.02$, $SE = -0.02$; $z = 0.14$, $p = .89$). The indirect effects and total effects were not statistically significant. Overall, given the poor model fit and absence of significant relationships between variables in the model, the hypothesis that grit builds cognitive reserve through persistence as measured by WCST was not supported. There was a trend for higher WCST persistence scores to be associated with higher CRIq scores, but this did not reach significance (see Figure 9).

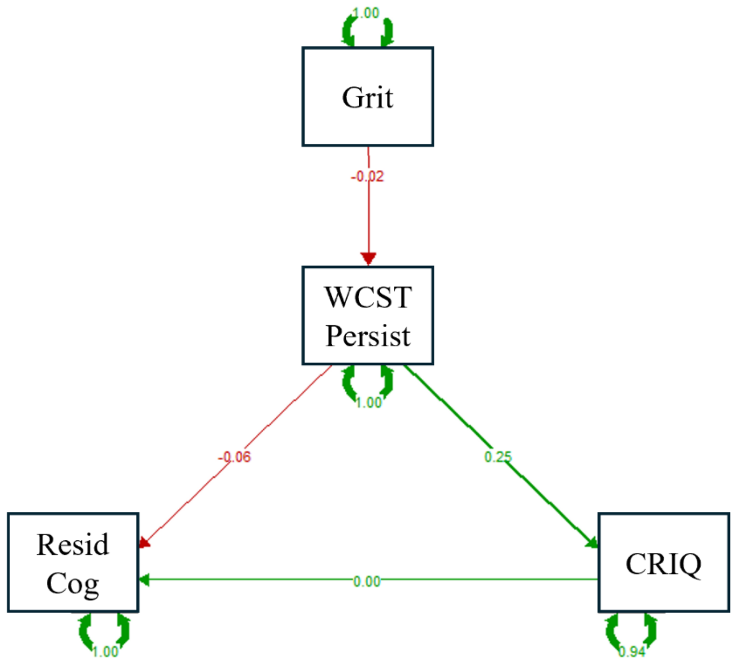

Figure 9. *Path Analysis Model of Grit, WCST Persistence, CRIQ, and Cognitive Processing.* Fit statistics for this model were poor ($\chi^2(2) = 9.18$, $p = .01$; $AIC = 436.56$, $BIC = 455.68$). WCST Persist = persistence measure from WCST; Resid cog = age-residualized cognitive variable.

Then the models incorporating persistence from APT as the mediator were evaluated. A model including a direct path from grit to the cognitive processing composite (Model 1) and a model without the direct path (Model 2) were compared. The chi-square test of Model 1 was significant ($\chi^2(1) = 9.47$, $p = .002$; $AIC = 437.98$, $BIC = 459.01$), indicating poor fit. Model 2 also showed a significant chi-square test ($\chi^2(2) = 9.70$, $p = .01$; $AIC = 436.21$, $BIC = 455.33$), indicating poor fit. An ANOVA comparing the two models was not significant, ($\Delta\chi^2(1) = 0.23$, $p = 0.63$) suggesting that removing the direct path from grit to the cognitive processing composite did not significantly worsen model fit. Given the non-significant difference and lower AIC and BIC values, Model 2, the more parsimonious model, was selected as the preferred model. In this model, the path from persistence to CRIQ total score was not statistically significant ($b = 0.05$, *SE* = 0.14; z = -0.36 p = .72), nor was the path from CRIQ total score to the cognitive processing composite (b = -0.02, *SE* = 0.14; z = -0.14, p = .89). The path from persistence to the cognitive processing composite was not significant (b = -0.13, *SE* = 0.14; z = -0.95, p = .34). The path from grit to persistence was statistically significant (b = 0.32, *SE* = 0.13, z = 2.39, p = .02). The indirect effects and total effects were not statistically significant. Again, the hypothesis that grit builds cognitive reserve through effects on persistence as measured by the APT was not supported. We did find evidence that higher grit is associated with more time trying to solve unsolvable anagrams, but this was not related to greater CRIq scores or age-adjusted cognitive processing (see Figure 10).

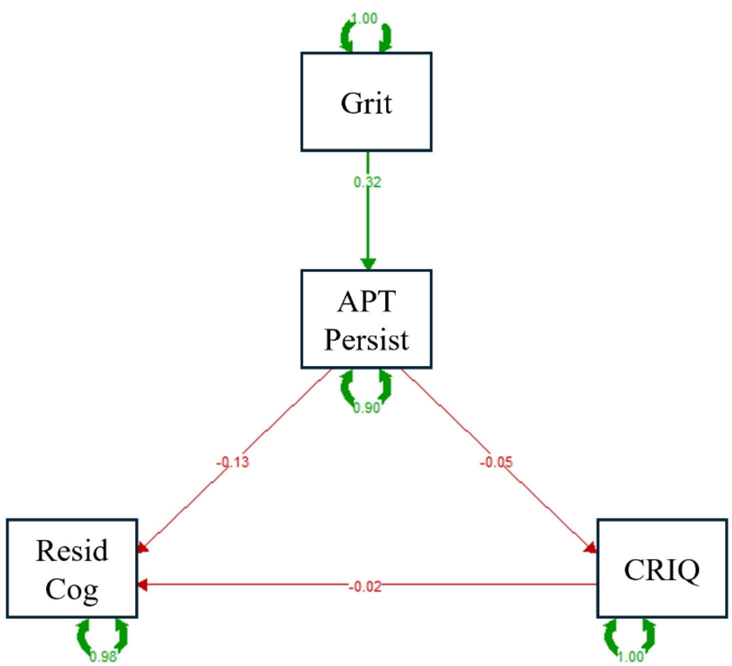

Figure 10. *Path Analysis Model of Grit, APT Persistence, CRIQ, and Cognitive Processing.* Fit statistics for this model were poor ($\chi^2(2)$ = 9.70, p = .01; *AIC* = 436.21, *BIC* = 455.33).

Results of Exploratory Statistical Analyses

Grit and persistence were not significantly related to the CRIQ, so we conducted exploratory analyses to better understand the null result. Correlations between persistence and grit with CRI-Education, CRI-Working Activity, and CRI-Leisure Time sub-scores were conducted. This evaluated if persistence and grit might be selectively related to CR in a particular lifestyle domain. If significant correlations were observed, the path model was re-evaluated using the CRI sub-scores that were identified as the dependent variable.

CRIQ section 1: education was significantly correlated with grit total score ($r(48) = 0.39$, $p = .005$). This suggests that individuals reporting higher levels of grit also achieved higher total scores in Section 1. CRIQ section 3: leisure time was also significantly and correlated with grit total score, ($r(48) = 0.33$, $p = .02$), with individuals reporting higher grit tending to have higher scores. As before, the path models conducted using CRIQ section 1, and the models using CRIQ section 3 did not reach significance.

Discussion

The findings did not support the hypothesized path models where grit builds cognitive reserve through persistence and influences cognitive processing, regardless of if persistence was measured by the WCST or APT. The poor fit of both tested models suggests that the proposed theoretical framework may not adequately capture the relationships among these variables in our sample. The lack of a significant correlation between WCST persistence and APT persistence contradicts the assumption that these tasks measure the same underlying construct of persistence and suggests that persistence may be a multi-faceted construct, with different tasks tapping into distinct behavioral or cognitive aspects of perseverance, an idea we explore in more detail below.

The decision to exclude WCST learning and MoCA from the composite cognitive processing variable was due to the lack of expected correlations with other cognitive measures and age in this sample. While the other included measures showed the anticipated age-related decline and correlations, the unexpected positive correlation between MoCA and age, although not significant, suggests potential sample-specific characteristics or limitations of the MoCA in this healthy lifespan group. Our CRIq education scores indicated that our participants were highly educated, which may have limited the range of cognitive reserve in our sample. Additionally, screening out individuals with neuropathology such as AD may selectively exclude older adults with low cognitive reserve; as the prevalence of AD diagnoses increases after age 65 years (Alzheimer's Association, 2025), our sample may include younger and middle-aged adults who will subsequently develop AD but is less likely to include older adults who will subsequently develop AD. Our data provides some support for this notion: CRIq scores were positively associated with age, suggesting that older adults in our sample had more cognitive reserve building experiences than younger adults did. Since the calculation of CRIq scores already corrects for age, due to the longer time older adults have to accumulate reserve building experiences, we had anticipated that CRIq would be an age-independent variable when building our path model. The remaining correlation between age and CRIq suggests that the age-correction was insufficient in the present highly educated and healthy lifespan sample.

The results of the path analyses indicate there was no statistical evidence to support the proposed pathways from grit to cognitive reserve and cognitive processing. While a significant association between grit and APT persistence was found, this specific measure of persistence did not appear to mediate the relationship between grit and cognitive reserve or cognitive processing in the hypothesized manner. This suggests that if grit does influence cognitive reserve or cognitive function, it may do so through different mechanisms or in conjunction with other factors not included in our models. The non-significant paths from persistence to CRIQ and from CRIQ to cognitive processing in both models further suggest that, in this sample and with these specific measures, persistence and cognitive reserve as measured by CRIQ did not function as hypothesized mediators in the pathway from grit to cognitive processing.

The finding that WCST persistence and APT persistence were not correlated could suggest that measures can be task-specific and that constructs like persistence may manifest differently depending on the demands of the task. Interestingly, these persistence metrics also had diverging correlations within the path model. Higher WCST persistence was marginally related to higher CRIq scores but was unrelated to grit. In contrast, higher APT persistence was significantly related to higher grit but was unrelated to CRIq scores. This may indicate two distinct dimensions to persistence: 1) effort-based persistence, measured by the WCST, which helps individuals pursue activities that build reserve, and 2) time-based persistence, measured by the APT, which is associated with a tendency to stick with tasks until they have been completed. Teubner-Rhodes et al. (2017) identified that the WCST metric of persistence differed from existing task-based measures of persistence in that WCST persistence examines effort-related variability in performance while other metrics examine time spent working on a task until quitting. Our results may be taken as preliminary validation for this distinction, as individuals with higher WCST persistence tended to pursue more years of education, occupational complexity, and social engagement, while those with higher APT persistence had greater grit. However, these relationships were small, with only the latter reaching statistical significance. Additional research explicitly designed to examine whether mental effort and time spent working reflect two separate aspects of persistence is warranted.

The limitations of this study include sample size, which was sufficient for the path analyses based on Kline's guidelines but may still be a limitation in detecting smaller effects or supporting more complex models. The finding that MoCA was not significantly related to age in this sample is also a limitation that affects the generalizability of the composite cognition variable. As MoCA is used as a diagnostic tool for cognitive impairment, it would be useful to relate cognitive reserve to performance on the MoCA to understand the extent to which cognitive reserve protects against age-related impairments. Further research should consider investigating this topic by including additional measures, such as more measures of Persistence (e.g. mirror tracing task) , further cognitive testing, and physiological markers of effort (e.g. pupillometry). Additionally, using longitudinal designs could provide more clarity about a person’s grit level and commitment to seeing tasks through. A longitudinal design would also allow tracking of CR levels as they are built up.

Chapter 4: General Discussion

The combined aims of the two projects included in this dissertation attempt to refine our understanding of how individual effort and aging interact when encountering cognitive challenges. The central conclusion is that persistence can act as a valuable compensatory mechanism in challenging cognitive environments, but its effectiveness is affected by age-related limitations such as deploying cognitive effort in a timely manner and cognitive capacity.

The results of both projects taken together suggest that persistence may have a generalized compensatory role. In Project 1, higher cognitive persistence predicted better word repetition accuracy for both younger and older adults, indicating that sustained effort mitigates the performance decline caused by increased task difficulty. In Project 2, the significant correlation between grit and APT Persistence shows that grit is associated with an increased tendency to work longer in demanding problem-solving situations. Taken together, this evidence supports persistence as a beneficial resource that potentially improves outcomes for cognitively challenging tasks.

The beneficial effect of persistence is affected by age. Pupillometry analysis demonstrated that this compensation is time-limited and resource-intensive for older adults. Older adults exhibited a significantly higher initial cognitive load (ΔPD in time window 1) upon task onset, suggesting an elevated baseline cognitive cost. Furthermore, older adults displayed a delayed physiological effort response to rapid speech, with their pupil response to the demands of time-compression occurring later (time window 3) than those of younger adults (time window 2). This timing difference suggests an age-related decline not just in processing speed, but in detecting demand and quickly mobilizing the necessary compensatory resources to meet task demand. This delay suggests that while persistence drives effort, age-related declines could limit the effectiveness of the additional cognitive resources an individual recruits, especially on speeded or time-limited tasks.

Project 2 did not support the hypothesis that grit enables CR and cognitive performance in healthy aging by increasing persistence. Nevertheless, results provided preliminary evidence for the distinction between personality and cognitive factors in the development of CR, as increased higher grit was associated with increased persistence as assessed by longer work times on unsolvable anagrams. While APT persistence was significantly aligned with grit, the overall path model did not confirm the proposed mediation pathway. This failure to support the model suggests that the relationship between grit, the cognitive deployment of persistence, and CRIQ could be more complex than a simple hierarchical chain. Furthermore, the lack of correlation between WCST persistence (effort-based) and APT persistence (time-based) suggests that these variables tap into distinct mechanisms, supporting the conceptual distinction highlighted by Teubner-Rhodes et al. (2017) separating effort-related persistence from persistence from time spent working on a task.

This overall pattern underscores that grit does not necessarily translate directly into all measures of cognitive persistence or CRIQ. This divergence suggests we need further research to test the hypothesis that persistence contributes to CR through the grit or the behavioral capacity to sustain effort, and that the specific type of persistence—time-based versus effort-based—may map onto different mechanisms of CR accumulation.

CR.

This dissertation concludes that persistence can serve as a compensatory mechanism during cognitive aging but is limited in its scope. Additionally, the relationship between grit and persistence is complex and future research should differentiate between effort-based and time-based persistence to be able to investigate their relationship to CR.

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Appendix

Table A1. *Results of the Best-Fitting Models of ΔPD in Time Windows 1-5*

Fixed effect	Time 1		Time 2		Time 3		Time 4		Time 5	
	β	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*	*β*	*SE*
Intercept	0.33	0.21	0.41	0.28	0.81^{***}	0.20	0.65^{+}	0.34	-0.02	0.30
Age	0.80^{*}	0.41	0.23	0.54	-0.03	0.39	-0.69	0.66	0.12	0.58
Persist	-0.02	0.30	1.23^{**}	0.41	0.55^{+}	0.29	0.06	0.50	-0.00	0.45
Comp	-12.03	7.38	0.52^{**}	0.19	-0.12	0.20	5.25	7.60	-0.23	0.25
Age × Persist	0.23	0.37	-0.72	0.51	-0.11	0.36	-0.17	0.62	-0.23	0.55
Age × Comp	10.53	14.66	-0.72^{+}	0.38	0.88^{*}	0.39	0.16	14.87	-0.71	0.49
Age × Persist × Comp	9.77	13.43	-1.40^{***}	0.35	-0.37	0.36	13.32	13.80	0.38	0.46
$Comp^2$	18.36^{*}	7.40					-28.05^{***}	7.59		
Age × $Comp^2$	-20.84	14.55					22.39	14.89		
Persist × $Comp^2$	-9.26	10.96					-0.12	11.23		
Age × Persist × $Comp^2$	2.59	13.53					10.65	13.85		

Note. $^{+}$ p < .10, * p < .05, ** p < .01, *** p < .001. Persist = Persistence; Comp = Compression.