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**ATTENTIONAL NEURAL MECHANISMS ASSOCIATED WITH COGNITIVE  
TRAINING IN HEALTHY OLDER ADULTS**

A Dissertation in  
Psychology

By

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## Abstract

Even without the presence of significant disease, aging is accompanied by marked declines in cognitive abilities. Notable among these deficits are reductions in facets of attention, specifically the ability to maintain a state of alertness, orient to new information, and resolve incongruent information. Such reductions are also accompanied by altered neural recruitment and resting state connectivity associated with attention processing in older compared to younger adults. These declines in attentional abilities with age have significant negative impacts on the daily lives of older adults. Critically, targeted cognitive training interventions offer evidence that declines in attention can be ameliorated in healthy aging. Improved behavioral performance is also often accompanied by neuroplasticity in the form of altered neural recruitment and improved resting state connectivity. Despite these efforts, little is known regarding how cognitive training may benefit the different facets of attention, nor the univariate and functional connectivity mechanisms by which training benefits manifest. The current study tests the hypothesis that process-based cognitive training in older adults will 1) enhance behavioral performance in alerting, orienting, and executive functioning, 2) alter neural recruitment in regions which selectively activate during attention processes, and 3) increase the segregation and efficiency of resting state networks associated with attention. I observed improved reaction times associated with executive functioning in trained older adults in conjunction with altered neural recruitment associated with alerting and orienting of attention, absent any network reconfigurations. The current dissertation therefore adds support to the notion that targeted cognitive intervention improves behavioral performance in healthy older adults, and offers insights as to which neural mechanisms underly these benefits. Implications and future directions are also discussed.

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## Introduction

Typical aging, even in the absence of significant disease, is associated with decline in cognitive processing. The number of older adults experiencing such cognitive deficits is increasing at a growing rate. For example, in the 2015 Census, the United States Government estimated that there will be 84 million adults older than the age of 65 by the year 2050. As the population size of older adults in the country increases, so too will the number of older adults who face the consequences on their cognitive abilities. Furthermore, these cognitive reductions place greater strain on caregivers and the public health system. As such, developing approaches to lessen the burden of cognitive decline on older adults, and the broader community, is of great interest to researchers and public policy officials. Therefore, it is critical that we evaluate methods for reducing cognitive deficits in older adults.

One such notable area of cognitive decline within older adults is visual attention. While attention often has a broad definition in the literature, for the purposes of the current dissertation I will define attention as the orienting of cognitive resources to new visual stimuli, maintenance of alertness, and resolution of conflicting perceptual information (Mahoney et al., 2010; McDonough et al., 2014). Older adults typically exhibit reduced reaction times and accuracy scores on cognitive tasks assessing these domains (Fu et al., 2020; Hartley et al., 1992; Kawagoe, 2022; Madden, 2007; Verhaeghen & Cerella, 2002), and such effects become magnified with the onset of disease-related pathology (e.g., Alzheimer's Disease) or increasing proximity to death (McDonough et al., 2014; Wilson et al., 2007). While age-related reductions in other cognitive faculties such as memory and processing speed are widely researched, age-related attentional decline is examined less frequently (McGaughy & Eichenbaum, 2002). These age-related declines in attentional capabilities have real-world consequences for older adults (Nguyen et al., 2020). For example, older adults report complaints that they are unable to maintain their attention on who is speaking or what is said in a conversation in a group of individuals (Getzmann et al., 2016). Additionally, older adults experience cognitive fatigue when needing to resolve conflicting pieces of information over an extended duration of time (Arnicane et al., 2021). These attentional deficits also have downstream consequences

on other cognitive domains such as memory and language production. Developing methods to reduce such cognitive deficits, and subsequent consequences, of attention are therefore of great interest.

Research regarding training of cognitive functioning suggests that these deficits can be lessened in older adults. Specifically, cognitive training studies frequently find that older adults experience benefits in the trained cognitive domain (Peng & Miller, 2016; Tennstedt & Unverzagt, 2013; Yam & Marsiske, 2013). While there is little evidence for “far transfer” of training benefits to cognitive domains not trained (i.e., improvements in memory after processing speed training), evidence suggests that older adults do experience benefits in their activities of daily activity, thereby improving their quality of living and daily experience overall (Salomon & Perkins, 1989). Cognitive training studies in older adults have recently begun utilizing functional magnetic resonance imaging (fMRI) and other neuroimaging modalities to examine the neural mechanisms underlying training-related improvements in cognitive outcomes. It may be that different cognitive training regimens engage similar neural mechanisms, resulting in improved behavioral performance and quality of life in older adults. While the cognitive training and neuroimaging literature is still in its youth, recent evidence suggests that cognitive training results in altered activation amplitude and improved connectivity among select cortical regions and networks (Lustig et al., 2009; Poldrack, 2015). These results are often interpreted as increased compensatory neural recruitment or improved efficiency of utilizing neural resources to meet increased task demands.

The current study sought to examine the neural mechanisms underlying successful behavioral improvements in facets of attention within healthy older adults. In this longitudinal intervention study, one group of healthy older adults received ten weeks of targeted cognitive intervention to improve their attention capabilities, while the other group of older adults received nonadaptive stimulating brain games. Older adults also underwent functional magnetic resonance imaging sessions at the beginning and end of the study. The current study examined training-related changes in neural activity associated with attentional domains (alerting, orienting, executive function), as well as reconfigurations of resting state networks associated with attention (dorsal attention,

ventral attention, cingulo-opercular, fronto-parietal control). The results from the current study will inform our understanding regarding how neural resources are reallocated to the betterment of attention in older adults. Such findings will be applicable to future studies that wish to engage similar neural mechanisms through cognitive training regimens.

### Brief Behavioral Overview

While the term ‘attention’ tends to be broad within the cognitive psychology literature, indeed even William James considered the multiple facets of attention to be both broad and well-known (James & Burkhardt, 1983), for the purpose of the current study I will utilize the following definition: that attention is a multifaceted cognitive construct in which information is filtered, selected, and weighted or modulated in response to internal representational demands or external environment signals (De Brigard, 2012). Reflecting this multifaceted perspective on attention, Posner and Peterson proposed three distinct yet interconnected neurocognitive networks underlying attention: alerting, orienting, and executive function (Petersen & Posner, 2012). Much of the previous work investigating the networks of attention is based on human lesion and behavioral studies, I summarize some of the key findings below regarding the extant evidence and how these facets of attention are and are not impacted by processes of aging. For the purpose of the current study, I will refer to the three behavioral networks of attention as *facets* of attention, to avoid any confusion when referring to later neural processes associated with attention.

Alerting refers to the presence of sustained and maintained arousal or vigilance in the presence of an ongoing task (Petersen & Posner, 2012; Posner & Petersen, 1990). Early work in cognitive psychology suggests that maintaining an alert state is dissociable from similar attention processes such as orienting our attention to specific perceptual stimuli in the environment (Posner, 1978). Specifically, previous work demonstrates that the presentation of a cue alerting participants to maintain an alert state assists in reducing response times in the presence of the subsequent target stimulus (Posner & Petersen, 1990). Our understanding of alerting processes is also informed by lesion studies in human patients. Notably, cerebellar infarcts in portions of the right visual cortex result in

reduced performance on tasks requiring attentional vigilance and alerting to the oncoming presence of new stimuli (Heilman et al., 2000). Additional work using pharmacological manipulation has found that manipulating norepinephrine levels in healthy humans selectively modulates alerting processes, exaggerating reaction time deficits when participants were not alerted to an oncoming stimulus (Coull et al., 2001).

Orienting refers to overtly shifting attention to novel visual stimulus information in the environment (Posner & Petersen, 1990). Previous work demonstrates that both humans and nonhuman primates respond to stimulus presentation more accurately and rapidly when their attention is shifted to the location of said visual stimulus (Eriksen & Hoffman, 1972; Posner, 1988). Neuropsychological lesion experiments have also been informative in our understanding of orienting as patient lesion studies demonstrate that damage to parietal regions results in an impaired ability to shift attention to new target locations compared to healthy control participants (Posner, 1988). Such patients also have difficulty in disengaging attention from a previous target location before shifting to a new location when oriented to do so (Posner et al., 1984; Rushworth et al., 1997). Orienting is a critical facet of attention as it draws our cognitive resources to portions of the environment relevant to future cognitive processes.

While executive function can refer to a large host of specific cognitive processes, for the purposes of the current study executive function will be defined as reconciling interfering information present when presented alongside target information (Posner & Petersen, 1990). Previous work demonstrates that participants have greater difficulty attending to visual cues when presented with an interfering stream of auditory information (Duncan, 1980). Reaction times are also slowed in humans and nonhuman primates when conflict is present in visual stimuli within cognitive tasks (Posner et al., 1987). Given the limited resources of the attentional system, resources must be allocated to reconcile the conflicting information, thereby requiring an increase in response times among experiment participants (Posner & Rothbart, 2007). Flanker tasks are frequently used to assess cognitive function in attentional tasks as participants must resolve the inconsistent information of a flanker array facing in a direction incongruent with the target arrow direction (Eriksen & Schultz, 1979).

Past work by Posner and Peterson highlights three distinct and dissociable attentional facets, with their framework being supported by both human and nonhuman behavioral and neuropsychological lesion studies. In an attempt to examine these constructs collectively, Fan (Fan et al., 2002) developed the Attention Network Test, a cognitive experiment designed to assess the alerting, orienting, and executive function facets in one task. The task is a modified visual flanker test in which participants must make judgements as to which direction a central arrow points (left/right) and the direction of the flanking arrows can either be congruent or incongruent with the central arrow (e.g., the central arrow pointing left while the flanking arrows point right). The location of the flanking array can be in one of two spatial positions in relation to a central fixation cross, typically above or below, or left or right of the fixation. Notably, cues appear during the task used to assess alerting and orienting of attention. Specifically, a visual asterisk can appear in the middle of the screen to alert participants that the flanker array will appear soon, or the asterisk can appear in the spatial location that the flanker array will appear in order to orient participants to the flanker array location either covertly or overtly. The difference in reaction time between incongruent flankers and congruent flankers is meant to assess executive function, the difference in reaction time to centrally cued trials to not cued trials is meant to assess alerting, and the difference in reaction time to locationally cued trials to centrally cued trials is meant to assess orienting (Fan et al., 2002).

The Attention Network Test has been used to assess the efficiency of the aforementioned attentional facets concurrently within a single task and has provided valuable insights regarding cognitive and neural underpinnings of attention as well as how these facets change in the presence of development or disease (de Souza Almeida et al., 2021). The task has been utilized in a number of different human sample populations including those with psychiatric conditions (including attention deficit hyperactivity disorder, schizophrenia, and posttraumatic stress disorder (Johnson et al., 2008; Leskin & White, 2007; Nestor et al., 2007). The task has been shown to provide reliable estimates of alerting, orienting, and executive function (Ishigami et al., 2016; Ishigami & Klein, 2011) in both younger adults and older adults with and without symptoms of dementia. Interestingly, the task has also demonstrated that portions of the attention facets, specifically executive functioning, are heritable (Kamboh et al., 2019). As will be

discussed in greater detail below, the Attention Network Test has been frequently used to assess the development and decline of attentional efficiency throughout the lifespan including adolescence and later adulthood (Konrad et al., 2005; Z. Zhang et al., 2015). The task has also been utilized to support neurocognitive hypotheses regarding the underlying neural activity associated with attentional networks, highlighting the cortical separability of each of the three attentional facets and ultimately how such attentional networks may be altered via targeted cognitive intervention in healthy aging (Xuan et al., 2016).

### Behavioral Age Deficits

While much early work in cognitive psychology has assisted in elucidating the existence of different attention networks, additional work suggests that these attentional facets are not static with age. That is, the efficiency of these facets is frequently impaired with later adulthood (McDonough et al., 2019; Verhaeghen & Cerella, 2002; Veríssimo et al., 2022). Furthermore, age-related deficits in attentional facets are hypothesized to become more accelerated with the onset of dementia-related pathology or increasing proximity to death (Wilson et al., 2007). The decline of different facets of attention, that is alerting, orienting, and executive functioning, are hypothesized to have differential downward trajectories across the lifespan into later adulthood (McDonough et al., 2019). Specifically, it is suggested that alerting functioning exhibits the steepest, or more accelerated, decline with advancing age, followed by executive functioning and then finally by orienting. This decline in alerting may be due, in part, by cognitive slowing, whereas declines in executive attention and orienting may result from a reduction in the ability to shift cognitive and neural resources to new spatial locations and inhibit irrelevant information while activating relevant information in accordance with task goals.

Age-related deficits are frequently observed in alerting attentional functions (Mahoney et al., 2010). Specifically, healthy older adults frequently exhibit slower reaction times compared to younger adults when presented with a cue to maintain their alertness to an oncoming target (Staub et al., 2013). This finding is supported by related research demonstrating that older adults frequently have deficits in maintaining their attention, or



an alert state, compared to younger adults (Festa-Martino et al., 2004). A recent meta-analysis found a consistent age-related increase in reaction times associated with sustained attention in older compared to younger adults, but often with a comparable accuracy to their younger counterparts (Vallesi et al., 2021). It is thought that this difference reflects a shift in older adults' strategies when in situations requiring sustained attention or alertness. Specifically, older adults may utilize a more conservative response approach in order to reduce the frequency of error commissions compared to younger adults who use a more liberal response approach. While this conservative approach in alerting is somewhat subtle in older adults, it becomes more exaggerated in older-old adults or those beginning to experience the onset of Alzheimer's disease (Karpouzian-Rogers et al., 2020). In these participants, not only does reaction time continue to increase in the presence of alerting trials, their response accuracy also begins to decline.

Older adults also tend to exhibit reduced ability to orient their attention to new information in their environment, although these age-deficits appear to be less consistently reported. In the Attention Network Test, older adults often exhibit an increased benefit of the orienting cue compared to younger adults (Erel & Levy, 2016; McDonough et al., 2019). Inconsistencies in age-related deficits in orienting may be driven in part by specific parameters used in a cognitive task, as well as the complexities of processes involved in attentional shifts (Chauvin et al., 2016; Heideman et al., 2018; Kaneko et al., 2004). This discrepancy in the finding of a linear age-related reduction in orienting has led some to hypothesize that orienting functioning declines in an inverted-U shape throughout the lifespan, with increases throughout earlier portions of adulthood followed by a steeper decline into later adulthood (Veríssimo et al., 2022). Supporting this perspective, deficits in orienting to novel information tend to become more pronounced in the presence of disease-related pathology in older adults (Tales et al., 2006). For example, older adults with mild cognitive impairment begin demonstrating difficulty with orienting as exhibited by increased reaction times compared to healthy older adults, and these differences become exacerbated in diagnosed Alzheimer's patients (Fernandez-Duque & Black, 2006; Mapstone et al., 2001).

Aside from a potential inverted-U trajectory in aging, the discrepancy in orienting deficits in healthy aging may be due in part to study design. In a recent review, Erel and Levy (2016) report that discrepant findings in older compared to younger adults may be a result of differences in task design, type of orienting cue, and the timing of the experiment. Age-deficits may be partially dependent on whether orienting is either covert or overt, as covert shifts in attention tend to be stable across age while overt shifts tend to decline in later adulthood (Beauchamp et al., 2001; Kingstone et al., 2002). Furthermore, age deficits can be shifted by using either endogenous or exogenous cues to orient attention. An endogenous cue is a symbol predictive of where the target visual information will be located in accordance with participant goals, whereas an exogenous cue is a peripheral cue meant to reflexively capture the participants attention (Woldorff et al., 2004). Exogenous cues in attentional orienting are thought to reflect more “bottom-up” processes while endogenous cues are thought to tap into more “top-down” processes (Friesen & Kingstone, 1998). Older adults tend to be more impaired when utilizing endogenous than exogenous cues compared to younger adults (Brodeur & Enns, 1997; Craik & Byrd, 1982). This is supported by the finding that older adults have a narrower spread or scope of visuospatial attention when shifting their attention compared to younger adults (R. K. Lawrence et al., 2018; Rösler et al., 2005). Given that the attention network test frequently uses a peripheral cue (exogenous orienting) in line with participant goals and instructions (endogenous orienting), it is possible that the combination of these two subprocesses in orienting may lead to subtle discrepancies in age effects.

Finally, deficits are frequently observed regarding the attentional facet of executive functioning within older compared to younger adults. These deficits are notable when completing the flanker component of the attention task as older adults exhibit greater reaction times when presented with the incongruent flanker array compared to their younger adult counterparts. Presumably this is due to the distracting nature of the incongruent flanker array and older adults are less able to inhibit this distracting information and this, in turn, necessitates additional resources to resolve the conflicting information (Friedman & Miyake, 2004). In one notable lifespan study examining participants, aged six to eighty-eight years old, executive functioning, as measured by the attention network test, was also impaired in healthy older adults compared to younger

adults. This age-deficit was also observed compared to middle-aged older adults as well (Craik & Bialystok, 2006). A small handful of studies have observed improved executive functioning via the attention network test in older compared to younger adults (Lu et al., 2016; Waszak et al., 2010), although such findings are often interpreted as some older adults being able compensate via alternative cognitive and neural resources (Cabeza et al., 2018; Reuter-Lorenz & Cappell, 2008).

Whereas there are some instances of healthy older adults displaying high functioning executive functioning as measured via the attentional facets, older adults with mild cognitive impairment consistently exhibit poorer executive functioning compared to healthy older adults and younger adults (Martella et al., 2014; Van Dam et al., 2013; Westlye et al., 2011). Even after controlling for general processing speed, these deficits still persist. Such effects become even more exaggerated in those with diagnosed Alzheimer's disease, as these older adults have additional difficulty resolving the conflicting information of the incongruent flanker array compared to healthy older adults and younger adults. Reports such as this suggest that the effects of aging on executive functioning in attention may become even more pronounced with the onset of pathological aging.

Collectively, it appears that efficiency in alerting, orienting, and executive function exhibit different age-related downward trajectories, further supporting the evidence that these three facets are behaviorally independent from one another in their informational computations. Further, in cases where age-deficits are not observed in healthy older adults, differences become increasingly prominent in the case of disease-related pathology such as mild cognitive impairment (MCI) or Alzheimer's. For example, older adults diagnosed with MCI frequently exhibit deficits in executive functioning compared to younger adults or healthy controls (Fernandez-Duque & Black, 2006; Westlye et al., 2011). Additionally, older adults diagnosed with Alzheimer's consistently display reductions in orienting compared to healthy older adults in addition to the deficits in executive functioning (Festa-Martino et al., 2004; Karpouzian-Rogers et al., 2020). In that case, as a whole, it is more a question of when older adults will begin to exhibit reductions in these attentional facets, for example, in MCI or dementia, rather than if they will exhibit

declines. Longitudinal studies will assist in determining the exact time-course of declines in the three attentional facets, but it remains clear that such functions decline in the course of age and age-related pathology.

While the impact of age on the different aforementioned components of attention processing is not always present, individual differences exist in which a negative impact can nonetheless be observed on the daily lives of older adults who have reduced attentional efficiency. For example, older adults with reduced attentional alerting also tend to report poorer metrics of self-rated health (Arnicane et al., 2021). Such metrics of self-reported health are valid predictors of a number of objective health deficits such as heart disease, gait mobility issues, mild cognitive impairment, and even mortality (Boxtel et al., 1996; Christian et al., 2011; Jylhä, 2009). Additionally, older adults who exhibit poorer executive functioning also report higher levels of cognitive fatigue on average. And finally, older adults with reduced attentional capacities also report challenges with daily activities including maintaining alertness while driving (Okonkwo et al., 2008). Older adults who exhibit reduced attentional abilities also have difficulties with gait as they walk through areas with distracting information and subsequently have impairments in step length and balance (Cornu et al., 2016; Inzitari et al., 2008). Given the negative cognitive impact of attention on components of daily life in older adults, it is critical to evaluate methods to ameliorate their cognitive difficulties and subsequently improve their quality of living.

### Relevant Behavioral Theories of Cognitive Aging

While the previous work has been firmly rooted in the attention network framework put forward by Posner and Peterson (Petersen & Posner, 2012; Posner & Petersen, 1990), several theories of cognitive aging are relevant to our understanding of attention deficits in older compared to younger adults, and can assist in contextualizing the neuropsychological and behavioral evidence of the observed age deficits in the facets of attention. Specifically, the Inhibition Deficit Hypothesis (Lustig et al., 2007) and the Processing Speed Theory (Salthouse, 1996) both provide supplemental information regarding the disinhibition of irrelevant information and slowing of cognitive resources relevant to the effects of aging on the different facets of attention. Even though work

assessing the attention facets in aging does not frequently invoke these theories, the Inhibition Deficit Hypothesis and Processing Speed Theory can nevertheless provide information relevant to how alerting, orienting, and executive functioning decline in older adulthood.

In the Inhibition Deficit Hypothesis, age-related reductions in cognitive faculties such as executive functioning in attention can be attributed to a lessened ability to suppress unwanted information or processes in older compared to younger adults (Hasher & Zacks, 1988; Lustig et al., 2007). Specifically, the Inhibition Deficit Hypothesis posits that inhibition of irrelevant information is critical in maintaining cognitive resources on information important to completing tasks or goals. In the hypothesis, older adults become less efficient at activating cognitive resources to inhibit such irrelevant information, which then results in age-related reductions in performance on tasks in cognitive domains (Gazzaley et al., 2005). Additionally, the Inhibition Deficit Hypothesis suggests that older adults may also suffer difficulties in activating task-relevant information, which then in turn exacerbates reductions behavioral output in tandem with the disinhibition of irrelevant information.

The Inhibition Deficit Hypothesis is supported by working memory and attentional executive functioning tests in which older adults must inhibit irrelevant or distracting information. Researchers frequently utilize go/no-go or stop signal tasks in which participants must withhold responses when a small set of stimuli are present (Bedard et al., 2002), or respond except when a tone plays indicating that the participant must not respond (Logan et al., 2014). Early work using tasks such as this observed that older adults are often less able to withhold their responses to irrelevant stimuli or tones compared to younger adults. Furthermore, early behavior work found that this age-related deficit in inhibiting distracting information is independent from the ability to activate relevant information in line with task goals, as older adults have no reductions in performance compared to younger adults on task-relevant activation tasks when inhibition is not required (Hasher et al., 1999).

The Inhibition Deficit Hypothesis is most relevant to the attentional facet of executive functioning. Specifically, older adults often exhibit increased reaction times in

the presence of the incongruent flanker array compared to the congruent flanker array (West, 1996). It may be that older adults are less able to inhibit the irrelevant or distracting information of the incongruent flanking array, which then in turn results in reduced accuracy and increased reaction time on those trials, leading to a reduced executive function score compared to younger adults. It is also theorized that when older adults are not able to inhibit the distracting information in the incongruent flanking array, this error then propagates beyond attention into working memory, thereby further reducing the amount of informational resources available on subsequent trials (Lustig et al., 2007; McDowd, 1997). It has been suggested that such effects contribute to “mental clutter” in older adults which reduces their ability to down-weight the presence of the distracting information in their environment (Anderson & Craik, 2017; Park & Festini, 2017). The Inhibition Deficit Hypothesis is also applicable to attention tests when non-informative orienting cues are presented, for example when the cue appears in the left portion of the screen whereas the target information appears in the right portion of the screen. Older adults exhibit greater reaction times to these non-informative cues, likely because they are not able to inhibit the now-distracting information, disengage, and shift information to the target stimulus (Rabbitt, 1965).

While an appealing and appropriate explanation, the Inhibition Deficit Hypothesis cannot fully explain the age-related deficits in executive functioning and attentional facets. Specifically, the Inhibition Deficit Hypothesis fails to account for a number of age-related cognitive deficits, particularly in higher-order processes including executive functioning and facets of attention. A recent meta-analysis suggests that the inhibition deficit hypothesis may not represent a reduction across cognitive domains generally, but that it may be present in select tasks or domains (Rey-Mermet & Gade, 2018, p.). That is, the age-deficit may depend on how the cognitive construct is operationally defined via the task used in a specific experiment. Specifically, work by (Rey-Mermet & Gade, 2018) suggests that any age-deficits in inhibition may depend on the type of task involved and therefore the form of inhibition employed by older adults. That is, there may be no generalized age-deficit in inhibition within older adults, but that age-deficits only occur when specific cognitive mechanisms are employed under different forms of interfering information.

A second theory relevant to age-related reductions in attention is the Processing Speed Theory suggested by Salthouse (Salthouse, 1996, 2014). Within the Processing Speed Theory, cognitive deficits in older adults can be attributed to a general reduction in the speed at which different cognitive faculties operate. Previous work by Salthouse demonstrates that reaction times with processing speed progressively increase across the adult lifespan into older age (Salthouse, 2016). Such observations have been found both cross-sectionally but also longitudinally in healthy older adults (Sliwinski & Buschke, 1999). With a reduction in processing speed, older adults have fewer cognitive resources to draw on compared to their younger adult counterparts, which then in turn results in reduced accuracy and performance on a range of cognitive tasks in domains including attention and memory (Albinet et al., 2012; Anderson & Craik, 2017). Support for the Processing Speed theory often comes from the finding that age-related reductions in cognitive performance are accounted for when using a measure of processing speed as a covariate in statistical models (Birren et al., 1979; Lorge, 1940). That is, age-deficits in cognitive faculties become non-significant after accounting for age-differences in processing speed, suggesting that deficits in processing speed can explain age-related deficits in relevant cognitive domains.

The Processing Speed Theory put forward by Salthouse is applicable to the findings of age-related deficits in the various facets of attention. For example, age deficits in alerting, orienting, and executive functioning may be explained in part by an overall reduced speed in cognitive processes associated with these domains (Stawski et al., 2013). If older adults process the cue visual stimuli or the flanking arrays more slowly, that may contribute to their increased reaction times compared to younger adults. Additionally, if older adults are not able to process the incongruent flanking array as quickly as younger adults, we may assume that such processing decrements would also lead to reduced accuracy. However, the Processing Speed Theory is not able to fully account for age-deficits in attentional facets, as age-related differences in alerting and executive function frequently remain after including generalized reaction time in models as a covariate (Fernandez-Duque & Black, 2006; Festa-Martino et al., 2004; Jennings et al., 2007). Further, previous research suggests that it may not be entirely deficits in processing speed that contribute to older adults altered performance, but differential

strategy usage and response biases that result in differential performance and reaction times (Davidson et al., 2003). Such findings suggest that while processing speeds may contribute in part, additional mechanisms contribute to the observed age-reductions in the facets of attention.

### Neural basis of Attentional Facets

Early work examining attentional facets primarily utilized behavioral and lesion approaches in humans and non-human primates. Neuroimaging methods, particularly functional magnetic resonance imaging (fMRI), have added further support to the distinction of the attentional facets of alerting, orienting, and executive function. These methods are particularly useful as it has been hypothesized that the attention facets comprise distinct yet interconnected functional and anatomical cortical regions (Hillyard et al., n.d.; Posner, 2012). Task-based fMRI studies frequently implicate cortical areas within frontal and parietal brain regions as well as visual cortex. Additionally, fMRI experiments using resting-state, or the lack of any explicit task, implicate several distinct networks associated with attention whose brain regions exhibit temporally covarying activity. As will be discussed in subsequent sections, univariate neuroimaging analyses provide useful information regarding how cortical regions process information associated with cognitive states or stimuli. Additionally, resting state analyses offer a supplementary set of information regarding the covariance of information between regions throughout the cortex associated with attention.

The original framework of the attentional network was predicated on the notion that the facets of attention of alerting, orienting, and executive function were not only separable cognitive functions, but that they also comprised distinct anatomical and function regions within the cerebral cortex. Early work using this proposed framework in conjunction with fMRI and univariate analyses has sought to understand how such facets of attention may be operationalized throughout the cortex.

Early visual work examining the neural substrates of alerting, observed that greater neural activity associated with a preparatory alerting cue compared to no cue elicited differential BOLD activation in portions of the visual cortex including fusiform and inferior



occipital cortex in addition to a small portion of the precuneus (Thiel et al., 2004). Such effects associated with alerting are also observed in the visual cortex via pharmacological manipulation, as participants who receive a noradrenergic agonist exhibit both reduced reaction times in the presence of the alerting cue, but also reduced BOLD amplitude in visual cortex in addition to fronto-parietal retrieval regions (Coull et al., 2001). Such results suggest that portions of the visual cortex conduct operations relevant to sensory preparation of the eventual target information in conjunction with frontal and parietal regions (Aston-Jones & Cohen, 2005; Nobre et al., 2004). Specifically, these conclusions are also supported by research utilizing transcranial magnetic stimulation (TMS). Such research consistently observes that applying TMS to posterior temporal cortex overlapping with visual cortex inhibits the level of alertness in attention prior to the appearance of the subsequent target stimuli (Battistoni et al., 2017; Peelen & Kastner, 2011). These results, in tandem with the pharmacological manipulation work, suggest a causal mechanism involved in the visual operations associated with alerting of attention, which then in turn has complex downstream dynamics with parietal and frontal cortices.

Similar work has uncovered the neural substrates associated with orienting, or the shifting of attention to either an endogenous or exogenous cue in the environment. Early fMRI research observed that anterior cingulate cortex is critically involved in processing valid spatial cues compared to non-informative cues (Thiel et al., 2004). Additional fMRI work has found that not only does anterior cingulate activate preferentially for spatial compared to non-informative cues, but also select portions of the intraparietal sulcus and frontal cortex (Corbetta et al., 2002; Hillyard et al., n.d.; Hopfinger et al., 2000; Wright & Ward, 2008). Such results are observed in visual attention but also in orienting tasks of other sensory modalities (Driver et al., 2004), reflecting the integration of sensory input with select computations necessary for shifting attentional resources to the subsequent target location. These findings are supported by single-cell recordings in non-human primates. Specifically, experiments utilizing macaques and single-cell physiological responses have found that cells in frontal cortex appear to briefly encode the location of an oncoming target following the spatial cue, distinctly separate from any recordings representing the physical movement of the eyes towards the cued target location (Schafer & Moore, 2007; Thompson et al., 2005). Collectively, these findings have led to the

proposal that portions of regions involved in orienting form a dorsal attention network in which the cortical regions coordinate their activity in the presence of task goals to orient attention effectively (Corbetta & Shulman, 2002). Additionally, it has been proposed that such regions operate in synchrony with additional cortical regions comprising a ventral attention network (Womelsdorf et al., 2007).

Finally, neuroimaging has been useful in elucidating the attentional facet of executive control. Initial fMRI studies investigating this control related cognitive construct observed increased neural activity when participants responded to incongruent compared to congruent stimuli (either using modified Stroop tasks or flanker tasks) primarily in anterior cingulate and lateral portions of the prefrontal cortex (Bush et al., 2000; MacDonald et al., 2000). Such preferential activations are frequently observed in loci spatially independent of those observed associated with either alerting or orienting processes. For example, both early and more recent meta-analyses of BOLD amplitude associated with the control component of the Stroop task have identified the anterior cingulate cortex and dorsolateral prefrontal cortex (Huang et al., 2020; Laird et al., 2005). A meta-analysis focusing on the interference effect of the flanker task observed similar results with a peak focus of activation in dorsolateral prefrontal cortex (Nee et al., 2007). More recent meta-analyses of functional neuroimaging of the flanker task also observe activity in anterior cingulate and dorsolateral prefrontal cortex during the incongruent flanking condition when participants must resolve the interference of the incongruent flanker array (R. Zhang et al., 2017). Activation in dorsolateral prefrontal cortex may be driven in part by the need to resolve interfering stimulus-response options in the presence of incongruent visual information. Neuroimaging focusing on gray matter volume, as opposed to task evoked activation, has also observed that gray matter volume in prefrontal cortex positively predicts the accuracy and reaction time of resolving the interference component of the flanker task (C. Chen et al., 2015).

Collectively, early work examining the separate components of the attentional network system proposed by Posner and Peterson suggests that an ensemble of integrated, but distinct, network of regions operate during the processing of the alerting, orienting, executive functioning processes in attention. While more early sensory regions,

such as visual cortex, appear engaged in the preparation of visual attention and the deployment of attention to cued locations, higher order cortical regions including portions of frontal and parietal cortex are also engaged and may assist in coordinating higher-level top-down task goals. Additionally, portions of the frontal and cingulate cortex are selectively engaged when presented with incongruent information, requiring the resolution of such interference in order to accurately complete the task. Besides the core regions in frontal and parietal cortex, other cortical regions are also selectively engaged during the processes of alerting, orienting, and executive functioning, perhaps in a more auxiliary capacity.

Additional neuroimaging work has sought to examine the cortical contributors of the facets of alerting, orienting, and executive functioning in a single task using the Attention Network Task. Early fMRI work using this task utilized similar contrasts as the behavioral version of the task to define their neural contrasts. Specifically, the alerting construct is defined as a contrast of trials associated with central cues versus no cues, the orienting construct is defined as a contrast of trials associated with the spatial cues versus the central cue, and the executive function construct is defined as a contrast of incongruent flanking trials versus congruent flanking trials (Fan et al., 2005; Xuan et al., 2016). Such work has observed significant cortical activation associated with alerting in inferior and superior parietal cortex and inferior frontal cortex. Activity associated with orienting is associated with neural activity in portions of the visual and parietal cortex including fusiform gyrus, superior parietal cortex, and pre and post central gyrus. Finally, neural activity associated with executive functioning in attention is observed in inferior frontal cortex and middle frontal cortex (Fan et al., 2005). Later work utilizing higher resolution fMRI and a larger sample size observed similar results as the original study by Fan et al. (2005), observing activity associated with alerting in prefrontal cortex, orienting in inferior frontal cortex and anterior cingulate, and executive function in inferior frontal cortex, anterior cingulate, and middle frontal cortex. While some of the foci of activation overlapped between the different facets of attention in fronto-parietal and visual regions, it appears the cognitive constructs also draw on distinct cortical regions for their information processing. Basic work examining the three facets in conjunction suggests that the three cognitive networks may operate via a set of discrete yet collaborative

cortical regions. While univariate methods have been greatly helpful in understanding the processing roles of these regions, resting state network analyses add further support to the notion that the regions implicated in the attentional facets operate in a coordinated manner while conducting their neurocognitive operations, with the supporting evidence of correlated timeseries among attentionally-relevant cortical regions.

Much work in the fMRI domain has utilized univariate analyses to examine differences in BOLD amplitude associated with the cognitive facets of attention. However, previous work suggests that these regions associated with the different facets of attention operate via different cortical networks. In that regard, resting state network analyses have provided additional evidence to suggest that the processes of attention are supported by distinct cortical networks whose regions maintain neural activity covarying. Network analyses provide a useful tool, as early work suggests that regions maintain correlated activity even in the absence of an explicit task to be completed (Biswal et al., 1995). The covariance of these functional signals displays non-random properties wherein the activity in nodes, or regions, are highly interconnected with other nodes comprising distinct networks of regions. These networks frequently send and receive connections in a way that maximizes efficiency of neural processing (Harriger et al., 2012). Furthermore, these correlations are frequently relevant to behavioral performance, such as attention, in both humans and non-human participants (Lurie et al., 2019).

Regarding attention, the early work by Posner and Peterson (Petersen & Posner, 2012) suggested that the neural correlates of the various attentional facets were distinct in their anatomical and neural correlates, yet that such cortical regions may operate in a coordinated manner. Early work utilizing resting state connectivity and the Attention Network Test observed that regions within frontal, parietal, and occipital regions exhibit time-courses of neural activity which are significantly correlated to one another, and that such neural connectivity is predictive of performance of the facets of attention. Specifically, correlated neural activity among regions, or nodes, in fronto-parietal and visual cortices distinctly contributes to individual differences in alerting, orienting, and executive functioning (Markett et al., 2014). Further work examining networks outside of the fronto-parietal regions, including the dorsal attention network and ventral attention

network, found correlated times series within these networks predicts behavioral indices of alerting and orienting (Madhyastha et al., 2015; Visintin et al., 2015). Additionally, alertness appears to be supported by the cingulo-opercular network (Sadaghiani & D'Esposito, 2015). More recent research utilizing resting state functional connectivity has examined network properties underlying the facets of attention with connectome-based modeling. These models seek to determine which resting state connections among nodes are predictive of a certain behavioral marker, such as attention performance, and then these models are evaluated on independent samples to determine their accuracy. Such approaches have revealed that resting state networks associated with alerting, orienting, and executive functioning are both internally and externally reliable when tested on independent samples, and that the correlated activity among the dorsal and ventral attention networks are predictive of attention indices of orienting in younger adults (Rosenberg et al., 2017). Connectome based modeling has also demonstrated that while resting state networks may rely on a similar set of nodes, distinct connections are observed in relation to the different facets of attention (Rosenberg et al., 2018).

Collectively, it appears that a specific set of primary networks are relevant to the various attentional facets, the dorsal attention network, ventral attention network, fronto-parietal control network, and cingulo-opercular network. Studies utilizing network connectivity, in the absence of any explicit task performed by participants while undergoing scanning, demonstrate that attention, and its facets, is associated with covarying activity among a core set of regions in the brain. In tandem with the extent univariate neuroimaging, it is clear that not only do cortical regions selectively activate and process cognitive states associated with attention, but that these regions also operate in tandem with one another to communicate attentionally-relevant signals even when no explicit task is being performed.

### Neuroimaging, Attentional Facets, and Aging

Just as behavioral metrics associated with attention are altered by processes of healthy aging, so too are neural processes associated with the facets of attention. Specifically, older adults frequently exhibit altered neural activity in frontal and parietal

cortical regions, often exhibiting a relative increase in frontal regions which may be viewed as compensatory (Cabeza et al., 2018; Davis et al., 2008; Festini et al., 2019). While relatively less work has examined how the neural correlates of alerting, orienting, and executive function are impacted by processes of healthy aging, extant evidence suggests that older adults frequently display reduced BOLD activity compared to their younger adult counterparts when conducting attentional processes. For example, older adults exhibit reduced activity in fusiform cortex associated with alerting compared to younger adults in a task requiring initiation and maintenance of alertness following a visual cue (Madden et al., 2004). However, in some cases older adults maintain increased neural activation associated with attention, such as increased activity associated with orienting in parietal cortex compared to healthy younger adults (Dash et al., 2019; Erel & Levy, 2016). Similar work has also found an age-related increase in activity associated with orienting to differential spatial locations of targets versus non targets in older compared to younger adults (Geerligs et al., 2014). Furthermore, in some cases this age-related increase in activation associated with orienting is positively predictive of response accuracy in older adults, suggesting a possible example of successful compensatory neural recruitment to address task demands in aging. In tasks of executive functioning in aging, older adults frequently fail to suppress distractor related neural activity within prefrontal cortex, whereas older adults who exhibit more “youth-like” neural signatures tend to perform with greater accuracy on tasks requiring inhibition of incongruent or distracting visual information (Clapp & Gazzaley, 2012). This work is supported by related studies in attention demonstrating that older adults maintain activity in frontal and parietal regions when top-down goals are required to address goals of resolving interfering information (Madden et al., 2007). It appears that older adults may also recruit additional subregions within the frontal cortex when needing to resolve attentional incongruity as compared to younger adults (Zhu et al., 2010).

Little work has been done examining the functional BOLD correlates regarding the attentional facets in older adults via the Attention Network Test. In one notable study examining the neural correlates of the three attentional facets in healthy older adults and older adults with MCI, two patterns of results emerged. One, older adults with MCI exhibit reduced activity associated with executive attention compared to healthy older adults in

anterior cingulate and portions of the medial and lateral prefrontal cortex. And two, older adults with MCI exhibit increased BOLD amplitude associated with alerting and orienting in portions of the parietal cortex compared to healthy older adults (Van Dam et al., 2013). This work is supported by anatomical imaging experiments examining how white matter microstructure in the context of aging and the attention facets. Specifically, in one experiment the accumulation of white matter hyperintensities surrounding the ventricles near frontal and parietal regions was associated with decreased executive functioning while white matter hyperintensities deep in the parietal cortex were associated with poorer orienting (Wang et al., 2020). In older adults with such damage to white matter tracts, there may be an increased burden as information is not as able to travel effectively between regions critical to executive functioning or orienting, thereby exacerbating their cognitive deficits in attention.

Some evidence suggests that older adults experience not only differences in BOLD amplitude compared to younger adults, but metrics of resting state connectivity among nodes are also influenced by processes of healthy aging (Damoiseaux, 2017; Jockwitz & Caspers, 2021). For example, older adults tend to exhibit reduced connectivity among regions in the fronto-parietal network in addition to the dorsal attention network (Andrews-Hanna et al., 2007; Tomasi & Volkow, 2012). It is hypothesized that aging also has a detrimental effect on the correlations between nodes in the ventral attention network and cingulo-opercular network (Deslauriers et al., 2017; Hardcastle, Hausman, Kraft, Albizu, Evangelista, et al., 2022; Z. Zhang et al., 2015). Additional work using resting state functional connectivity has demonstrated that the segregation (the difference of correlations within a network and between other networks) of attentionally-relevant networks also declines with increasing age throughout the lifespan, and that this reduction is associated with reduced cognitive performance in aging (Chan et al., 2014; Malagurski et al., 2020). Specifically, older adults tend to have lower within-network connectivity and greater between-network connectivity in the dorsal attention network and fronto-parietal network (Grady et al., 2016; Spreng et al., 2016). These deficits in connectivity become exacerbated in older adults with the onset of dementia-related pathology. Specifically, older adults with MCI tend to exhibit reduced connectivity among regions within the dorsal attention network while an inverted U-shaped decline is observed in the ventral attention

network. Additionally, older adults with MCI display greater connectivity among regions in the ventral attention network compared to healthy older adults, but this is followed by a decline in ventral attention network connectivity with the onset of diagnosed Alzheimer's disease (Z. Zhang et al., 2015).

The previous work examining altered neural activity and network connectivity associated in attention in aging observes that such metrics of neural functioning are reduced by processes of healthy aging in older compared to younger adults. In some instances, reduced neural activity in older compared to younger adults is interpreted as less efficient neural processing or perhaps a dedifferentiation of neural signals in regions maintaining neural populations with preferential response tunings (Cabeza et al., 2018; Grady, 2012). In other instances, older adults exhibit equivalent neural activity or even increased BOLD amplitude compared to younger adults. Some scholars interpret this age-related increase in neural activity as compensatory, however it is difficult to evaluate without an accompanying metric of behavioral performance. For example, an age-related increase in neural activity was observed in older adults accompanied with an increase in cognitive performance on a behavioral task, as compared to those older adults whose regions were recruited to a greater degree also exhibited better performance overall. On the other hand, however, an age-related increase in neural activity accompanied by a decrease in performance may be viewed as aberrant neural activity. This position is supported by investigations in patients of traumatic brain injury (TBI), who frequently exhibit a negative correlation between frontal cortex BOLD and performance on cognitive tests (Hillary et al., 2006). In either regard, a deeper understanding of the neural changes associated with attention in aging assists in identifying which potential pathways may respond following targeted cognitive training.

### Attention Training in Younger Adults

Previous work suggests that attentional faculties decline with age and contribute to declines in measures of daily living in older adults, it is therefore critical to develop methods that reduce such cognitive deficits in this vulnerable population and improve their quality of daily life. However, it remains a question as to whether attention-based



cognitive training relates to any improvement in behavior. Work within healthy younger adult populations suggests that attention-training can indeed be effective and can have long-last positive impacts (Jaeggi et al., 2011; Peng & Miller, 2016). Such studies in younger adults provide a foundation for additional cognitive training paradigms in older adults to build upon, and also offer a possible avenue for behavioral plasticity in later adulthood.

Early cognitive training work in healthy younger adults sought to enhance attention via interactive attention-based video games that become progressively more challenging. Meta-analyses suggest that while different forms of video games do not equivalently impact attention, participants who play such games have a greater increase in a generalized measurement of attention compared to participants in control groups (Bediou et al., 2018). Several studies have used the facets of attention directly in their training within healthy younger adults, and such studies frequently observe an improvement in alerting, orienting, and especially executive functioning (Bednarek et al., 2021; Posner et al., 2015). In an additional review, authors found that cognitive training targeting the attentional facets of alerting, orienting, and executive function resulted in improved performance in trained compared to control younger adults (Peng & Miller, 2016). Benefits were found in the trained participants compared to not only a passive control group, but also active control groups, suggesting that training engaging the facets of attention is highly effective in younger age groups. Additional analyses observed that completing computerized training, and receiving adaptive training, both resulted in increased improvements in the training group. This was opposed to participants who completed training via a class or received nonadaptive training. In younger adults, the accrued benefits from training regimens such as these can be somewhat long lasting, with sustained improved performance in the training group lasting at least three months following training (Jaeggi et al., 2011). Such work suggests that the cognitive facets of attention are plastic in nature and can be improved with behavioral intervention.

## Cognitive Training in Healthy Aging

Given the age-related declines in attentional facets and their impact on daily lives of older adults, it is critical to develop and assess methods for ameliorating such declines. Cognitive training serves as a potential mechanism for doing so and has exhibited success in reducing behavioral deficits in older adults (Sprague et al., 2019). These benefits from cognitive training are long lasting (in some cases lasting five to ten years), and improve older adults' activities of daily living (Rebok et al., 2014). Early cognitive training work relevant to the attentional facets in older adults focused on improving speed of processing. Such studies utilizing computerized games found that older adults in training groups indeed incur a benefit in their processing speed compared to control groups, and that such benefits positively predict scores on neuropsychological tests involving executive functioning and alerting (Goldstein et al., 1997). Later studies utilizing both processing speed training and executive functioning training observed that older adults who receive either processing speed or executive functioning training exhibited improved performance compared to control groups (Burge et al., 2013; Edwards et al., 2017; Gross et al., 2018). These training benefits lead to increases in instruments of daily living as well, demonstrating the efficacy of cognitive training on improving older adults' behavioral performance as well as quality of life. Critically, large-scale cognitive training studies in healthy older adults demonstrate that benefits from both processing speed and executive functioning can be long lasting, between five and ten years following the cessation of cognitive training as compared to participants in control groups (Rebok et al., 2014). While research in younger adults suggests benefits could last beyond training, the research in older adults suggests that one, older adults cognitive processes are plastic and can be influenced in a behaviorally beneficial manner, and two, that these benefits can last well into later adulthood.

Additional cognitive training research has focused solely on attention in healthy older adults and older adults with age-related disease pathology. For example, older adults with mild cognitive impairment randomized into a training group in which they received training in the executive functioning facet of attention exhibit an improvement compared to an active control group as operationalized by fewer errors on executive functioning metrics, even at six months post training (Yang et al., 2019). Older adults with

mild cognitive impairment in a similar study targeting the attentional facet of alerting also experienced a benefit to performance on independent tasks of attention (Yang et al., 2020). It appears that both bottom-up process-based and top-down executive functioning-based trainings appear to have a positive impact on attention in healthy aging. For example, studies using the Useful Field of View (UFOV) training, in which participants are cued to and must respond to objects in the visual periphery, consistently demonstrate improvements in attentional metrics compared to control groups (Edwards et al., 2018). Experiments utilizing pupillometry in tandem with UFOV training in healthy older adults suggest that older adults in the training groups incur a benefit via more efficient attentional cognitive resources (Burge et al., 2013). Further, work suggests that simply pairing a monitoring incentive (such as a monetary study completion incentive) with the cognitive training leads to greater improvements in attentional processes via enhanced alerting (Bagurdes et al., 2008).

Some work has also explicitly targeted the various facets of attention within healthy older adults. Specifically, two previous studies have explicitly targeted the executive functioning attentional facet via training in older adults. While each study trained a slightly different cognitive domain, verbal fluency in one case and working memory in the other, both studies targeted their training on inhibition of irrelevant or distracting information via the executive functioning facet of attention. Both studies observed that older adults in the training groups incurred benefits in this facet on later tasks of attention as compared to both passive and active control groups (Gao et al., 2014; Sutter et al., 2013). These critical training studies in aging further support the notion that attentional faculties can be improved in healthy older adults via training. Additionally, these studies support the notion that either top-down or bottom-up based interventions can serve as viable routes for behavioral benefits in attention in older adults.

Collectively, the cognitive training work in healthy older adults suggests that older adult's cognitive processes are indeed plastic and can be modified to the behavioral benefit of participants in the training group. Furthermore, it appears that cognitive training can enhance attention in older adults through two pathways, a more bottom-up processing speed-based approach and a more top-down higher-order processing-based

approach. These benefits can even extend to older adults who are suffering from disease-related pathology in aging. While these benefits in cognitive training do not typically transfer to untrained cognitive domains, such as memory, they do improve older adults' quality of living (Rebok et al., 2014; Salomon & Perkins, 1989). For example, older adults who engage in cognitive training report fewer driving accidents, greater ability to fill out a checkbook, and maintain prescription medicine schedules (Ross et al., 2017; Ross, Sprague, et al., 2018). Critically, however, no studies to date have examined the influence of cognitive training on all three facets of attention in older adults.

### Neural Mechanisms Associated with Cognitive Training in Older Adults

Given the efficacy of cognitive training studies and their benefit to older adults' attentional functions and activities of daily living, utilizing fMRI methods assists in uncovering the neural mechanisms that support such behavioral benefits in older adults. It may be that multiple cognitive training regimens tap into similar neural mechanisms, or that cognitive training regimes operate through distinct neural pathways. The cognitive neuroscience of cognitive training and aging is still in its younger years and stands to benefit greatly from the advances of fields using univariate and resting state methods. However, the field of cognitive neuroscience of cognitive training and aging has provided useful information regarding the neural mechanisms engaged as a result of targeted training and offer insights as to which neural pathways may be utilized to examine the underlying pathways of training in older adults and the subsequent impact on attentional processing. Understanding if multiple cognitive training paradigms impact neural activity or connectivity through similar or disparate cortical routes, as future clinicians or gerontologists could use such information when providing an older adult with a regimen for assisting with the specific reductions of their cognitive faculties. Even though the cognitive training and neuroimaging literature is still in infancy, a fair amount of work to date has been completed utilizing univariate BOLD analyses to examine how the magnitude of neural activity changes as a result of targeted cognitive training in older adults.

A recent univariate whole-brain meta-analysis of cognitive training studies attempted to examine locations of cortex exhibiting consistent training related changes neural activity in healthy older adults. The authors observed a common effect of cognitive training on increased univariate activity in portions of middle frontal cortex, posterior parietal cortex, and superior occipital cortex (Duda & Sweet, 2019). Additionally, the meta-analysis revealed reductions in univariate neural activity following cognitive training in portions of middle frontal cortex, supramarginal gyrus, and superior temporal cortex within older adults. Such increases in activity are frequently interpreted as compensatory whereas decreases are often interpreted as changes in efficiency. The results of the meta-analysis should be interpreted with caution as there was great variability in the types of cognitive training underlying the univariate activity. For example, studies included in the meta-analysis utilized different dosages of training (one day vs fourteen weeks), various forms of difficulty (adaptive, non-adaptive), different cognitive domains of training (episodic memory, working memory, attention), strategy versus process-based, and different inclusion of control groups (active, passive, no control group). Overall, however, the results from the meta-analysis suggest that engaging in cognitive training may result in both increased activity and decreased activity within fronto-parietal and visual sensory cortical regions within older adults.

In an early study employing neuroimaging and specifically targeting attention training, investigators utilized a targeted attention training intervention in a sample of healthy older adults (Mozolic et al., 2010). Older adults in the training group received attention training focusing on inhibiting irrelevant visual information for one hour per week for eight weeks, and participants in the control group received an education program where they attended lessons on health topics such as heart disease or nutrition for eight weeks. All participants underwent a perfusion MRI scan pre-training and post-training to assess changes in cerebral blood flow (CBF) during rest. The authors observed a significant time-point (pre, post-training) by group (training, control) interaction in right prefrontal cortex where older adults in the training group had an increase in CBF above and beyond that observed that observed in the education control group. Additionally, participants who exhibited greater increases of CBF in this region also exhibited greater reductions in reaction time associated with the irrelevant visual information. This early

work suggests that additional neural recruitment occurs following cognitive training in the presence of increasing attentional demands within older adults, and that such compensatory recruitment is behaviorally relevant.

Additional work utilizing attention-based cognitive training and fMRI scanning in older adults has found similar results when examining BOLD amplitude in healthy older adults following cognitive training. Specifically, it appears that attention-based cognitive training frequently leads to alterations in BOLD amplitude in portions of lateral prefrontal cortex and visual cortex. Additionally, attention-based training often leads to both increases and decreases in neural activity within fronto-parietal cortical regions (Duda & Sweet, 2019; Osaka et al., 2012). It appears that these findings occur through both processing speed and top-down higher order-based training regimens (Buschman & Miller, 2007). Neural activity is not the only cortical factor that is influenced, as some of these altered BOLD responses occur alongside increased white matter integrity, specifically within the ventral attention network (Strenziok et al., 2014). Altered neural processing occurs in tandem with an increased efficiency in sending and receiving signals via white matter pathways following cognitive training, adding support to the notion that not only are regions being impacted in isolation, but that networks of cortical regions and their connections are altered as a product of cognitive training in healthy older adults.

Several cognitive training studies have also examined the influence of training on network connectivity among cortical regions during task and rest. While univariate outcomes in cognitive training provide information regarding the allocation of neural resources being used associated with cognitive constructs, resting state connectivity and network outcomes provide useful information regarding how communication between regions or networks shifts in response to cognitive training. In this regard, previous work in healthy older adults has found ten hours of training involving the exogenous orienting of attention to the visual periphery results in increased resting state connectivity between regions associated with bottom-up processes above and beyond any changes observed in a no-contact and active control group (Ross, Webb, et al., 2018). Specifically, the authors observed increased connectivity between anterior cingulate, anterior insula, dorsolateral prefrontal cortex, inferior parietal cortex, and visual cortex.

A select few cognitive training and neuroimaging studies have examined resting state connectivity and network properties in healthy older adults. These studies typically observe increased connectivity within attentionally-relevant networks such as the dorsal attention network and cingulo-opercular network following cognitive training targeting specific aspects of attention such as executive control (Cao et al., 2016; Hardcastle, Hausman, Kraft, Albizu, O'Shea, et al., 2022; Tang et al., 2017). Additionally, resting state studies also find increases in network connectivity between nodes functionally defined by more processing speed-based functions, and that these increases in connectivity can occur in tandem with reductions in BOLD amplitude in the defining nodes (Ross, Webb, et al., 2018). This presents a subtle, yet complex, picture of results, that while regions are becoming more efficient in their neural processing, they are also simultaneously increasing their covaried activity among regions carrying out similar neural operations. Additional studies using network properties provide evidence that cortical networks do not only adjust their connectivity strength following cognitive training, but that they may also reconfigure their connections between regions and become more efficient in response to training (Barban et al., 2017; Q. Chen et al., 2022). In this case, nodes have fewer pathways to other nodes following training. For example, several studies have observed that the fronto-parietal network becomes more segregated following training, that is it becomes more connected to itself and less connected to other networks (Jordan et al., 2021). Additionally, there is evidence that networks become more efficient, that is, that there are fewer paths between two nodes, following attention-based cognitive training in older adults (Cotier et al., 2017; Jordan et al., 2021; Taya et al., 2015). These results further suggest that cortical processing is plastic and that regions alter their connections with relevant regions as a result of cognitive training.

Given the varied outcome of neuroimaging findings, that both increases and decreases in neural outcomes are reported as a result of training, interpreting such results and how they relate to the training regimens is a critical step in the literature of neuroimaging and cognitive training. Increases in BOLD univariate activity following cognitive training have frequently been interpreted as enhanced compensatory neural recruitment in response to the training regimen. Investigators hypothesize that older adults who improve their performance in the trained cognitive domain or task utilize

increased neural resources in the form of blood flow to those regions. This in turn results in a longitudinal increase in BOLD level above and beyond any changes observed in the control group. Previous neuroimaging work assessing working memory training in healthy older adults supports this hypothesis. Specifically, training-related increases in BOLD amplitude associated with working memory have been interpreted as compensation allowing older adults to increase performance on cognitive tasks of greater difficulty or demand (Festini et al., 2019; Jordan et al., 2020). In contrast, cognitive training studies also frequently result in decreases in BOLD amplitude in the training group compared to the control group at the end of the intervention (Duda & Sweet, 2019; Ross, Webb, et al., 2018). Such findings are initially counterintuitive in the framework of compensatory neural recruitment, especially when such decreases in BOLD amplitude are associated with improvements in behavioral performance on cognitive tests. However, an alternative perspective proposes that such reductions in BOLD response are reflective of enhanced efficiency following the cognitive training. It is suggested that cognitive resources are more readily allocated to the computational processes conducted, and therefore require fewer neural resources as a consequence. This interpretation is frequently invoked when training-related reductions in neural recruitment are accompanied by increased performance on behavioral metrics.

The examination of enhanced compensatory neural recruitment or improved efficiency of utilizing neural resources in response to cognitive training is not limited to evaluations of BOLD amplitude in task-based studies. Such interpretations have also been extended to cognitive interventions examining connectivity between nodes, or regions, during rest and task. Cognitive training studies utilizing functional connectivity have often observed both increases and decreases in the correlation of time-series activity between cortical nodes within healthy older adults. However, it is critical to consider which pairs of nodes are exhibiting such training-related increases or decreases in connectivity. Several studies examining the impact of cognitive training on functional networks have observed changes in the connections of regions both within and between specific networks. For example, some work has observed increased connectivity among regions comprising the default mode network and fronto-parietal control network, and decreased connectivity among regions between the default mode network and other



networks such as the sensorimotor network, thereby leading to an overall greater degree of segregation of specific networks (Gallen et al., 2016; Hardcastle, Hausman, Kraft, Albizu, O'Shea, et al., 2022). Interestingly, however, some work in cognitive training has observed increased between-network connectivity following working-memory based cognitive training in healthy older adults, a finding that has also been observed in participants with mild cognitive impairment who completed cognitive training (Pantoni et al., 2017). In this case, enhanced between-network connectivity following training is interpreted as a form of compensatory neural recruitment as different cortical networks covary their activity more after the increasing demands of the training regimen.

The extant previous literature suggests that healthy older adults benefit from targeted cognitive training in attention, and that cognitive training can induce changes in both univariate BOLD activity as well as alterations in resting state connectivity and network properties. However, no training studies to date have utilized cognitive training to examine how the facets of alerting, orienting, and executive function benefit from targeted training in older adults, nor how functional BOLD activity and resting state network metrics change in tandem following cognitive training in healthy older adults. Given that training-related improvements in cognition can arise from multiple neural mechanisms, it is critical to assess the potential neural pathways leading to enhanced behavioral improvement in older adults following training. For this reason, it is suggested that an important step in the cognitive training and neuroimaging literature is to collect and examine multiple imaging modalities (Baykara et al., 2021). Furthermore, advances in the neuroimaging field at large, such as graph theoretical advances (Hallquist & Hillary, 2018) in the network neurosciences, can be applied to cognitive training studies to examine the various mechanisms in which the brain changes as a result of targeted behavioral intervention. It may be that training results in altered neural BOLD amplitude associated with the different facets of attention, either increases in neural activity representing compensation, or decreased neural activity representing enhanced efficiency of neural resources. It is also possible that attention training results in the reconfiguration of networks associated with attention during rest, via altered efficiency or segregation. Finally, it is possible that both changes in BOLD amplitude and network connectivity occur in trained older adults. Understanding if attention training results in

BOLD amplitude and or resting state connectivity would greatly deepen our understanding of the neural mechanisms that respond to cognitive training.

### The Current Study

As prior work demonstrates that attentional faculties decline with aging and such declines are accompanied by altered neural activity and resting state connectivity, it is imperative to evaluate methods which seek to lesson such deficits in older adults and improve their overall quality of living. It is therefore critical to not only evaluate the behavioral alterations following cognitive training, but also the potential neural mechanisms underlying successful improvements in cognitive functioning in trained older adults. With this in mind, the current study examined changes to the univariate and resting state neural networks associated with attention-based cognitive training in a sample of healthy older adults. The study therefore attempts to answer three primary questions:

1. Does cognitive training enhance performance in the attentional facets of alerting, orienting, and executive functioning in healthy older adults?
2. Does cognitive training result in alterations in BOLD amplitude in regions implicated in alerting, orienting, and executive functioning in healthy older adults?
3. Does cognitive training increase segregation and efficiency of the dorsal attention, ventral attention, fronto-parietal, and cingulo-opercular networks in healthy older adults?

### Participants

The sample used in the study consisted of a total of 38 older adults (M = 72 years old, SD = 6.50 years, range = 65– 87 years old; M = 17.63 years education, SD = 2.20 years education, range = 12 – 21 years education; 28Female). One participant had below chance performance on the Attention Network Test at the post-test assessment MRI session and was excluded from analyses, leaving 16 training participants and 21 control participants with complete pre- and post-assessment data for the current dissertation. Participants were recruited via community centers, retirement communities, religious

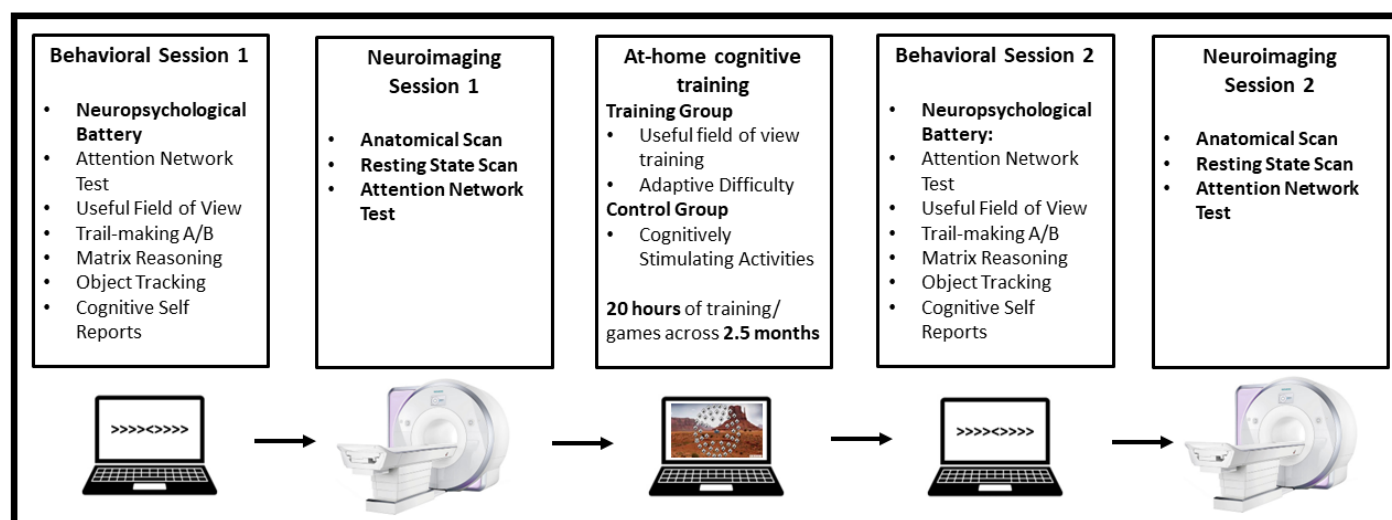
facilities, and flyers posted in public areas, in addition to the Participants Across the Lifespan (PALS) database in which potential participants are then contacted via phone call or mail.

\*Note that the larger training study from which this study is taken consists of an additional behavioral sample of older adults, but I do not discuss their involvement here for the purposes of the dissertation.

## Procedure

Participants were recruited as part of a clinical trial cognitive training study (R21AG060216) in which older adults completed a battery of behavioral tests, sleep surveys and metrics, and evaluations of everyday functioning. One group of participants received cognitive training in the form of process-based cognitive training whereas the other (control) group simply retrieved computer-based brain teaser games (See Fig 1. for overview of testing timeline).

This study examined the transfer of cognitive training to cognition and neural functioning. This is a prospective, randomized, masked trial. Due to COVID, the study team conducted this study as a remote study for all data collection with the exception of



**Figure 1.** Study Overview. Participants completed baseline behavioral and neuroimaging sessions prior to group assignment. They then completed training or stimulating games across 2.5 months prior to a second behavioral and neuroimaging session.

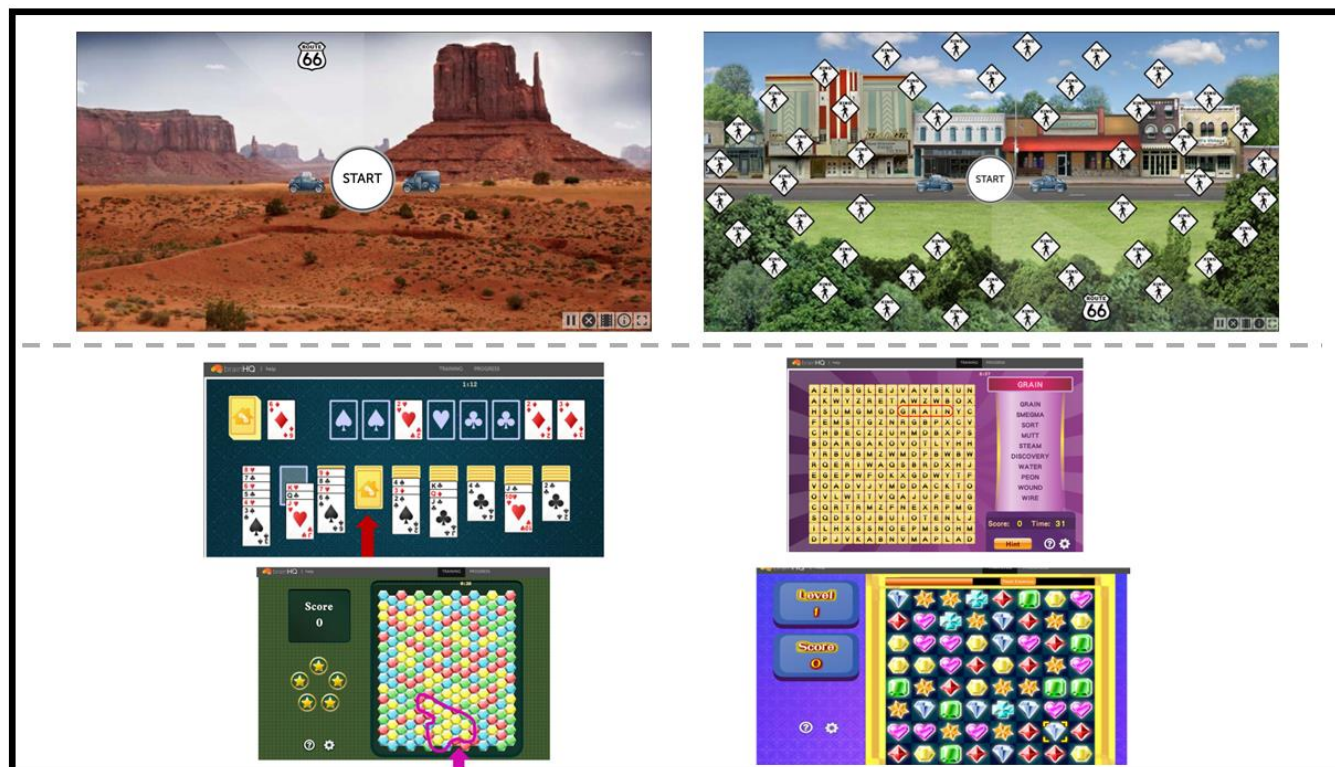
MRI visits, which took place in-person for any participants who were interested and eligible in the MRI, had the COVID-19 vaccine, and were comfortable coming in for an in-lab visit. Any persons who wished to participate, but who did not have the COVID-19 vaccine and/or were uncomfortable coming in for an in-lab visit, were asked if they were willing to postpone study entry until such time as they had the COVID-19 vaccine and were comfortable coming in for an in-lab visit. If they did not wish to delay study entry (i.e., they wanted to start immediately, did not plan to receive the COVID-19 vaccine, or did not feel comfortable coming into the lab at any time in the few months close to recruitment), the study team proceeded with the study alone.

After phone screening, eligible participants were provided the written consent document either by paper form in the mail or via a RedCap link to an e-consent. Following consent, participants were randomized to one of two types of brain games and arrangements were made for delivery of study-provided equipment (laptop, mobile smart phone, and written instruction for their use). During daily mobile phone surveys and laptop sessions, participants were asked about perceptions, health, and daily life as well as activities to assess cognitive skills (such as memory) and simulated daily activities (such as balancing a checkbook). All surveys and activities were performed remotely by participants on the study provided laptop at 3 time periods during the study. They were also provided with and trained on how to use a study-provided mobile phone. They used the mobile phone to answer daily lifestyle, psychosocial, and cognitive assessments throughout the study period. The phone had all functions not related to the study disabled. Participants were instructed on the use of the mobile phone and how to perform the study activities through links on the laptop to instruction manuals as well as printed material. If the participant was eligible and interested in the study, they were scheduled to enter the study immediately if they received the COVID-19 vaccine and were comfortable coming in for an in-lab visit. Once enrolled, they completed the baseline MRI at the Chandlee lab on campus. This baseline MRI visit occurred shortly after behavioral Session 1 and prior to the beginning of the cognitive training.

After Session 1 and before the brain games begin, the participant received a call from a staff member to complete a MoCA test over the phone, as a part of Session 1.

After 2 weeks of baseline survey and cognitive assessment data collected via the mobile phones, the participants were contacted by phone and instructed on how to access and play the brain games on the laptop. Additional instructions were available for reference on the laptop. All non-study related functions on the laptop were disabled. Participants were asked to complete approximately 2 hours of training or games per week in their homes across 10 weeks for a total of 20 hours of training. Training brain games consisted of visual games similar to the Useful Field of View task in which participants are cued to the image of a vehicle in their visual periphery and must identify the image of that vehicle (i.e., a truck versus a compact car). The training difficulty was adaptive and became more challenging as participants' accuracy level increased. Non-training brain games consisted of games that are stimulating but not cognitively engaging, such as sudoku and crossword puzzles. Training compliance was monitored by study staff (Fig. 2).

Participants completed a second behavioral session (Session 2) after training. They repeated a subset of the same cognitive battery from Session 1. They were then



**Figure 2.** Training and games examples. Participants in to training group completed useful field of view (UFOV) training tasks (top half), while participants in the control group completed cognitive stimulating games (bottom half).

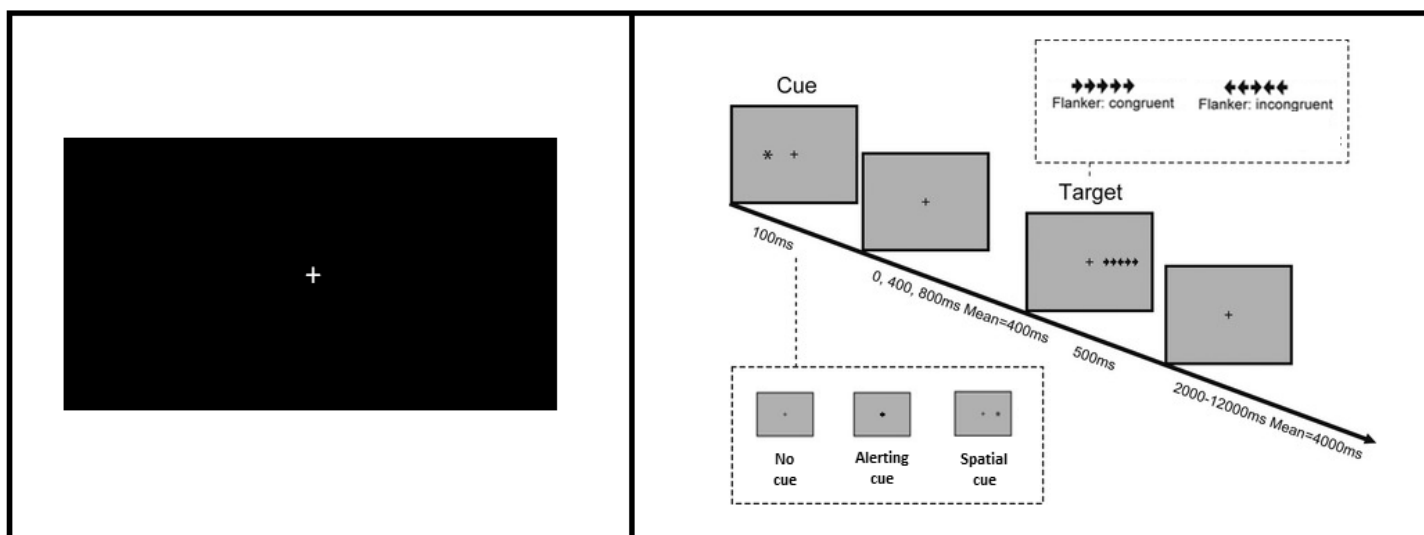
scheduled for a repeat MRI to be completed shortly after Session 2 (within two weeks). This was the end of the participant visits in the optional portion of the study for those who participate. After the final session they returned the study-provided equipment arranged by pick up via study staff and this completed the study.

The study was comprised of one phone screening, one phone administration of the t-MoCA test, and two remote Sessions completed on a study-provided laptop at the participants home (intended to collect neuropsychological battery data). The MRI portion of the study added two additional visits to the Chandlee lab at Penn State University for those who were COVID-19 vaccinated, comfortable with an in-lab visit, and interested and consented to participate. All participants received study-provided mobile devices (laptop and phone) on which they completed 20 hours of either training or control training as well as daily mobile cognitive and psychosocial questionnaires/tasks.

The MRI scans for the study were completed at the Chandlee Lab. While in the scanner, participants completed the Attention Network Test were asked to respond to stimuli using an MRI-capable push button pad. The visit lasted two hours; however, the time in the MRI was approximately 50 minutes. Participants lied on the MRI scanner bed which slid inside the scanner bore for imaging. Participants viewed a projection display from inside the bore of the scanner by looking at a set of mirrors attached to the head coil. Anatomical and functional images were acquired (acquisition parameters are detailed below). These included high-resolution structural images to examine gray and white matter, and functional images (ANT and resting state; Fig. 3). All sequences were collected at the Social, Life, and Engineering Sciences Imaging Center (SLEIC) on the University Park Campus at Penn State. Each participant participated in two MRI scans that lasted approximately one hour. All COVID CDC and SLEIC guidelines for participant safety which are in place at that time were utilized.

The resting state scan preceded the task scans. During the resting scan, participants viewed a fixation cross on the back-projected monitor and were instructed to keep their eyes open, to lay still and relax, and that they did not need to think about anything in particular. The resting state scan lasted for 10 minutes.

During the Attention Network Test functional task, participants completed a version of the Attention Network Test similar to that used by Fan et al. (2005). Whereas the Fan et al. 2005 task presents flanking arrays and cues above and below the fixation cross, in the current task the flanking arrays and cues were presented to the left and right of the fixation cross. Specifically, during the task participants completed 288 trials separated across 4 runs, with 72 trials per run. The order of a trial was as follows, participants viewed a brief cue (spatial, central, no cue) for 100 ms, followed by a fixation cross of either 400 or 800 ms, after the cue and first fixation, participants were presented with the flanking array for 500 ms and then a second fixation cross ranging from 2000-11000ms. This second fixation served as an inter-trial-interval and the durations followed a pseudo-exponential function with a mean of 4000ms. Participants used their right hand to make responses via a buttonbox to indicate the direction of the central arrow in the flanking array, pressing with their index finger if the central arrow pointed to the left and pressing with their middle finger if the central arrow pointed to the right. Participants were allowed to make responses during the second fixation, but were instructed to respond as quickly and accurately as possible. Of the 288 total trials, 144 trials were congruent flanking arrays and 144 were incongruent, 96 trials were cued for alerting (central cue), 96 trials received no cue (viewing a fixation), and 96 trials were spatially cued for orienting (48



**Figure 3.** Neuroimaging Tasks. At baseline and posttest MRI sessions participants first completed a resting state scan in which they were instructed to relax and not think about anything in particular (left panel). They then completed four runs of the Attention Network Task (right panel).

trials are left-cued and 48 trials are right-cued). Participants were instructed to always respond to the direction of the central arrow surrounded by other arrows, regardless of the direction of the surrounding arrows or where on the screen the arrows appeared. Participants were also instructed that cues could sometimes appear indicating that the arrows would soon appear or indicate where the arrows would appear. Each run of the task lasted for 6 minutes for a total of 24 minutes of Attention Network Test scanning.

### Participant Inclusion and Exclusion Criteria

Participants needed to maintain the following criteria to be included in the study:

- Community-dwelling adults aged 65 to 90
- Ability to understand and communicate with written and spoken English
- No reported diagnosis or evidence of Alzheimer 's disease or other dementia; score of 5 or greater on the MIS-t administered during phone screening
- Able and willing to complete the 6 month protocol
- Not currently engaged in another cognitive program
- Willing to undergo an MRI of the brain two times during the study
- Be able to lie flat on the MRI table in a supine position for at least 60 minutes
- Pass the standard IRB-approved SELIC MRI-safety screening criteria
- Live within 40 miles of Penn State
- Has received the COVID-19 vaccine

### Hypotheses and Analyses:

All primary research questions, hypotheses, and analysis approaches were preregistered with the Open Science Foundation (OSF) at <https://osf.io/tj3w2>.

### Primary Question 1.

1. Does cognitive training enhance behavioral performance in the attentional facets of alerting, orienting, and executive functioning in healthy older adults?



Given the effectiveness of previous cognitive training studies on the separate facets of attention, I hypothesized that the facets of alerting, orienting, and executive functioning would have an increase in their efficiency as operationalized by reaction times. Specifically, alerting efficiency is calculated as the difference in reaction times between trials with central cues and trials with no cues. Orienting efficiency is defined as the difference in reaction times between trials with spatial cues and trials with central cues. Finally, executive functioning efficiency is calculated as the difference in reaction times between incongruent flanking array trials and congruent flanking trials. I submitted each attention facet score to an ANCOVA with change in attention facet score (session two minus session one) as the outcome, and session one attention score and group (train/control) as the predictors. This approach tests for group differences in the change of attention facet score while controlling for participants baseline behavioral performance. This approach therefore is more stringent than ANOVAs which look for simple differences in means. I utilized follow-up t tests to investigate the nature of any significant group differences. I predicted training related improvements in the behavioral facets of attention. An increase in the efficiency of alerting, orienting, or executive functioning observed in the training group above and beyond any changes observed in the control group was taken as evidence of the successful effects of training. Specifically I predicted reductions (reflecting reduced reaction times) for the incongruent flankers, center cue, and spatial cue conditions in the difference scores for the facets of attention. Given the specific nature of hypotheses and limited family of statistical tests, the statistics for Primary Question 1 were not corrected for multiple comparisons.

#### Primary Question 2.

2. Does cognitive training result in altered BOLD amplitude in regions implicated in alerting, orienting, and executive functioning in older adults?

Previous work suggests that cognitive training results in altered neural processing in trained participants as compared to participants in control groups. This effect is frequently observed as a reduction in BOLD amplitude within the training group compared to the control group. I predicted that regions that selectively activate in

association with alerting, orienting, and executive functioning would exhibit reduced BOLD amplitude at posttest compared to the control group. The neural effects of alerting, orienting, and executive functioning are defined with the following separate contrasts. The alerting functional contrast is defined as central cues versus no cues (fixation). The orienting functional contrast is defined as spatial cues versus central cues. Finally, the executive functioning contrast is defined as incongruent flanking arrays versus congruent flanking arrays. Regarding alerting, I expected altered functional recruitment in visual cortex and inferior parietal cortex reflecting a more efficient preparatory processing of alertness. Reflecting enhanced orienting, I expected altered neural activity in visual cortex, superior parietal cortex, and dorsolateral prefrontal cortex. And finally, regarding executive functioning, I expected altered BOLD amplitude in anterior insula and dorsolateral prefrontal cortex. As will be discussed in greater detail in the subsequent analysis section, I attempted to first anatomically define regions of interest (ROIs) associated with the three attentional facets, and extract contrast estimates associated with each contrast from the ROIs at each time point (session 1, session 2) and for each group (train, control). I then submitted contrast estimates within each region of interest to an ANCOVA with change in contrast estimate (session two minus session one) as the outcome, and session one contrast estimate and group (train/control) as the predictors. This approach tests for group differences in the change score of univariate contrast estimate while controlling for participants baseline activity. I predicted to observe training related decreases in univariate contrast estimates in the training group compared to the control group when controlling for baseline activity, reflecting training-induced efficiency. I also utilized exploratory univariate whole-brain analyses to examine regions outside the regions of interest that exhibited either a hypothesized decrease in neural functioning in the training group as compared to the control group, or an increase in neural functioning in the training group as compared to the control group.

Image acquisition: Structural and functional images were acquired using a Siemens 3T scanner using a 12-channel head coil, parallel to the AC-PC plane. Structural images were collected with a 2,300ms TR, 2.32 ms TE, 240 mm field of view, 192 slices, 8 degree flip angle, and a 0.9 mm slice thickness for each participant. Functional images

were collected with a 2,500ms TR, 25 ms TE, 240 mm field of view, 42 slices, 80 degree flip angle, 192 slices and a 3 mm slice thickness for each participant.

Analysis: Functional data were preprocessed using fMRIPREP (20.2.1) and processed with SPM12 (Statistical Parametric Mapping; Wellcome Department of Cognitive Neurology, <http://www.fil.ion.ucl.ac.uk/spm>). The T1-weighted (T1w) image was corrected for intensity non-uniformity (INU) with N4BiasFieldCorrection (Tustison et al. 2010), distributed with ANTs 2.3.3 (Avants et al. 2008, RRID:SCR\_004757), and used as T1w-reference throughout the workflow. The T1w-reference was then skull-stripped with a Nipype implementation of the antsBrainExtraction.sh workflow (from ANTs), using OASIS30ANTs as target template. Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and gray-matter (GM) was performed on the brain-extracted T1w using fast (FSL 5.0.9, RRID:SCR\_002823, Zhang, Brady, and Smith 2001). Brain surfaces were reconstructed using recon-all (FreeSurfer 6.0.1, RRID:SCR\_001847, Dale, Fischl, and Sereno 1999), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (RRID:SCR\_002438, Klein et al. 2017). Volume-based spatial normalization to two standard spaces (MNI152NLin6Asym, MNI152NLin2009cAsym) was performed through nonlinear registration with antsRegistration (ANTs 2.3.3), using brain-extracted versions of both T1w reference and the T1w template. The following templates were selected for spatial normalization: FSL's MNI ICBM 152 non-linear 6th Generation Asymmetric Average Brain Stereotaxic Registration Model [Evans et al. (2012), RRID:SCR\_002823; TemplateFlow ID: MNI152NLin6Asym], ICBM 152 Nonlinear Asymmetrical template version 2009c [Fonov et al. (2009), RRID:SCR\_008796; TemplateFlow ID: MNI152NLin2009cAsym].

For each of the BOLD runs found per subject (across all tasks and sessions), the following preprocessing was performed. First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. The BOLD reference was then co-registered to the T1w reference using bregister (FreeSurfer) which implements boundary-based registration (Greve and Fischl 2009). Co-registration was configured with six degrees of freedom. Head-motion parameters with respect to the

BOLD reference (transformation matrices, and six corresponding rotation and translation parameters) were estimated before any spatiotemporal filtering using *mcflirt* (FSL 5.0.9, Jenkinson et al. 2002). These motion parameters were inspected to ensure no participants exhibited motion greater than three voxels. BOLD runs were slice-time corrected using *3dTshift* from AFNI 20160207 (Cox and Hyde 1997, RRID:SCR\_005927). The BOLD time-series (including slice-timing correction when applied) was resampled onto their original, native space by applying the transforms to correct for head-motion. These resampled BOLD time-series will be referred to as preprocessed BOLD in original space, or just preprocessed BOLD. The BOLD time-series were resampled into standard space, generating a preprocessed BOLD run in MNI152NLin6Asym space. First, a reference volume and its skull-stripped version was generated using a custom methodology of *fMRIPrep*. Automatic removal of motion artifacts using independent component analysis (ICA-AROMA, Pruim et al. 2015) was performed on the preprocessed BOLD on MNI space time-series after removal of non-steady state volumes and spatial smoothing with an isotropic, Gaussian kernel of 6mm FWHM (full-width half-maximum). Corresponding “non-aggressively” denoised runs were produced after such smoothing. Additionally, the “aggressive” noise-regressors were collected and placed in the corresponding confounds file. Several confounding time-series were calculated based on the preprocessed BOLD: framewise displacement (FD), DVARS and three region-wise global signals. FD was computed using two formulations following Power (absolute sum of relative motions, Power et al. (2014)) and Jenkinson (relative root mean square displacement between affines, Jenkinson et al. (2002)). FD and DVARS were calculated for each functional run, both using their implementations in *Nipype* (following the definitions by Power et al. 2014). The three global signals were extracted within the CSF, the WM, and the whole-brain masks. Additionally, a set of physiological regressors were extracted to allow for component-based noise correction (*CompCor*, Behzadi et al. 2007). Principal components were estimated after high-pass filtering the preprocessed BOLD time-series (using a discrete cosine filter with 128s cut-off) for the two *CompCor* variants: temporal (*tCompCor*) and anatomical (*aCompCor*). *tCompCor* components are then calculated from the top 2% variable voxels within the brain mask. For *aCompCor*, three probabilistic masks (CSF, WM and combined CSF+WM) were generated in anatomical

space. The implementation differs from that of Behzadi et al. in that instead of eroding the masks by 2 pixels on BOLD space, the aCompCor masks are subtracted from a mask of pixels that likely contain a volume fraction of GM. This mask is obtained by dilating a GM mask extracted from the FreeSurfer's aseg segmentation, and it ensures components are not extracted from voxels containing a minimal fraction of GM. Finally, these masks are resampled into BOLD space and binarized by thresholding at 0.99 (as in the original implementation). Components are also calculated separately within the WM and CSF masks. For each CompCor decomposition, the  $k$  components with the largest singular values are retained, such that the retained components' time series are sufficient to explain 50 percent of variance across the nuisance mask (CSF, WM, combined, or temporal). The remaining components are dropped from consideration. The head-motion estimates calculated in the correction step were also placed within the corresponding confounds file. The confound time series derived from head motion estimates and global signals are expanded with the inclusion of temporal derivatives and quadratic terms for each (Satterthwaite et al. 2013). Frames that exceeded a threshold of 0.5 mm FD or 1.5 standardized DVARS were annotated as motion outliers. All resamplings can be performed with a single interpolation step by composing all the pertinent transformations (i.e. head-motion transform matrices, susceptibility distortion correction when available, and co-registrations to anatomical and output spaces). Gridded (volumetric) resamplings were performed using `antsApplyTransforms` (ANTs), configured with Lanczos interpolation to minimize the smoothing effects of other kernels (Lanczos 1964). Non-gridded (surface) resamplings were performed using `mri_vol2surf` (FreeSurfer).

Prior to the univariate neuroimaging analysis, I defined ROIs anatomically via the Human Labels segmentation in the aal PickAtlas to then examine neural effects within at baseline, given previous evidence that such regions are implicated in neural processing associated with the facets of attention. Specifically, for alerting, I selected the fusiform cortex and inferior parietal cortex. For orienting, I selected the dorsolateral prefrontal cortex and superior parietal cortex. And for executive functioning, I selected the anterior insula and dorsolateral prefrontal cortex. This approach was intended to identify functionally defined clusters within anatomically defined regions to examine training-related changes in BOLD amplitude.

To estimate neural activity associated with alerting, orienting, and executive functioning, I first utilized a whole-brain univariate contrast approach. Trial-related activity during the attention network test was modeled using a general linear model (GLM) and a stick function corresponding to trial and stimuli onsets (ex: the onset of a spatial cue, the onset of an incongruent flanking array), then convolved with a canonical hemodynamic response function (hrf). I specified and estimated five trial types of interest: no cue (fixation), central cues, spatial cues, congruent flanking arrays, and incongruent flanking arrays. Null-response trials and motion parameters provided by fMRIPrep were included in the model as regressors of no interest. The univariate contrast of alerting was defined as central cue vs no cue, orienting was defined as spatial cues vs central cues, and executive functioning was defined as incongruent flanking arrays vs congruent flanking arrays. The neural contrasts were estimated for all participants at session 1 and session 2. I then extracted the contrast estimates from the aforementioned regions of interest from each contrast for each participant for each timepoint.

I then submitted contrast estimates within each region of interest to an ANCOVA with change in contrast estimate (session two minus session one) as the outcome, and session one contrast estimate and group (train/control) as the predictors. This approach tests for group differences in the change score of univariate contrast estimate while controlling for participants baseline activity. I utilized follow-up t tests to investigate the nature of any significant group effects.

I also conducted exploratory whole brain univariate analyses to examine any regions beyond the functionally defined regions of interest also exhibited the hypothesized training-induced reduction in univariate amplitude, or if any regions exhibited a training-induced increase in univariate amplitude beyond any observed in the control group. To do so I submitted the first level alerting, orienting, and executive functioning contrast maps from baseline and post-test MRI sessions to the Sandwich Estimator (SwE version 2.2.2) toolbox implemented in SPM (Guillaume et al., 2014), masking for gray matter. The SwE toolbox applies non-iterative marginal models to the functional MRI dataset while also accounting for correlations due to repeated measurements and error variation across individual participants. The toolbox is well

adapted to handle datasets that are small or potentially unbalanced. Specifically, I examined regions that displayed decreases across time in the training group, above and beyond any observed in the control group, while controlling for baseline neural activity. I also examined if any regions displayed increases across time in the training group, above and beyond any observed in the control group, while controlling for baseline neural activity.

I predicted to observe training related decreases in univariate contrast estimates in the training group compared to the control group when controlling for baseline activity, reflecting training-induced efficiency. Alterations in neural activity associated with the attentional facets in the training group, beyond any observed in the control group, were evidence for training related benefits in attentional neural recruitment. Training-related decreases in neural recruitment were taken as evidence of training-induced efficiency, whereas training-related increases in neural recruitment were taken as evidence of training-induced compensatory neural recruitment. Given the specific nature of hypotheses and limited family of statistical tests, the statistics for Primary Question 2 were not corrected for multiple comparisons.

Primary Question 3.

3. Does cognitive training increase segregation and efficiency of the dorsal attention, ventral attention, fronto-parietal, and cingulo-opercular networks?

Finally, research suggests that four networks maintain covarying timeseries of activity associated with attentional functioning, even at rest when not engaged in any explicit cognitive task: the dorsal attention, ventral attention, fronto-parietal, and cingulo-opercular networks. It is hypothesized that the dorsal and ventral attention networks correspond to orienting, the cingulo-opercular network corresponds to alerting, and the fronto-parietal network corresponds to executive functioning. These networks are defined using spherical nodes in pre-existing atlases (such as the Power et al., 2011 atlas). Specifically, resting state connectivity among spherical nodes in these atlases maintain correlations with the separate facets of attention. While previous work has assessed that these networks often become more connected within themselves following cognitive

training (i.e., greater within network connectivity among nodes), initial evidence suggests that networks may also become more segregated and efficient following cognitive training in aging. Segregation is defined as the difference of average within-network connectivity minus between-network connectivity (i.e., the dorsal attention network maintains greater correlation coefficients among nodes within the networks than between nodes in other networks). Efficiency is defined as the average inverse shortest pathway in a given network. Networks with fewer pathways among nodes have greater efficiency. As will be discussed in greater detail below, I defined regions corresponding to attentionally-relevant networks using five-millimeter spheres according to the Power et al. (2001) atlas. I then calculated correlation coefficients among nodes in the atlas, and then calculated the metrics of segregation and efficiency for each network of interest using these correlation coefficients. I predicted that the dorsal attention, ventral attention, fronto-parietal, and cingulo-opercular networks would exhibit increases in segregation and efficiency in the training group above and beyond any changes in the control group post training.

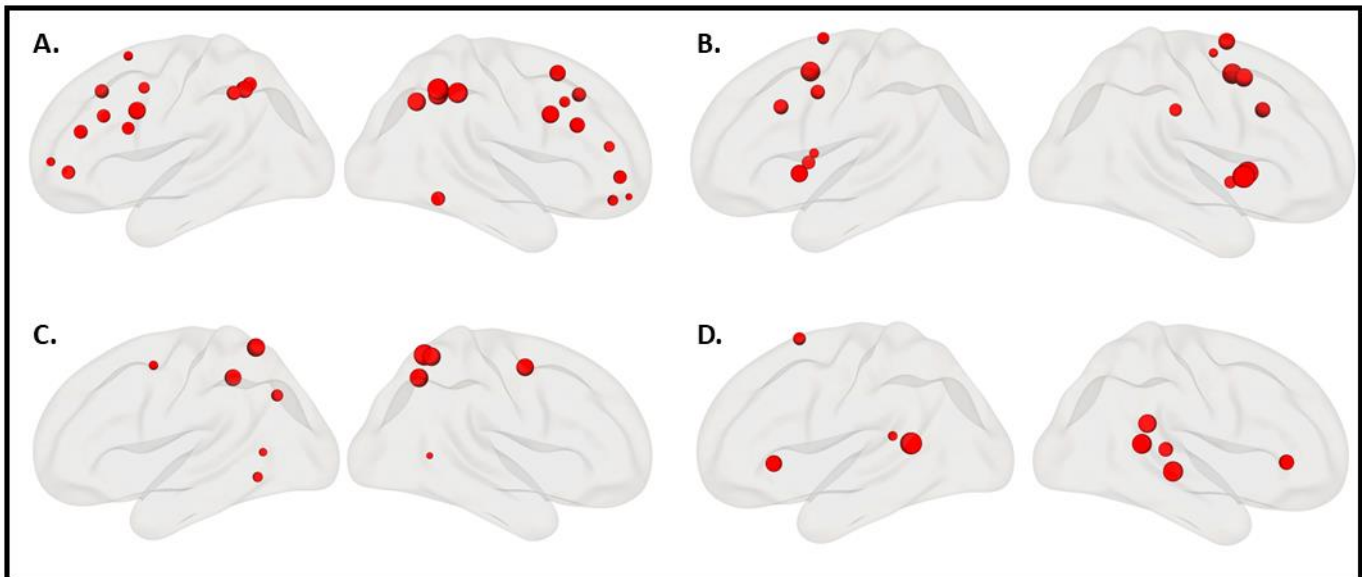
Image acquisition: Structural and functional images were acquired using a Siemens 3T scanner using a 12-channel head coil, parallel to the AC-PC plane. Structural images were collected with a 2,300ms TR, 2.32 ms TE, 240 mm field of view, 192 slices, 8 degree flip angle, and a 0.9 mm slice thickness for each participant. Functional image acquisition parameters for rest were identical to the task functional acquisition patterns and are included here for completeness. Functional images were collected with a 2,500ms TR, 25 ms TE, 240 mm field of view, 42 slices, 80 degree flip angle, 192 slices and a 3 mm slice thickness resulting in 3 mm isotropic voxels for each participant.

Analysis: Functional data were preprocessed using fMRIPREP (20.2.1) and processed with SPM12 (Statistical Parametric Mapping; Wellcome Department of Cognitive Neurology, <http://www.fil.ion.ucl.ac.uk/spm>). Anatomical and functional preprocessing followed the same steps as used in hypothesis 2. In addition, volumes identified as motion outliers by fMRIprep were scrubbed from the timeseries. I also denoised the functional images using the tissue segmentation images and confound regressors output by fmriprep. Specifically, CSF and white matter masks were included as nuisance ROIs. Additionally, signal related to CSF, white matter, and motion was



regressed out of the functional image time-courses prior to the calculation of connectivity coefficients.

To examine resting state network connectivity, I conducted a connectivity analysis using the Conn toolbox ([www.nitrc.org/projects/conn](http://www.nitrc.org/projects/conn), RRID:SCR\_009550) in SPM12. Specifically, I conducted participant-level ROI-to-ROI analyses to calculate the correlation coefficients among timeseries in all nodes in the cortex as defined by 5 mm spheres in the Power et al. (2011) atlas. I then extracted the z-scored correlation coefficients from pairs of nodes within the specific networks of interest (Fig. 4), and between the specific networks of interest and all other nodes, to calculate segregation scores for each network of interest. Segregation is defined as the difference of within-network connectivity of the network of interest and between-network connectivity with all other cortical networks measured, divided by within connectivity of the network of interest, to receive a normalized segregation score for each network of interest. Networks typically have greater within network connectivity than between network connectivity. I also calculated efficiency for each network of interest using standard thresholding approaches as implemented in the Conn toolbox. Efficiency is defined as the inverse shortest pathway in a network. Networks that have fewer pathways among nodes are more efficient. I then submitted these network segregation and efficiency scores to individual change score ANCOVAs with change in network metric (session two minus session one) as the outcome, and session one segregation and group (train/control) as the predictors for each network of interest. I predicted that the dorsal attention, ventral attention, fronto-parietal, and cingulo-opercular networks would exhibit increases in segregation and efficiency in the training group above and beyond any changes in the control group post training. Increases in segregation and efficiency within the networks of interest in the training group above those observed in the control group were taken as evidence of training-induced alterations in network properties. Given the specific nature of hypotheses and limited family of statistical tests, the statistics for Primary Question 3 were not corrected for multiple comparisons.



**Figure 4.** Resting State Networks of Interest. Four networks were derived from the Power et al. (2011) atlas: the fronto-parietal network (A.), cingulo-opercular network (B.), dorsal attention network (C.), and ventral attention network (D.)

## Results

### Behavioral Results

At baseline, participants exhibited high overall accuracy (average = 95.17%, standard deviation = 6.04%) and a mean reaction time of 943 ms (standard deviation = 106 ms). I next used reaction times to calculate attention facet scores for alerting (no cue minus center cue), orienting (center cue minus spatial cue), and executive functioning (incongruent flanking array minus congruent flanking array).

To test for greater changes in attention facet scores in the training compared to the control group, I submitted each attention facet score to an ANCOVA with change in attention facet score (session two minus session one) as the outcome, and session one attention score and group (train/control) as the predictors. This approach tests for group differences in the change of attention facet score while controlling for participants baseline behavioral performance. This approach therefore is more stringent than ANOVAs which look for simple differences in means. I predicted training-related performance increases

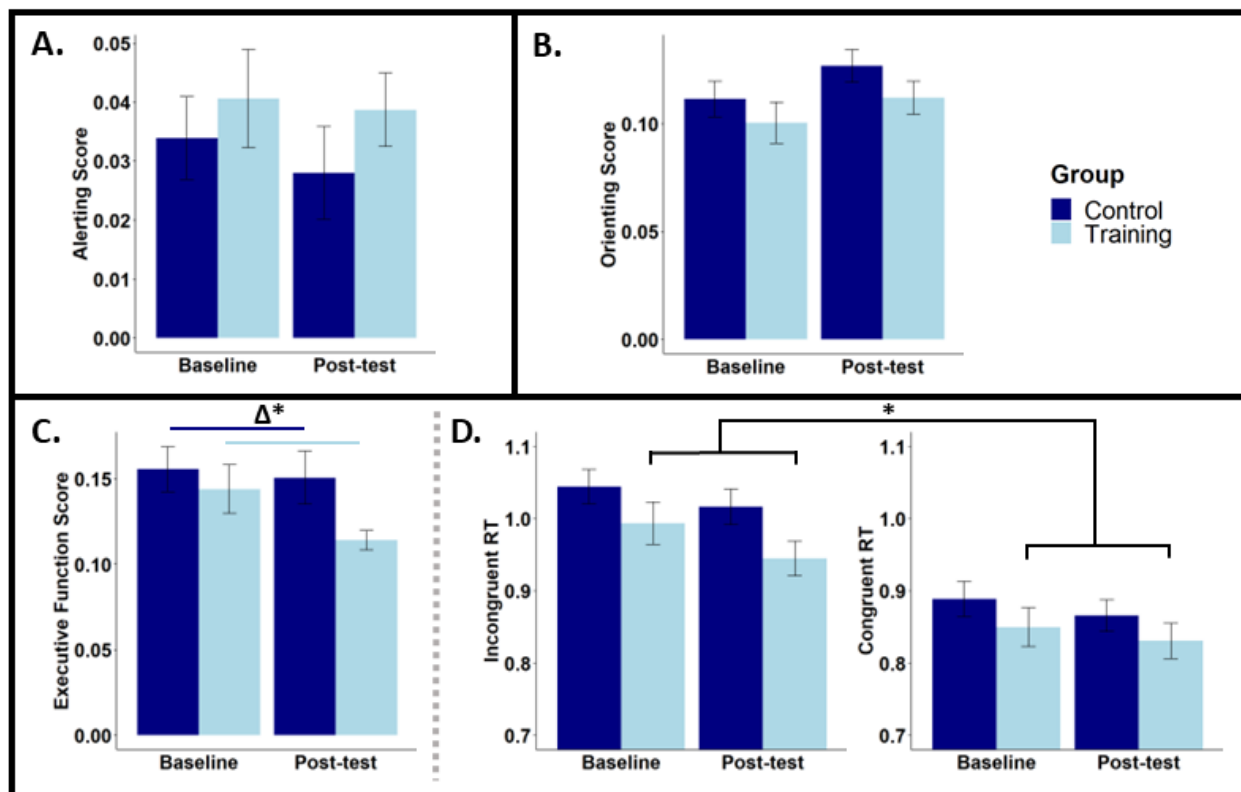
in the behavioral facets of attention as operationalized by reduced reaction times driven by the no-cue, center cue, and the incongruent flanker conditions.

When examining alerting, I failed to observe group differences in the change of alerting performance ( $b(34) = .008$ ,  $p = 0.41$ ) while baseline alerting negatively predicted change in alerting ( $b(34) = -.069$ ,  $p = 0.001$ ) (Fig. 5A). While paradoxical at first glance, such negative correlations with baseline metrics reflect a beneficial outcome, where participants who exhibited lower baseline metrics also tended to receive the greatest improvements in that metric.

When examining orienting, I failed to observe group differences in the change of orienting performance ( $b(34) = -.009$ ,  $p = 0.32$ ), while baseline orienting negatively predicted change in orienting score ( $b(34) = -.45$ ,  $p = 0.04$ ) (Fig. 5B).

When examining executive functioning, I observed a group difference in change of executive functioning score ( $b(34) = -.029$ ,  $p = 0.04$ ), and baseline executive functioning negatively predicted the change in executive functioning reaction time ( $b(34) = -.37$ ,  $p = 0.004$ ) (Fig. 5C). I next conducted follow-up t-tests to investigate the nature of the group differences in change of executive functioning score. I observed the training group had a marginally significant difference in change of executive functioning compared to the control group ( $t(33.26) = -1.59$ ,  $p = .06$ ). Additionally, at post-test assessment, the training group had a lower executive functioning compared to the control group ( $t(25.09) = -2.22$ ,  $p = .02$ ). While paradoxical at first glance, this difference reflects a significant within-group reduction in reaction times in the training group, who exhibited a greater reduction in reaction times for incongruent flanker arrays (Fig. 5D left hand side) compared to congruent flanker arrays (Fig 5D right hand side) ( $t(15) = -2.60$ ,  $p = .01$ ), whereas the control group had no differences in changes in reaction time between incongruent and congruent flanking arrays ( $t(20) = -.47$ ,  $p = .3$ ). As the executive functioning attentional facet score is calculated as incongruent minus congruent, this greater reduction for incongruent reaction times led to the reduced executive functioning score at post-test assessment. Thus, the training group exhibited greater changes in reaction times for the incongruent flanking arrays compared to the congruent flanking arrays, whereas the

control group exhibited no such difference. It is also possible that since the attentional facets are operationalized with difference scores (ex: center cue minus spatial cue), that



**Figure 5.** Behavioral Results. Baseline and posttest scores for the training and control group are depicted for the attentional facets of A) Alerting, B) Orienting, C) Executive Functioning, and for D) Incongruent and Congruent reaction times comprising the Executive Functioning Facet. \* Indicates significance at  $p < .05$ .

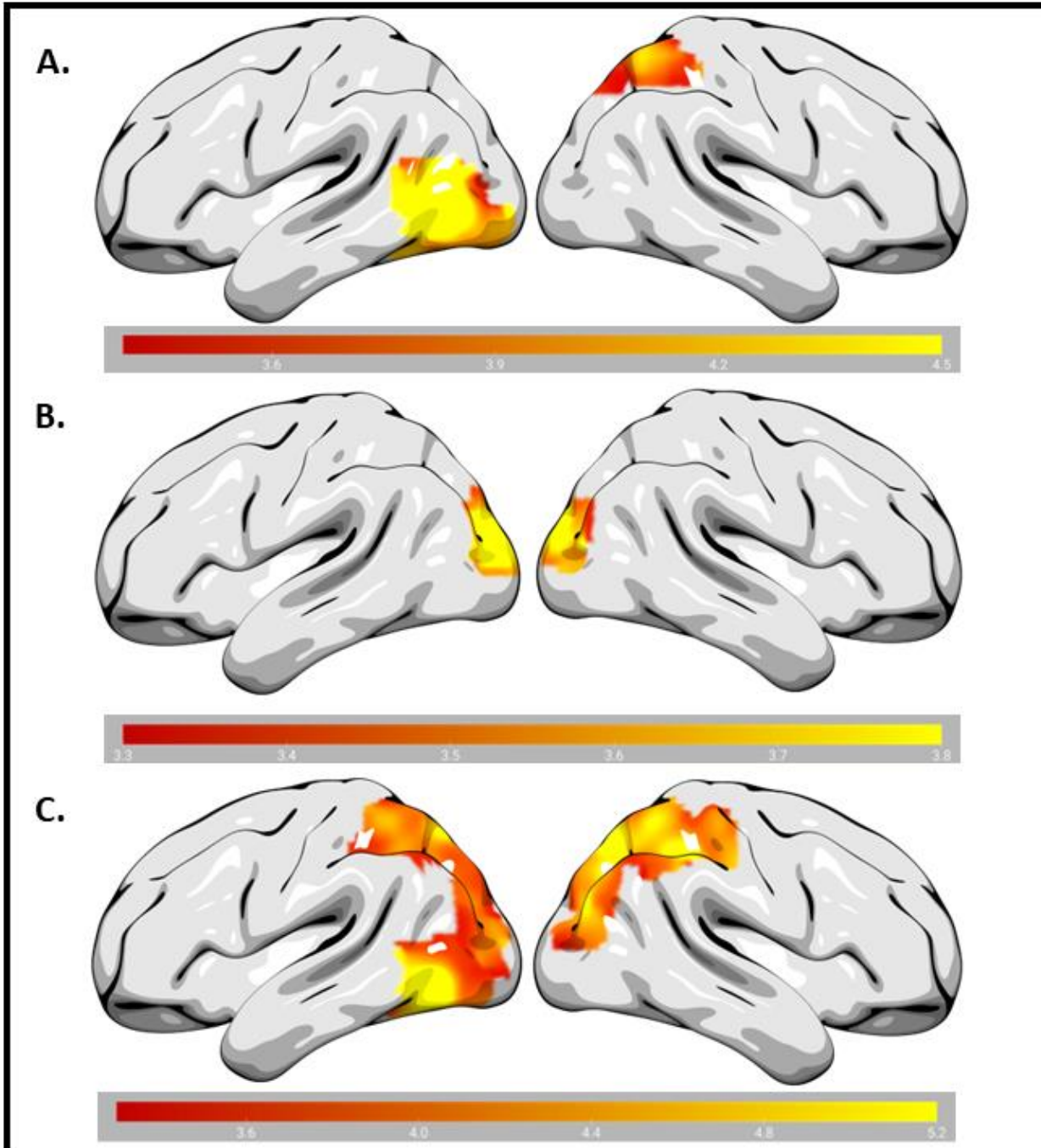
training-related effects occur for at a similar magnitude for the individual components of the attentional facets, but the difference scores compress these effects.

## Univariate Results

### Baseline Region of Interest Definition

At baseline, I defined several masks anatomically using the Human Labels Atlas of the WFU picatlas, to assess neural functioning associated with alerting, orienting, and executive functioning. Specifically, for alerting I defined the fusiform gyrus and inferior parietal gyrus. For orienting, I defined the dorsolateral prefrontal cortex and superior parietal gyrus. And for executive functioning, I defined the dorsolateral prefrontal cortex

and anterior cingulate. When using a cluster extent threshold of  $k > 32$  and  $p < .001$  as defined by monte carlo simulations (Cox & Hyde, 1997), no supra threshold clusters were present in the a-priori regions of interest. I then utilized a whole-brain examination (see



**Figure 6.** Baseline Univariate Contrast Results. Significant clusters depicting neural activity associated with A) alerting, B), orienting, and C) executive functioning in the full sample at the baseline MRI session.

Turney, Chamberlain, et al. *bioRxiv* for the same procedure) with the same cluster extent and p value threshold to define functionally relevant regions of interest. Several distinct clusters were observed using this approach. For alerting, greater neural activity for the central cue compared to no-cue was observed in left middle occipital cortex and right superior parietal cortex (Fig. 6A). For orienting, greater neural activity for the spatial cue compared to the central cue was observed in left and right middle occipital cortex (Fig. 6B). Finally, for executive function, greater activity for the incongruent flanking array than the congruent flanking array was observed in left inferior temporal cortex and bilateral superior parietal cortex (Figure 6C). Please see Table 1 for more information on each cluster. While not my a-priori regions, these clusters are functionally relevant to the attentional facets of alerting, orienting, and executive functioning in the current sample of participants (see more in Discussion). These clusters were therefore utilized to extract contrast estimates from participants at session one and session two to examine possible training-related changes in univariate BOLD estimates.

**Table 1.** Baseline Full Sample Whole-brain Univariate Analyses

| Region                       | H | MNI |     |    | k    | t    |
|------------------------------|---|-----|-----|----|------|------|
|                              |   | x   | y   | z  |      |      |
| <i>Alerting</i>              |   |     |     |    |      |      |
| Middle Occipital             | L | -52 | -72 | 2  | 189  | 7.3  |
| Superior Parietal            | R | 38  | -58 | 60 | 89   | 6    |
| <i>Orienting</i>             |   |     |     |    |      |      |
| Middle Occipital             | L | -28 | -94 | 14 | 105  | 5.39 |
| Middle Occipital             | R | 30  | -90 | 20 | 57   | 4.52 |
| <i>Executive Functioning</i> |   |     |     |    |      |      |
| Inferior Temporal            | L | -46 | -64 | -4 | 87   | 9.05 |
| Superior Parietal            | B | 24  | -72 | 54 | 1379 | 5.75 |

H = hemisphere (L = left, R = right, B = bilateral), Coordinates (x, y, z) represent peak MNI coordinates, k = voxel extent, t = statistical t value

### Univariate ROI Pre-Post Changes

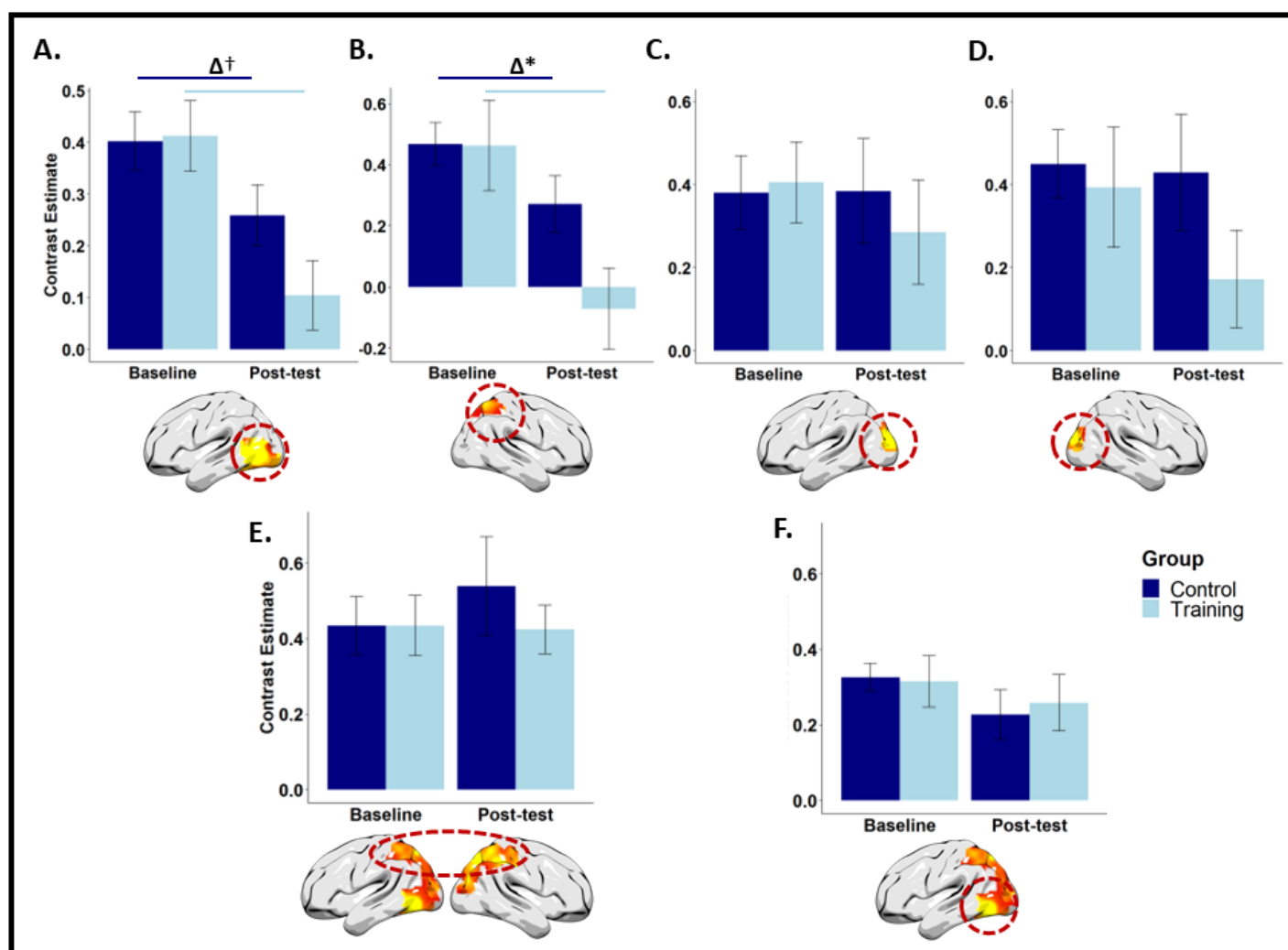
To test for greater reductions in univariate contrast estimate in the training compared to the control group, I submitted contrast estimates within each region of

interest to an ANCOVA with change in contrast estimate (session two minus session one) as the outcome, and session one contrast estimate and group (train/control) as the predictors. This approach tests for group differences in the change score of univariate contrast estimate while controlling for participants baseline neural activity. I predicted to observe training related decreases in univariate contrast estimates in the training group compared to the control group when controlling for baseline activity, reflecting training-induced functional efficiency.

For alerting, when examining the contrast estimates of the middle occipital cortex I observed a marginal difference in change of contrast estimates ( $b(34) = -.15, p = 0.09$ ), while baseline middle occipital activity negatively predicted change in contrast estimate ( $b(34) = -1.18, p < 0.001$ ) (Fig.7A). Follow-up t tests revealed a within-group decrease in contrast estimate in the training group from baseline to post-test ( $t(15) = 3.03, p = .008$ ), whereas the control group exhibited no such effect ( $t(20) = 1.58, p = .13$ ). This marginal difference in change of contrast estimates is likely due to variance accounted for baseline differences in contrast estimates. Additionally, the training group exhibited lower contrast estimate compared to the control group at post-test assessment ( $t(32.46) = -1.73, p = .04$ ). For alerting, when examining the contrast estimates for the superior parietal cortex I observed a significant group difference in change of contrast estimate ( $b(34) = -.34, p = 0.04$ ), and baseline superior parietal activity negatively predicted change in contrast estimate ( $b(34) = -.92, p < .001$ ) (Fig. 7B). Follow-up t tests revealed the training group had a marginally greater reduction in alerting contrast estimate compared to the control group ( $t(28.18) = -1.56, p = .06$ ). The training group had a significant within-group reduction in alerting contrast estimate ( $t(15) = 3.01, p = .009$ ), whereas the control group did not ( $t(20) = 1.58, p = .13$ ). Additionally, at post-test assessment the training group had lower alerting contrast estimate compared to the control group ( $t(28.22) = -2.11, p = .02$ ).

For orienting, when examining the left middle occipital cortex I failed to observe group differences in change in contrast estimate ( $b(34) = -.10, p = 0.60$ ), while baseline orienting activity negatively predicted change in contrast estimate ( $b(34) = -1.08, p < 0.001$ ) (Fig. 7C). When examining the right middle occipital cortex I failed to observe group differences in change in contrast estimate ( $b(34) = -.25, p = 0.20$ ), while baseline

orienting activity negatively predicted change in contrast estimate ( $b(34) = -.95, p < 0.001$ ) (Fig. 7D).



**Figure 7.** Pre and Post Univariate Results. Baseline and posttest contrast estimates for the training and control group are depicted for the attentional facets of alerting (A & B), orienting (C and D), and executive functioning (E and F). † indicates marginal significance at  $p < .1$ ; \* indicates significance at  $p < .05$

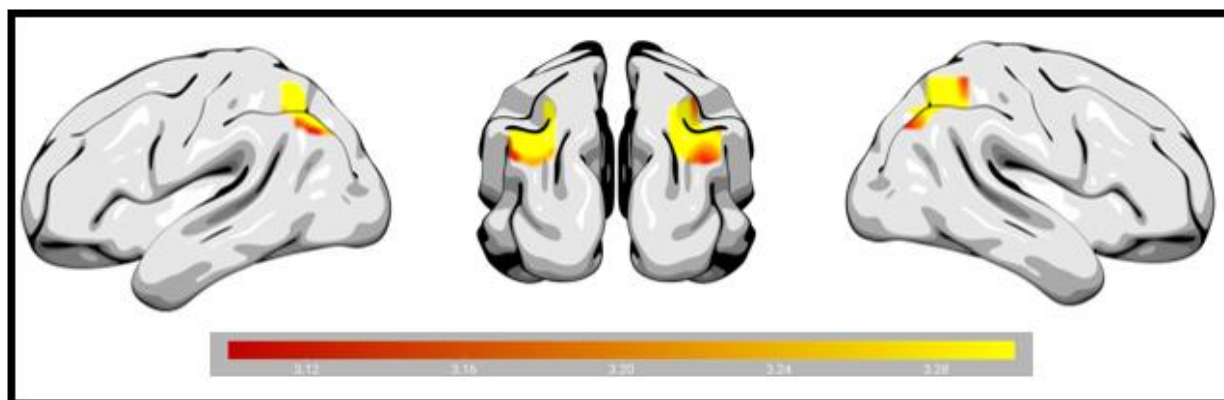
Finally, for executive functioning, when examining the bilateral parietal cortex I failed to observe group differences in change in contrast estimate ( $b(34) = -.16, p = 0.41$ ), as well as baseline executive functioning predicting change in contrast estimate ( $b(34) = -.25, p = 0.23$ ) (Fig. 7E). And when examining the left inferior temporal cortex I failed to observe group differences in change in contrast estimate ( $b(34) = .03, p = 0.74$ ), while



baseline executive functioning activity negatively predicted change in contrast estimate ( $b(34) = -.79, p = 0.002$ ) (Fig. 7F).

### Exploratory Whole-brain Univariate Changes

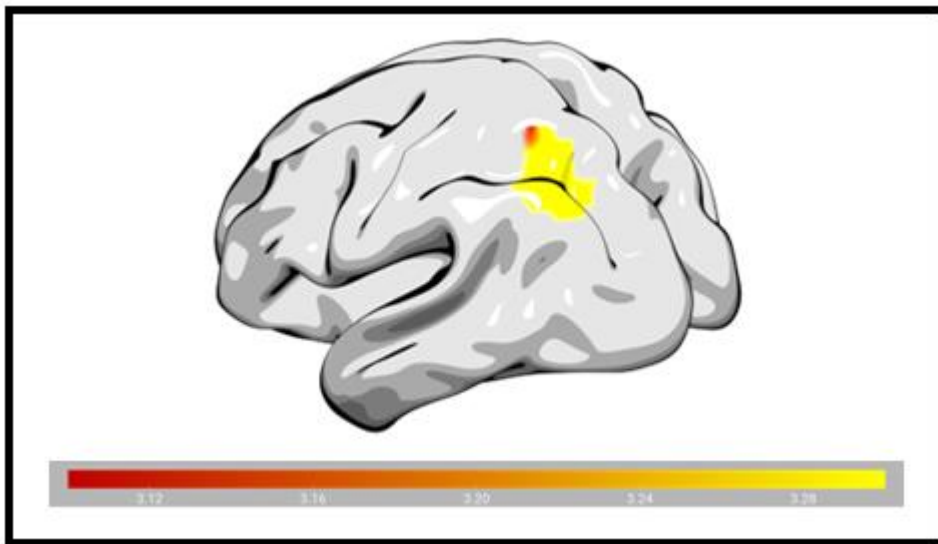
Cognitive training fMRI studies typically include whole-brain univariate assessments. These results allow the studies to be included in meta-analyses assessing training-related changes in univariate BOLD amplitude. ROI analyses are not included in such meta-analyses (Duda & Sweet, 2019). In the previously described ROI analyses, I defined regions to examine according to baseline clusters in the full sample of healthy older adults. Here, for the whole brain analyses, I examined if any regions across the cortex depicted the hypothesized pattern of results: where trained older adults exhibited a reduction in activity compared to control participants while controlling for neural activity at baseline. This exploratory approach is intended to localize where the hypothesized pattern of activation changes occurs when using a cluster extent threshold of  $k=16$  contiguous voxels and a  $p$  value threshold of .001. I first examined regions depicting the hypothesized direction of results in which the training-group exhibits a reduction in contrast estimate whereas the control group does not after controlling for baseline univariate activity. For alerting, I observed decreases in univariate contrast estimates in the training group compared to the control group in left and right angular gyrus (Fig. 8).



**Figure 8.** Exploratory Whole-Brain Decreases. Exploratory analyses revealed training related decreases in contrast estimates associated with alerting within the angular gyrus in the training group compared to the control group.

For orienting, I observed no suprathreshold clusters. For executive functioning, I observed no suprathreshold clusters. Please see additional details in Table 2.

I also conducted whole-brain univariate analyses examining if there were any cortical regions depicting a training related increase in univariate contrast estimate in the training group compared to the control group. Such increases are typically associated with training-induced compensatory processes. I again used a significance threshold of  $k = 16$  contiguous voxels and  $p < .001$ . For alerting, I observed no suprathreshold clusters. For orienting, I observed increases in the training group compared to the control group in left inferior parietal cortex (Fig. 9). For executive functioning, I observed no suprathreshold clusters. Please see additional details in Table 2.



**Figure 9.** Exploratory Whole-Brain Increases. Exploratory analyses revealed training related decreases in contrast estimates associated with orienting within the inferior parietal cortex in the training group compared to the control group.

**Table 2.** Exploratory Whole-brain Univariate Analyses

| Region                       | H | x   | MNI |    |    | Z    |
|------------------------------|---|-----|-----|----|----|------|
|                              |   |     | y   | z  | k  |      |
| <i>Alerting</i>              |   |     |     |    |    |      |
| Train Increase               |   |     |     |    |    |      |
| No Suprathreshold Clusters   |   |     |     |    |    |      |
| Train Decrease               |   |     |     |    |    |      |
| Angular Gyrus                | L | -40 | -66 | 50 | 20 | 4.3  |
| Angular Gyrus                | R | 32  | -58 | 50 | 17 | 3.71 |
| <i>Orienting</i>             |   |     |     |    |    |      |
| Train Increase               |   |     |     |    |    |      |
| Inferior Parietal            | L | -36 | -64 | 48 | 21 | 4.76 |
| Train Decrease               |   |     |     |    |    |      |
| No Suprathreshold Clusters   |   |     |     |    |    |      |
| <i>Executive Functioning</i> |   |     |     |    |    |      |
| Train Increase               |   |     |     |    |    |      |
| No Suprathreshold Clusters   |   |     |     |    |    |      |
| Train Decrease               |   |     |     |    |    |      |
| No Suprathreshold Clusters   |   |     |     |    |    |      |

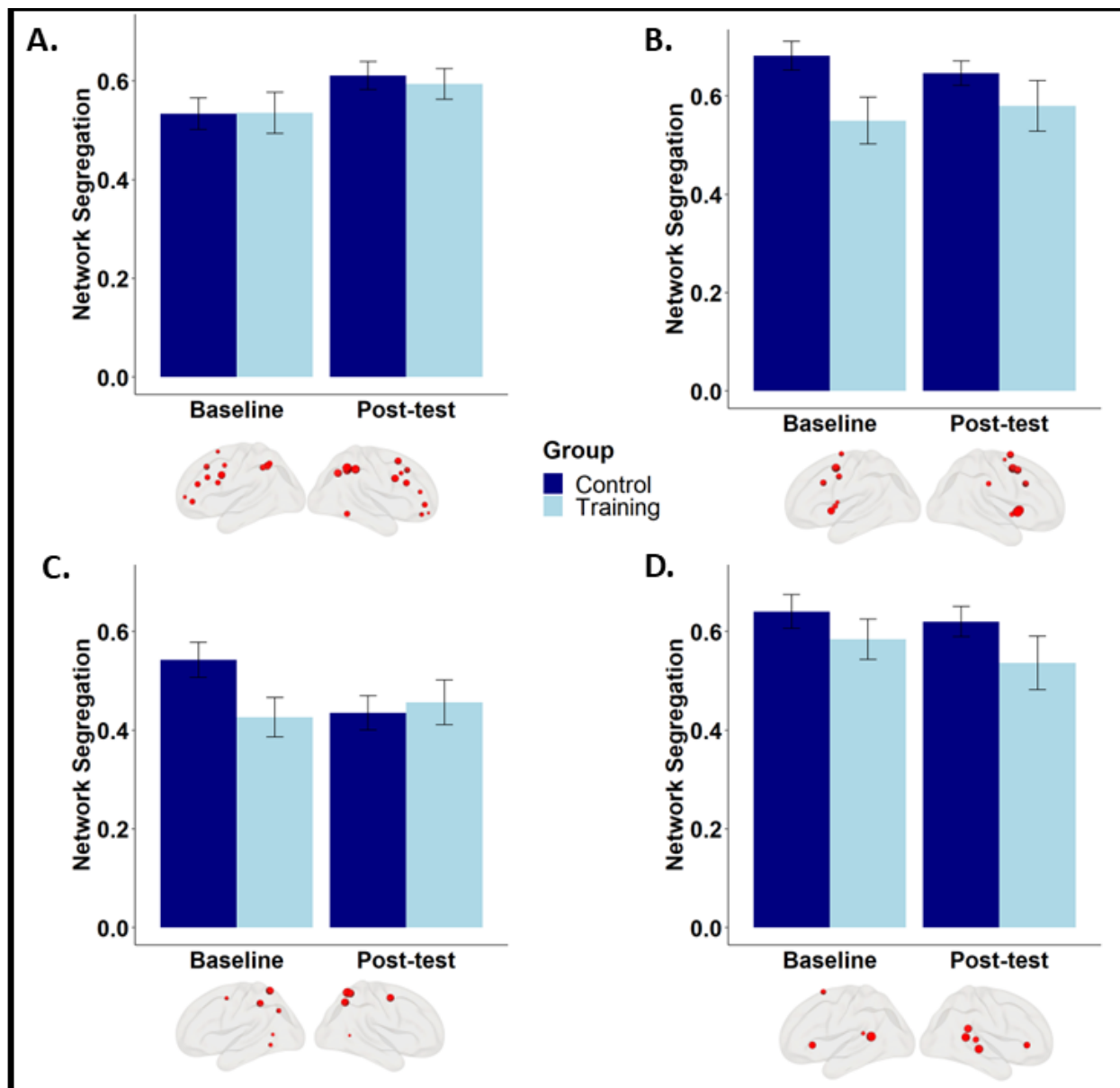
H = hemisphere (L = left, R = right, B = bilateral), Coordinates (x, y, z) represent peak MNI coordinates, k = voxel extent, z = statistical z value

## Resting State Results

### Network Segregation

To assess potential training-related changes in resting state network segregation, I calculated segregation scores for each of the four networks of interest (fronto-parietal, cingulo-opercular, dorsal attention, ventral attention). Segregation was defined as the difference of within-network connectivity and between-network connectivity, divided by within-network connectivity. I then submitted these network segregation scores to individual change score ANCOVAs with change in network segregation (session two minus session one) as the outcome, and session one segregation and group (train/control) as the predictors. I predicted to observe training related increases in network efficiency.

For the fronto-parietal network, I failed to observe group differences in change in segregation ( $b(34) = -.02$ ,  $p = 0.64$ ), while baseline segregation negatively predicted change in segregation ( $b(34) = -.59$ ,  $p < .001$ ) (Fig. 10A). For the cingulo-opercular network, I failed to observe group differences in change in segregation ( $b(34) = -.04$ ,  $p = 0.52$ ), while baseline segregation negatively predicted change in segregation ( $b(34) = -.77$ ,  $p < .001$ ) (Fig. 10B). For the dorsal attention network, I failed to observe group



**Figure 10.** Network Segregation. Baseline and Posttest network segregation scores are depicted for the training and control groups in the A) fronto-parietal, B) cingulo-opercular, C), dorsal attention, and D), ventral attentional networks.

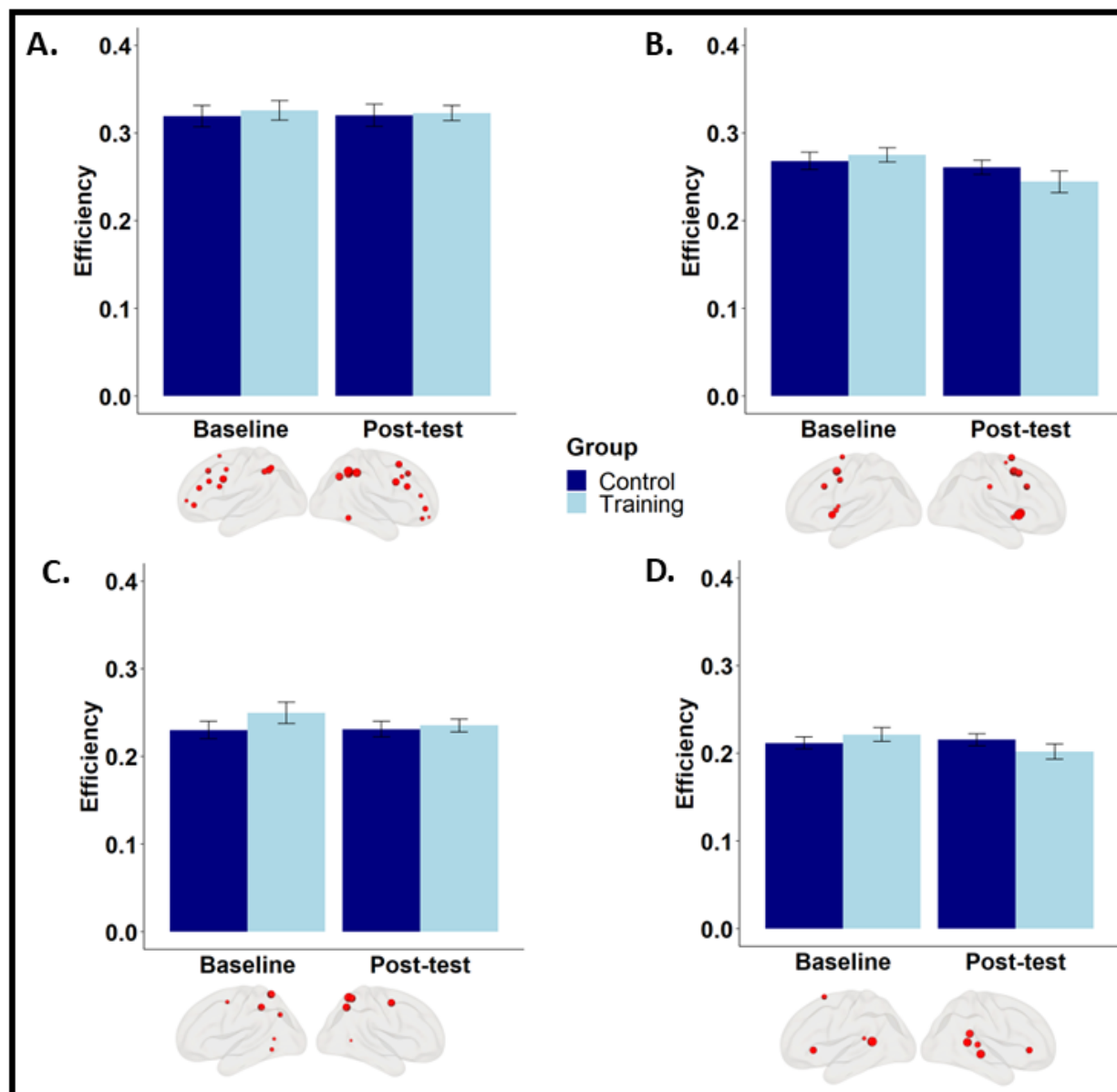
differences in change in segregation ( $b(34) = -.10$ ,  $p = 0.14$ ), while baseline segregation negatively predicted change in segregation ( $b(34) = -.50$ ,  $p = .003$ ) (Fig. 10C). And for the ventral attention network, I failed to observe group differences in change in segregation ( $b(34) = -.06$ ,  $p = 0.30$ ), while baseline segregation negatively predicted change in segregation ( $b(34) = -.55$ ,  $p = .003$ ) (Fig. 10D).

Network segregation is typically defined by setting negative correlations to zero prior to calculating within-network connectivity and between-network connectivity (Cassady et al., 2019; Chan et al., 2014). As changes in network segregation could potentially be due to changes in anti-correlated regions, I recalculated network segregation including negatively correlated connections and re-conducted the change score ANCOVAs. When using this approach, I observed no changes in significance.

## Efficiency

I next examined efficiency (inverse of shortest pathway) for the networks of interest (fronto-parietal, cingulo-opercular, dorsal attention, ventral attention). Networks with fewer pathways are more efficient. I submitted these network efficiency scores to individual change score ANCOVAs with change in network efficiency (session two minus session one) as the outcome, and session one efficiency and group (train/control) as the predictors. I predicted to observe greater training-related increases in network efficiency in the training group compared to any increases observed in the control groups after accounting for baseline differences in efficiency.

For the fronto-parietal network, I failed to observe group differences in change in efficiency ( $b(34) = .0001$ ,  $p = 0.99$ ), while baseline efficiency negatively predicted change in efficiency ( $b(34) = -.65$ ,  $p < .001$ ) (Fig. 11A). For the cingulo-opercular network, I failed to observe group differences in change in efficiency ( $b(34) = -.02$ ,  $p = 0.24$ ), while baseline efficiency negatively predicted change in efficiency ( $b(34) = -.87$ ,  $p < .001$ ) (Fig. 11B). For the dorsal attention network, I failed to observe group differences in change in efficiency



**Figure 11.** Network Efficiency. Baseline and Posttest network efficiency scores are depicted for the training and control groups in the A) fronto-parietal, B) cingulo-opercular, C), dorsal attention, and D), ventral attentional networks.

( $b(34) = -.0003$ ,  $p = 0.98$ ), while baseline efficiency negatively predicted change in efficiency ( $b(34) = -.76$ ,  $p < .001$ ) (Fig. 11C). And for the ventral attention network, I failed to observe group differences in change in efficiency ( $b(34) = -.02$ ,  $p = 0.14$ ), while baseline efficiency negatively predicted change in efficiency ( $b(34) = -.70$ ,  $p < .001$ ) (Fig. 11D).

## Discussion

### Overview

Previous research demonstrates that cognitive processes decline with increasing age, even in the absence of any disease related pathology. One such domain that exhibits reduced efficacy is attention, specifically the ability to bring attention online, shift or re-orient attention, and resolve incongruent interfering visual information (Hartley et al., 1992; Madden, 2007; Mahoney et al., 2010; McDonough et al., 2019; Verhaeghen & Cerella, 2002). These cognitive constructs have been hypothesized to reflect distinct, yet interconnected, neurocognitive networks (Fan et al., 2005; Posner et al., 1987; Posner & Rothbart, 2007). Fan and colleagues put forward the Attention Network Test as a framework to examine these three attentionally relevant constructs in tandem (Fan et al., 2005). Findings from the ANT reveal both age-related reduction in efficacy as well as neural basis of alerting, orienting, and executive functioning via fMRI (de Souza Almeida et al., 2021; Fan et al., 2002; Konrad et al., 2005; Z. Zhang et al., 2015). Additionally, neural networks, that is, regional covariation of neural activity at rest absent an explicit task, associated with attention are known to become less segregated and efficient with advancing age (Cassady et al., 2019; Chan et al., 2014; Damoiseaux, 2017; Malagurski et al., 2020). While reductions in attentional performance have been observed, targeted cognitive training interventions offer promise in improving cognitive processes in older adults, and subsequently their indicators of everyday living (Gross et al., 2018; Jaeggi et al., 2011; Peng & Miller, 2016; Tennstedt & Unverzagt, 2013). Furthermore, cognitive training has successfully benefited specific aspects of attention, as well as offers evidence of altered neural processes as measured via univariate analyses, and improved resting state segregation and efficiency (Burge et al., 2013; Duda & Sweet, 2019; Edwards et al.,

2018; Gao et al., 2014; Sutter et al., 2013). Critically, however, it remains unclear if process-based cognitive interventions improve the three facets of attention in healthy older adults, or if training benefits occur in tandem with altered neural activity or resting state network reconfiguration.

The current dissertation sought to address this gap by examining attentional behavioral and neural (univariate and network) changes associated with process-based cognitive training in a sample of healthy older adults. Specifically, I assessed the behavioral facets of attention (alerting, orienting, executive functioning), univariate contrasts of attentional facets (alerting, orienting, executive functioning), and resting state network segregation and efficiency of networks known to process attentional information (fronto-parietal, cingulo-opercular, dorsal attention, ventral attention networks). I predicted to observe increased performance (reduced reaction times) in the behavioral facets of attention, decreases in univariate contrast estimates, and increases in network segregation and network efficiency. I observed improved reaction times for the executive functioning attentional facet in the training group, as well as reduced univariate contrast estimates associated with alerting functioning in parietal cortical regions. Whole-brain univariate analyses revealed both training-related decreases and increases within the parietal system associated with alerting and orienting. I failed to observe any differences in change in resting state network connectivity metrics in the training group above and beyond those observed in the control groups. Such results suggest benefits from cognitive training emerge at both a behavioral and neural level within healthy older adults, yet may not alter the segregation or efficiency of regions connected via covarying activity, and provide implications regarding the potential mechanisms associated with improved cognitive functioning in healthy aging. I discuss these findings in greater detail below.

### Behavioral Changes

As described earlier, even in the absence of disease-related pathology, older adults typically exhibit reductions in the attentional facets of alerting, orienting, and executive functioning. These deficits become particularly pronounced with the onset of diseases such as dementia (Wilson et al., 2007). Following the cognitive training via



UFOV, older adults in the training group exhibited greater reductions in reaction times associated with the executive functioning facet of attention in the ANT compared to control participants after controlling for baseline performance. These reductions in executive functioning reaction times were primarily due to reduced reaction times associated with the incongruent flankers as opposed to the congruent flankers. Critically, and excitingly, these changes reflect near-transfer effects in which participants receive benefits on a task they were not trained on. Due to this, the behavioral benefits observed in the training group can be attributed to benefits of training, as opposed to practice effects given the older adults only completed the ANT before and after training or games. I failed to observe any reductions in reaction times associated with the attentional facets of alerting or orienting within the training group above any observed within the control group. Our results offer support to the notion that targeted process-based cognitive interventions improve attentional performance in healthy older adults compared to those completing cognitively stimulating games (solitaire, candy crush, etc.), even when the cognitive outcomes are not what was trained on (Kueider et al., 2012; Lampit et al., 2014). Additionally, our results suggest that process-based cognitive interventions do not improve attentional processing in older adults as a whole, but appear to influence select processes associated with attentional facets, specifically the ability to resolve incongruent information in the presence of distractors.

The current results support similar findings from processing-based cognitive training interventions in healthy older adults examining different aspects of attention. Specifically, previous work has demonstrated that video-game based cognitive training improves selective components of attentional processing in younger adults (Bediou et al., 2018; Jaeggi et al., 2011; Peng & Miller, 2016). These benefits appear when using both a no-contact control group as well as active control groups, and in healthy older adults as well (Chambon et al., 2014; Sprague et al., 2019). Changes are often observed across the various cue types of the attentional facets in trained younger adults when compared to control groups (Bednarek et al., 2021). Furthermore, a meta-analysis in younger adults revealed that both computer-based cognitive training and adaptive increasing difficulty were critical components for improved attentional performance. Initial work utilizing cognitive training in younger adults demonstrates that all attention facets can be improved

at earlier ends of the lifespan (Peng & Miller, 2016). The current findings suggest that while the alerting and orienting systems may be plastic in younger adulthood, they may be less prone to change with advanced age. Alternatively, it is possible that alerting and orienting are plastic in later adulthood, but are not prone to near transfer effects from processing-speed based training. Examining the individual components of the attentional facets (e.g., center cue and spatial cue reaction times) in the future will further assist in resolving this discrepancy. However, the current dissertation observed improved reaction times in the executive functioning facet of attention, and this has been observed previously in the literature (Burge et al., 2013; Edwards et al., 2018; Sprague et al., 2019; Tennstedt & Unverzagt, 2013). Specially, one training regimen observed participants with mild cognitive impairment improved in executive functioning after cognitive training, and that this benefit persisted for six months post training (Q. Chen et al., 2022). Additional studies have observed benefits to alerting cognitive processes in healthy older adults following multi-domain interventions (Cespón et al., 2018; Sprague et al., 2019; Yang et al., 2020). This discrepancy in benefits to alerting between the current dissertation and other investigations is unclear. It may be the domain of training (multidomain versus processing speed), dosage of training, or control groups used may contribute to discrepant findings. However, it appears that benefits in the attentional facet of executive functioning are consistently observed as a result of cognitive training. The finding of discrepant behavioral benefits compared to other studies is itself a strength of the current dissertation, as other cognitive intervention studies have not examined the three attentional facets concurrently in older adults and how they benefit from cognitive training. This information will assist future investigators who wish to specifically target executive functioning, or who wish to assess alternatives modes to improve alerting and orienting processing in healthy older adults.

The behavioral findings of the current dissertation also fit within the theories of cognitive aging discussed earlier. Specifically, the current results fit within the context of the inhibitory deficit hypothesis as put forward by (Hasher et al., 1999; Lustig et al., 2007). Regarding cognitive mechanisms associated with the benefit in reaction times observed in the training group above and beyond those observed in the control group, it may be that older adults in the training group received a boost in the ability to inhibit the distracting

flanking arrows once they received benefits in neural processes in alerting and orienting (discussed in greater depth below). It could be that older adults became better able to focus attention on the target arrow within the incongruent flanker, or that older adults became better at inhibiting the incongruent flankers surrounding the central arrow. Either cognitive mechanism could lead to a benefit in reaction times with the incongruent flankers as opposed to the congruent flanker arrays. However, it cannot be ruled out that older adults did not simply have a benefit in processing speed related functions as put forward in the Processing Speed Theory by Salthouse (Salthouse, 1996, 2016). While older adults experience a general cognitive slowing with advanced age, a consistent finding within the process-based cognitive intervention literature is that processing-speed training protocols lead to benefits in reaction times more broadly (Burge et al., 2013; Edwards et al., 2017). This reflects more efficient utilization of cognitive resources as a result of increasing task demands. It is possible that older adults in the training group were better able to draw on a pool of neurocognitive resources in the presence of task demand. However, if this was the case, then I likely would have observed benefits to all three attentional facets, alerting, orienting, and executive functioning. To account for the influence of processing speed, a measure of processing speed could be used as a covariate in statistical models in follow-up analyses beyond the current dissertation.

### Near-Transfer Behavioral Effects

Older adults in the training group received UFOV-like training in which they needed to identify a vehicle that briefly appeared as well as the location of a Route 66 sign that appeared in the periphery. As performance increased, the difficulty of the task also increased, specifically with more perceptually similar vehicles, background scenes of greater complexity (a city versus a vista), and with greater numbers of irrelevant distracting signs in the visual periphery (Edwards et al., 2018). The UFOV task is hypothesized to tap into multiple cognitive constructs, such as processing speed, orienting of attention, and inhibition of distracting information (Edwards et al., 2018; Ross, Webb, et al., 2018). All participants also completed a UFOV task at baseline and post-test behavioral sessions as a component of broader neuropsychological assessment.

However, the task the participants completed during the MRI sessions was the Attention Network Test, which is hypothesized to tap into related constructs as the UFOV task. This distinction of training on one task, with training-related benefits observed in a related, yet separate, task therefore falls under the umbrella of near-transfer effects (Salomon & Perkins, 1989). Components of the ANT are positively correlated with aspects of the UFOV task, specifically the executive functioning facet of the ANT with the reaction time of the UFOV (Weaver et al., 2009). It is therefore likely that similar cognitive processes underly both the executive functioning component construct of the ANT and the processing speed component of the UFOV task. This is supported by a cognitive training study in younger adults who received executive functioning training and exhibited benefits to processing in the ANT, specifically to alerting and orienting components of the ANT (Bednarek et al., 2020). This notion is further supported by the driving literature in older adults. The UFOV task is highly predictive of number accidents and driving cessation in older adults (Choi et al., 2019; Clay et al., 2005). It has been found that the ANT is also predictive of driving performance in healthy older adults, specifically the executive functioning component of older adults is predictive of driving performance in the presence of distracting information in the visual environment while driving (Weaver et al., 2009).

Due to time constraints in data cleaning, pre- and post-assessment neuropsychological UFOV data were not made available by study staff for the current dissertation. A natural next step is therefore to evaluate training-related improvements in the various components of the UFOV when data are available. It is likely that trained older adults receive cognitive enhancements as displayed via reduced reaction times on the UFOV task as well as improved reaction times in the executive functioning component of the ANT. Additionally, while the sample is small and somewhat underpowered, if neural changes associated with alerting and orienting were also predicative of trained improvements on the UFOV task then that would also add support of near transfer effects in the current dissertation. While far-transfer effects, training in one cognitive domain (such as attention) leading to improvements in a distantly-related construct (such as language) are not frequently observed in the cognitive training of older adult literature, instances of near-transfer are consistently observed. Additionally, transfer effects are also frequently observed in tasks of everyday living, as well as indicators of emotional

wellbeing (Rebok et al., 2014; Salomon & Perkins, 1989). As improving aspects of cognitive functioning and everyday living is a primary goal in the cognitive training literature, future work with data from the current grant should also examine whether participants in the training group also exhibit improved indicators of everyday living and emotional wellbeing.

### Baseline Univariate Results

At baseline, prior to any cognitive training or stimulating games, I observed cortical activity associated with the various facets of attention throughout portions of the visual and parietal cortex in the full sample of healthy older adults. While the specific loci of activation I observed were not the a-priori hypothesized regions of interest specific to each attentional facet, they nonetheless are associated with known attentional processes both in younger populations and healthy older adults. Typical work regarding the attentional facets within the context of aging specifically looks at how neural activity is altered in healthy older adults compared to younger adults, or how neural activity is altered in older adults with MCI compared to healthy older adults (Geerligs et al., 2014; Van Dam et al., 2013; Wang et al., 2020). To my knowledge, this is the first functional magnetic resonance imaging study examining ANT-related activation in older adults alone. The current dissertation therefore offers critical information regarding the functional neural underpinnings of the facets of attention in healthy older adults. Such information may be useful to future investigators who wish to develop their own regions of interest examining the attentional facets in healthy participants at the far end of the lifespan.

When examining the alerting contrast (central cues > no cues), I observed significant clusters of activity in left middle occipital cortex and right superior parietal cortex. Early work regarding the attentional facet of alerting revealed that pharmacological or physical lesions to either occipital cortex or parietal cortex impairs reaction times when presented with cues that a target stimulus will appear soon (Coull et al., 2001; Heilman et al., 2000). Additionally, functional neuroimaging work using the ANT with the same contrast in humans, specifically younger adults, demonstrates that both visual cortex and portions of parietal cortex are activated when presented with a cue to alert participants to

oncoming stimuli (Fan et al., 2005). It is suggested that visual cortex engages in perceptual preparatory processes for the oncoming stimuli, which then sends downstream signals to the parietal cortex which engages additional engagement processes (Battistoni et al., 2017; Hahn et al., 2006; N. S. Lawrence et al., 2003; Nobre et al., 2004). In some cases, it is hypothesized that such exogenous cueing stimuli are associated with a signal analogous to a “watch out” process engaged in the parietal cortex (Lachat et al., 2012). The results of the current study support such findings within the visual stream and higher order parietal regions. Specifically, the current results speak to the engagement of such processes in healthy older adults.

When examining the contrast of orienting (spatial cues > central cues), I observed significant clusters of activity in left and right middle occipital cortex. The specific cue-related activity of middle occipital cortex reflects the necessary shift of visuospatial attention from the central fixation cross to other portions of the visual environment. This exogenous “pulling” of attention therefore likely reflects stimulus-driven perceptually relevant reorientation of attentional processes (Craig & Byrd, 1982; Friesen & Kingstone, 1998). The current results are in line with those previously observed in visuospatial processing tasks. Specifically, previous work demonstrates that middle occipital cortex processes preparatory signals when shifting to target-congruent stimuli as compared to target locations incongruent with the orienting cue (Serences et al., 2004). While previous studies using the ANT examining the orienting contrast in healthy younger adults have observed portions of the ventral visual stream to be activated when processing the spatial cue compared to the central cue, the current finding of middle occipital cortex activity in older adults alone is novel to the ANT-related literature (Fan et al., 2005; Xuan et al., 2017). Given the presence of middle occipital cortical activity and absence of parietal or frontal neural activity, the current results suggest the orienting-related activity in the sample of healthy older adults reflects more of a bottom-up exogenous “pulling” of attention to the target location as opposed to a top-down endogenous “pushing” of attention to target location as a function of task or participant goals. This may be due in part to a disengagement of attention from the fixation cross to re-engage attention at the cued spatial location (Parisi et al., 2020).

When examining executive functioning (incongruent flankers > congruent flankers), I observed significant clusters of activity in bilateral superior parietal cortex and left inferior temporal cortex. While previous studies of younger adults examining executive functioning in the ANT typically observe incongruent flanker related activity in inferior parietal cortex and portions of frontal cortex, the current observation of superior parietal cortex activity in healthy older adults is consistent with previous reports examining the flanker task. Indeed, previous meta-analyses demonstrate consensus in superior parietal activity associated with executive functioning in the flanker task, specifically associated with action withholding processes (R. Zhang et al., 2017). In particular, the superior parietal is engaged in allocating neural and cognitive resources in the presence of interfering information by filtering out the interfering perceptual information received via the occipital cortices (Berron et al., 2015; C. Chen et al., 2015). Inferior temporal cortical activity has also been observed during completion of the flanker task in younger adults completing the ANT. Indeed, previous work suggests that the activation of portions of the visual stream, such as inferior temporal cortex, during executive control processes reflects a top-down impact of attention within the visual stream (Casey et al., 2000; Hazeltine et al., 2000; Liu et al., 2004; Rusnáková et al., 2011). It is suggested that because the incongruent flanker becomes the stimulus of interest during the task, these regions are weighted to emphasize information related to “what”-related properties of the stimulus as opposed to “where”-related properties during the incongruent flanking condition compared to the congruent flanking condition (Liu et al., 2004). Interestingly, I failed to observe significant executive control related activity in frontal cortices. This does not preclude the involvement of frontal cortex in the processing of the incongruent and congruent flanking arrays, only that older adults in the current study did not exhibit greater BOLD recruitment for the incongruent flankers as compared to the congruent flankers. While previous studies have examined age and pathology-related differences in activation associated with the attentional facets of the Attention Network test, to my knowledge, no previous studies have examined neural effects associated with the Attention Network tests in older adults alone, making it a novel addition to the field of neurocognitive aging.

## Training-related Univariate Changes

A primary aim of the current dissertation was to examine potential training related decreases in neural recruitment associated with the facets of attention in healthy older adults. Following training, I observed reduced neural activity in the training group compared to the control group within the superior parietal cortex, after controlling for baseline alerting activity. Such reductions in neural functioning follow the hypothesized direction of change in the training group as compared to the control group, reflecting altered functional neural efficiency associated with alerting to the presence of oncoming target information. Using whole-brain exploratory analyses, I also observed both a training-related decrease in neural activity associated with alerting in angular gyrus, and a training-related increase in neural activity associated with orienting in inferior parietal cortex. Again, all results were observed while controlling for baseline univariate activation in both groups of older adults.

The observed decreases in neural activity are consistent with a recent meta-analysis examining training-induced neural changes within healthy older adults. Specifically, a recent meta-analysis revealed consistent training-related decreases in neural activity in select portions of the parietal cortex in healthy older adults (Duda & Sweet, 2019). While the meta-analysis included many different forms of cognitive training, different dosages of training durations, and varied forms of control groups utilized, it nonetheless suggests that adaptive difficulty during cognitive training in healthy older adults leads to altered neural functioning in higher order processing regions. The authors suggest that such alterations in parietal cortical regions may be reflective of enhanced bottom-up attentional processes (Buschman & Miller, 2007). Additional cognitive training studies specifically relevant to attention in healthy aging also observe altered neural functioning in the parietal system. For example, following UFOV training, older adults exhibited reduced cortical activity within inferior parietal cortex associated with detecting and responding to a vehicle in the visual periphery, suggesting that the training resulted in enhanced allocation of attentional resources within this region (Ross, Webb, et al., 2018). Given that the UFOV examines multiple cognitive processes simultaneously, making it difficult to fully disentangle which specific processes is altered, my finding of inferior parietal and angular gyrus reduced activation supports and extends previous work



by Ross, Webb et al. (2018), by suggesting that it is specifically the initiation, or alerting, of attentional resources as well as orienting of attention within the visual environment that are impacted by UFOV-based training which benefits, and transfers to, components of executive functioning and interference resolution as a consequence. While similar results have been found in younger adults (Burge et al., 2013), the finding that older adults also exhibit reductions in neural recruitment associated with initiating attention offers promise in ameliorating cognitive deficits associated with aging. Additionally, the current findings offer a great degree of novelty in revealing training related transfer of improvement not only to behavior, but also to neural functioning. To my knowledge, only one other study has examined near-transfer effects to neural functioning. Specifically (Q. Chen et al., 2022) observed older adults with mild cognitive impairment who engaged in UFOV training received benefits in neural functioning in a working memory task. This therefore makes the current dissertation one of the first to examine how cognitive training extends to neural benefits in other related domains.

Regarding theories of neuro-cognitive aging and training effects, the results largely support the notion of training-induced task BOLD efficiency associated with alerting, as well as training-related compensation associated with orienting of attentional processes. Processing-speed based cognitive interventions, as opposed to strategy-based interventions in which participants are taught an explicit strategy, frequently result in reductions in neural activity associated with cognitive functioning (Belleville et al., 2014). Specifically, following UFOV training, older adults exhibit reduced BOLD amplitude associated with car target identification in portions of a fronto-parietal network. However, training-related increases in neural activity are also frequently observed in the cognitive training literature (Duda & Sweet, 2019). For example, while in younger adults, training in orienting of attention has resulted in increases in BOLD amplitude associated with orienting to stimuli when the cue is congruent with the oncoming target stimulus (Sturm et al., 2006). Investigators suggest that this compensatory neural recruitment is a result of re-engaging cortical mechanisms that remained either disused or neglected as a function of advanced age (Bryck & Fisher, 2012; Cespón et al., 2018; Duda & Sweet, 2019; Nguyen et al., 2020; Poldrack, 2015). While the current dissertation offers initial evidence of both training related task efficiency and compensatory mechanisms (both

decreases and increases in BOLD recruitment, respectively), it is important to note that such claims cannot be fully made without relationships with behavior. Specifically, a debate exists as to whether or not increases or decreases in neural functioning can be claimed as “successful”, given that patients with traumatic brain injuries typically exhibit hyperactivation associated with poorer cognitive performance (Cabeza et al., 2018; Hillary et al., 2006; Reuter-Lorenz & Cappell, 2008). Thus, future follow-ups will need to examine whether participants with greatest alterations in neural recruitment (decreases for task BOLD efficiency, increases for compensation) also exhibit the greatest behavioral improvements following the cognitive training.

It is curious that older adults exhibited training-related behavioral improvements in the attentional facet of executive functioning, yet exhibited training-related alterations in univariate neural estimates of alerting and orienting. The original framework of attentional facets hypothesized that the various attentional faces and their neural substrates were distinct, yet interconnected (Fan et al., 2005; McDonough et al., 2019; Petersen & Posner, 2012; Posner, 2012; Xuan et al., 2016). Further, while much is known regarding how the attentional facets change behaviorally with advanced age, little is known regarding the neural mechanisms associated with the various facets of attention at further ends of the lifespan. Given that the facets of attention are hypothesized to comprise an interconnected network, it may be that altered neural recruitment associated with alerting of attentional resources and orienting to the oncoming target location allowed older adults to redirect greater attentional resources when the incongruent flanking array became present. This would be in contrast to when the incongruent flanking array appeared when trained older adults were not alerted to the oncoming flanker array or oriented to the location of the oncoming flankers. It may be that enhancement of neural processes associated with more bottom-up stimulus-driven attention, as opposed to the top-down engagement of attentional resources in line with task or participant goals, led to participants being in a state more prepared for when the incongruent flankers appeared, thus leading to altered neural recruitment associated with alerting and orienting while resulting in improved reaction times in the presence of incongruent flankers.

What neural mechanisms may underly the enhancement of neural processing as a function of targeted cognitive intervention in healthy older adults? Previous work suggests that cognitive training in healthy older adults can lead to both neural compensation (typically via increased neural activity following training) and neural efficiency (typically reduced neural activity following training). It is suggested that in the case of compensation, neural systems are better able to engage to a greater degree to meet greater task demands. And in the case of neural efficiency, it is hypothesized that neural systems are better able to process information or manage task demands (Bryck & Fisher, 2012; Nguyen et al., 2020; Strenziok et al., 2014). These neural alterations, efficiency and compensation, can be derived from two different neural changes, specifically neural plasticity and neurogenesis. Cognitive training studies are frequently implicated in processes of neural plasticity, specifically in the firing rate of neurons via long term potentiation (LTP), the strengthening of neural synapses via recent activity (Cespón et al., 2018). Investigations in elderly mouse models in which environments are cognitively enriched suggest that LTP may occur via alterations in levels of brain-derived neurotrophic factor (BDNF) and nerve growth factor (NGF) in addition to changes in expression of NMDA and AMPA receptor units (Nithianantharajah & Hannan, 2006). Conversely, neurogenesis is associated with growth of neurons and dendritic branches in response to environmental changes. While neurogenesis may have occurred in the current study, and is not exclusive from neuroplasticity, methods examining gray matter volume or white matter fractional anisotropy would be needed to investigate this process. Obviously, the use of fMRI, with reduced temporal and spatial resolution, precludes direct support from investigations using rodent models, but these models offer initial insight regarding the potential neural changes occurring in human adult neuroplasticity.

### Resting State Network Metrics

One of the other primary aims of the current dissertation was to assess potential changes in resting state network segregation and efficiency. Training-increases in network segregation and network efficiency are interpreted as improvements in efficiency. I failed to observe any significant group differences in change in network properties within

any of the networks of interest (fronto-parietal, cingulo-opercular, dorsal attention, and ventral attention) when accounting for baseline network metrics. This stands in contrast to other cognitive training and aging studies which have observed changes in strength among connected nodes in networks, as well as graph theoretical properties in cortical networks ((Gallen et al., 2016; Hardcastle, Hausman, Kraft, Albizu, O'Shea, et al., 2022; Iordan et al., 2020, 2020; Pantoni et al., 2017). While surprising, a number of factors could influence this pattern of results. It may be that other networks of connections other than the hypothesized resting state networks (e.g., salience), or even a subset of connections within the networks of interest, exhibited changes as a result of the cognitive training. For example, (Ross, Webb, et al., 2018) examined specific connections among a network of regions functionally implicated in UFOV processing. They observed only a subset of connections within their network of interest of eight ROIs exhibited increases in functional connectivity in the training group. By that reasoning, while I did not observe any changes in network segregation among my four networks of interest, it is possible that select connections among nodes within the networks of interest exhibited an increase in connectivity following the cognitive training. Additionally, I selected the graph theoretical metric of efficiency within each network of interest as it provided an empirical metric of neural efficiency. Previous work demonstrates that the level of network metric is also critical (Hallquist & Hillary, 2019). For example, regarding efficiency, each network may not have become more efficient in isolation, but efficiency may have improved between the four networks of interest collectively. Likewise, I calculated network segregation as the difference in within network similarity and between network similarity in which between network similarity was comprised of all other networks in the Power et al. (2011) atlas (including vision, motor, default mode, etc.). It is possible that the networks of interest did not become more segregated from such a large host of other networks, but that they may have become more segregated from the other three attentionally-relevant networks. Finally, other graph theoretical metrics of network integrity, such as clustering coefficient, may have depicted changes in the training group as compared to the control group. For example, while I did not observe evidence of network segregation or efficiency changing as a result of training, it is possible that neighbors of nodes may have become more interconnected within the networks of interest. That is, select clusters of nodes within the

networks of interest may have become more specialized or connected as a result of training. Future follow-up work should therefore examine training-related changes in select connections among attentionally-relevant networks of interest, segregation among the four networks of interest specifically, as well as how neighbors of nodes become more connected within networks associated with attentional processing.

### Baseline Metrics Predicting Changes

A common theme emerged in the results that participants with lower baseline assessments exhibited greater change in the metric of interest and participants with higher baseline assessments exhibited lower change in the metric of interest, on average. For example, participants with reduced network segregation at baseline exhibited the greatest increases in network segregation at the second scanning session. Interestingly, this result was observed regardless of which group the participants were in. These results mirror previous findings within the behavioral cognitive training literature in which participants who exhibit reduced scores on behavioral functioning prior to enrolling in the cognitive study receive the largest benefit from the training or practice sessions (Cespón et al., 2018; Shaw & Hosseini, 2021). It may be that participants with lower baseline behavioral and neural metrics have more “room for growth”, so to speak. This is supported by the “supply-demand-mismatch” hypothesis put forward by Lovden (Lövdén et al., 2010). Specifically, Lovden suggests that participants with lower cognitive and neural resources (“supply”) experience the greatest changes in neural and behavioral functioning when task demands are high. In this framework, even low performing control participants receive benefits if the mismatch between supply and demand is adequate. However, it is noted that lower baseline individuals do not increase performance when task demands are exceedingly high as lower baseline individuals simply cannot perform the task adequately. This concern is ameliorated when cognitive training regimens, practice sessions, or stimulating games, are adaptive in nature (Sprague et al., 2019). This allows for difficulty to scale with older adults’ cognitive improvement. Understanding individual differences underlying which older adults benefit from cognitive training studies (training and practice), and which older adults do not, is of great importance to the field

and should be examined with studies with greater statistical power. For example, it may be that participants who received the greatest behavioral benefits also had lower baseline in neural activity or network connectivity metrics. Presumably, the participants who received the greatest behavioral increases also exhibited the greatest alterations in neural recruitment. Such findings have been observed previously in a study examining training-related changes in a sample of older adults with MCI. While no group by time differences in resting state metrics were observed, participants who exhibited the greatest change in network participation coefficient also exhibited the greatest improvement in working memory performance (Chen et al., 2022). Additionally, it may be that participants who had lower baseline UFOV performance in the current dissertation also exhibited the greatest neural and ANT behavioral benefits. Such questions can be answered with additional data from the current grant.

#### Limitations.

While the current dissertation had many strengths in its design and theory, there were of course limitations that should be considered. First, the sample size is relatively small (N=16 training, 21 control per group) compared to other fMRI studies in healthy older adults. However, cognitive training & fMRI studies in older adults typically have sample sizes of approximately 16-25 participants given the challenges of collecting longitudinal MRI data in older adults (see Belleville et al. and Duda & Sweet for review). Additionally, it is possible that the negative relations between baseline metrics and change indicate statistical regression to the mean. While this cannot fully ruled out, recent evidence using permutation testing (Turney, Chamberlain, et al., BioRxiv) offers evidence that relationships between baseline metrics and training-related changes in older adults persist following random shuffling of data of interest. Additionally, the ANT typically uses difference scores to operationalize the facets of attention. Because of this, it is possible that older adults in the trained group experienced change in both metrics of the difference score, but change in this score is equivalent across time points because the facet score changes with the same magnitude across sessions. Future examinations should examine each component of the attention facet scores individually to examine more subtle training

effects. While powered to answer the primary questions of interest, the current dissertation's sample size per group, and particularly for the training group, falls at the low end of this spectrum. Part of this issue is due to participant attrition during the study, as multiple participants in the training condition dropped out of the study in between baseline assessment and the second MRI session. A related limitation contributing to this issue is that data for the current dissertation was collected during the waning period of the COVID-19 pandemic, as lockdowns were being eased. The cognitive training and stimulating activities were therefore administered remotely via laptop at the participants' place of residence and compliance was monitored by research staff. While this approach was meant to assist in improving ecological validity of the training approach, it is possible that older adults had distractions present when using the laptops and engaging with the cognitive training and stimulating activities. Furthermore, recent research suggests the COVID-19 pandemic exhibited negative impacts on older adults' sense of motivation and mental wellbeing (De Pue et al., 2021; Kivi et al., 2021). Such effects may have had a negative outcome on adherence to the study protocol and potential attrition in the sample.

### Strengths and Future Directions

While the current dissertation is not without limitations, there are multiple strengths that should be considered. The current dissertation is among the first cognitive training and aging investigations to consider multimodal pathways of neural mechanisms within the same study. The current study utilized multiple imaging modalities (task-based neural activation and resting state network connectivity). The current dissertation therefore offers insights regarding which specific neural mechanisms are at play in the same sample and same cognitive training paradigm. A primary strength of the current dissertation is the examination of near transfer effects of cognitive training in one domain to behavioral benefits and altered neural recruitment in a related domain, making it one of the first studies to do so. Additionally, the current study examined multiple attentional processes in tandem, where many cognitive training studies typically examine one specific attention process in isolation (ex: divided attention or alerting). Also, given that the same older adults were scanned at baseline and post-test assessments, we can claim the observed

differences in performance and neural functioning are changes resulting from the training, rather than simple cross-sectional differences. Few studies examine neural changes associated with cognitive training in healthy older adults, and even fewer examine multiple neural pathways concurrently. Regarding near transfer effects, the older adults were trained on a UFOV-like task in which they needed to respond to identify a car in the central field of view, and indicate the spatial location of a “Route 66” road sign in the presence of distractors. While participants in the training group received more challenging levels of the UFOV task, behavioral benefits were observed in a component of the Attention Network Test. Finally, behavioral and neural benefits were observed as a product of older adults completing cognitive training in their own homes via laptops, providing ecological support to the notion of cognitive training not just in the laboratory environment, but in spaces where participants go about their daily lives. Future studies should incorporate additional timepoints of behavioral and neural testing to exam the trajectory of behavioral and neural changes. It may be that participants exhibit linear benefits to neurocognitive functioning; however, it is also possible that participants exhibit an inverted ‘U’ shaped trajectory or plateaued trajectory as a function of time. Future work should also examine the duration of benefits of processing based cognitive training to attentional facets and their associated neural processes in healthy older adults, and further disentangle the interconnected relationship regarding how changes in neural processes associated with attention benefit specific behavioral outcomes.

## Conclusions.

In conclusion, the current dissertation sought to examine possible behavioral and neural changes associated with attention processes following process-based cognitive training in a sample of healthy older adults. The dissertation observed improvements in executive functioning reaction times in the training group as compared to the control group, as well as improved univariate efficiency associated with alerting of attention in the superior parietal cortex as operationalized by reduced BOLD amplitude, with no observed benefits to attentionally-relevant resting state networks. The current dissertation therefore



provides evidence that targeted behavioral intervention is a pathway to improved behavioral performance, and that altered univariate amplitude, as opposed to differences in resting state network segregation or efficiency, serves as a neural pathway accompanying processing speed-based cognitive interventions in healthy older adults. Additional work examining the extent of near-transfer effects as well as duration of behavioral benefits will assist in deepening our understanding regarding the benefits of process-based cognitive interventions on attentional processes in healthy aging, as well as how such mechanisms may ultimately improve older adults' quality of life.

## References

- Albinet, C. T., Boucard, G., Bouquet, C. A., & Audiffren, M. (2012). Processing speed and executive functions in cognitive aging: How to disentangle their mutual relationship? *Brain and Cognition*, *79*(1), 1–11.  
<https://doi.org/10.1016/j.bandc.2012.02.001>
- Anderson, N. D., & Craik, F. I. M. (2017). 50 Years of Cognitive Aging Theory. *The Journals of Gerontology: Series B*, *72*(1), 1–6.  
<https://doi.org/10.1093/geronb/gbw108>
- Andrews-Hanna, J. R., Snyder, A. Z., Vincent, J. L., Lustig, C., Head, D., Raichle, M. E., & Buckner, R. L. (2007). Disruption of Large-Scale Brain Systems in Advanced Aging. *Neuron*, *56*(5), 924–935. <https://doi.org/10.1016/j.neuron.2007.10.038>
- Arnicane, A., Oberauer, K., & Souza, A. S. (2021). Validity of attention self-reports in younger and older adults. *Cognition*, *206*, 104482.  
<https://doi.org/10.1016/j.cognition.2020.104482>
- Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450.  
<https://doi.org/10.1146/annurev.neuro.28.061604.135709>
- Bagurdes, L. A., Mesulam, M. M., Gitelman, D. R., Weintraub, S., & Small, D. M. (2008). Modulation of the spatial attention network by incentives in healthy aging and mild cognitive impairment. *Neuropsychologia*, *46*(12), 2943–2948.  
<https://doi.org/10.1016/j.neuropsychologia.2008.06.005>
- Barban, F., Mancini, M., Cercignani, M., Adriano, F., Perri, R., Annicchiarico, R., Carlesimo, G. A., Ricci, C., Lombardi, M. G., Teodonna, V., Serra, L., Giulietti, G., Fadda, L., Federici, A., Caltagirone, C., & Bozzali, M. (2017). A Pilot Study on Brain Plasticity of Functional Connectivity Modulated by Cognitive Training in Mild Alzheimer's Disease and Mild Cognitive Impairment. *Brain Sciences*, *7*(5), Article 5. <https://doi.org/10.3390/brainsci7050050>

- Battistoni, E., Stein, T., & Peelen, M. V. (2017). Preparatory attention in visual cortex. *Annals of the New York Academy of Sciences*, 1396(1), 92–107.  
<https://doi.org/10.1111/nyas.13320>
- Baykara, E., Könen, T., Unger, K., & Karbach, J. (2021). MRI Predictors of Cognitive Training Outcomes. *Journal of Cognitive Enhancement*, 5(2), 245–258.  
<https://doi.org/10.1007/s41465-020-00188-y>
- Beauchamp, M. S., Petit, L., Ellmore, T. M., Ingeholm, J., & Haxby, J. V. (2001). A Parametric fMRI Study of Overt and Covert Shifts of Visuospatial Attention. *NeuroImage*, 14(2), 310–321. <https://doi.org/10.1006/nimg.2001.0788>
- Bedard, A.-C., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Developmental Neuropsychology*, 21(1), 93–111.  
[https://doi.org/10.1207/S15326942DN2101\\_5](https://doi.org/10.1207/S15326942DN2101_5)
- Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological Bulletin*, 144(1), 77–110.  
<https://doi.org/10.1037/bul0000130>
- Bednarek, H., Przedniczek, M., Olszewska, J. M., Niewiarowski, J., & Orzechowski, J. (2021). The near- and far-transfer effects of cognitive training on attentional networks in women and men. *Journal of Cognitive Psychology*, 33(4), 453–469.  
<https://doi.org/10.1080/20445911.2021.1916508>
- Belleville, S., Mellah, S., Boysson, C. de, Demonet, J.-F., & Bier, B. (2014). The Pattern and Loci of Training-Induced Brain Changes in Healthy Older Adults Are Predicted by the Nature of the Intervention. *PLOS ONE*, 9(8), e102710.  
<https://doi.org/10.1371/journal.pone.0102710>
- Berron, D., Frühholz, S., & Herrmann, M. (2015). Neural Control of Enhanced Filtering Demands in a Combined Flanker and Garner Conflict Task. *PLOS ONE*, 10(3), e0120582. <https://doi.org/10.1371/journal.pone.0120582>

- Birren, J. E., Woods, A. M., & Williams, M. V. (1979). Speed of Behavior as an Indicator of Age Changes and the Integrity of the Nervous System. In F. Hoffmeister & C. Müller (Eds.), *Brain Function in Old Age* (pp. 10–44). Springer.  
[https://doi.org/10.1007/978-3-642-67304-7\\_3](https://doi.org/10.1007/978-3-642-67304-7_3)
- Biswal, B., Yetkin, F. Z., Haughton, V. M., & Hyde, J. S. (1995). Functional connectivity in the motor cortex of resting human brain using echo-planar MRI. *Magnetic Resonance in Medicine*, *34*(4), 537–541.  
<https://doi.org/10.1002/mrm.1910340409>
- Boxtel, M. P. J. V., Langerak, K., Houx, P. J., & Jolles, J. (1996). Self-reported physical activity, subjective health, and cognitive performance in older adults. *Experimental Aging Research*, *22*(4), 363–379.  
<https://doi.org/10.1080/03610739608254017>
- Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *51*(1), 20–35. <https://doi.org/10.1037/1196-1961.51.1.20>
- Bryck, R. L., & Fisher, P. A. (2012). Training the brain: Practical applications of neural plasticity from the intersection of cognitive neuroscience, developmental psychology, and prevention science. *The American Psychologist*, *67*(2), 87–100.  
<https://doi.org/10.1037/a0024657>
- Burge, W. K., Ross, L. A., Amthor, F. R., Mitchell, W. G., Zotov, A., & Visscher, K. M. (2013). Processing speed training increases the efficiency of attentional resource allocation in young adults. *Frontiers in Human Neuroscience*, *7*.  
<https://doi.org/10.3389/fnhum.2013.00684>
- Buschman, T. J., & Miller, E. K. (2007). Top-Down Versus Bottom-Up Control of Attention in the Prefrontal and Posterior Parietal Cortices. *Science*, *315*(5820), 1860–1862. <https://doi.org/10.1126/science.1138071>

- Bush, null, Luu, null, & Posner, null. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences*, 4(6), 215–222. [https://doi.org/10.1016/s1364-6613\(00\)01483-2](https://doi.org/10.1016/s1364-6613(00)01483-2)
- Cabeza, R., Albert, M., Belleville, S., Craik, F. I. M., Duarte, A., Grady, C. L., Lindenberger, U., Nyberg, L., Park, D. C., Reuter-Lorenz, P. A., Rugg, M. D., Steffener, J., & Rajah, M. N. (2018). Maintenance, reserve and compensation: The cognitive neuroscience of healthy ageing. *Nature Reviews Neuroscience*, 19(11), Article 11. <https://doi.org/10.1038/s41583-018-0068-2>
- Cao, W., Cao, X., Hou, C., Li, T., Cheng, Y., Jiang, L., Luo, C., Li, C., & Yao, D. (2016). Effects of Cognitive Training on Resting-State Functional Connectivity of Default Mode, Salience, and Central Executive Networks. *Frontiers in Aging Neuroscience*, 8. <https://doi.org/10.3389/fnagi.2016.00070>
- Casey, B. J., Thomas, K. M., Welsh, T. F., Badgaiyan, R. D., Eccard, C. H., Jennings, J. R., & Crone, E. A. (2000). Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging. *Proceedings of the National Academy of Sciences*, 97(15), 8728–8733. <https://doi.org/10.1073/pnas.97.15.8728>
- Cassady, K., Gagnon, H., Lalwani, P., Simmonite, M., Foerster, B., Park, D., Peltier, S. J., Petrou, M., Taylor, S. F., Weissman, D. H., Seidler, R. D., & Polk, T. A. (2019). Sensorimotor network segregation declines with age and is linked to GABA and to sensorimotor performance. *NeuroImage*, 186, 234–244. <https://doi.org/10.1016/j.neuroimage.2018.11.008>
- Cespón, J., Miniussi, C., & Pellicciari, M. C. (2018). Interventional programmes to improve cognition during healthy and pathological ageing: Cortical modulations and evidence for brain plasticity. *Ageing Research Reviews*, 43, 81–98. <https://doi.org/10.1016/j.arr.2018.03.001>
- Chambon, C., Herrera, C., Romaguere, P., Paban, V., & Alescio-Lautier, B. (2014). Benefits of computer-based memory and attention training in healthy older adults. *Psychology and Aging*, 29(3), 731–743. <https://doi.org/10.1037/a0037477>

- Chan, M. Y., Park, D. C., Savalia, N. K., Petersen, S. E., & Wig, G. S. (2014). Decreased segregation of brain systems across the healthy adult lifespan. *Proceedings of the National Academy of Sciences*, *111*(46), E4997–E5006. <https://doi.org/10.1073/pnas.1415122111>
- Chauvin, J. J., Gillebert, C. R., Rohenkohl, G., Humphreys, G. W., & Nobre, A. C. (2016). Temporal Orienting of Attention Can Be Preserved in Normal Aging. *Psychology and Aging*, *31*(5), 442–455. <https://doi.org/10.1037/pag0000105>
- Chen, C., Yang, J., Lai, J., Li, H., Yuan, J., & Abbasi, N. ul H. (2015). Correlating Gray Matter Volume with Individual Difference in the Flanker Interference Effect. *PLOS ONE*, *10*(8), e0136877. <https://doi.org/10.1371/journal.pone.0136877>
- Chen, Q., Turnbull, A., Cole, M., Zhang, Z., & Lin, F. V. (2022). Enhancing cortical network-level participation coefficient as a potential mechanism for transfer in cognitive training in aMCI. *NeuroImage*, *254*, 119124. <https://doi.org/10.1016/j.neuroimage.2022.119124>
- Choi, H., Kasko, J., & Feng, J. (2019). An Attention Assessment for Informing Older Drivers' Crash Risks in Various Hazardous Situations. *The Gerontologist*, *59*(1), 112–123. <https://doi.org/10.1093/geront/gny079>
- Christian, L. M., Glaser, R., Porter, K., Malarkey, W. B., Beversdorf, D., & Kiecolt-Glaser, J. K. (2011). Poorer self-rated health is associated with elevated inflammatory markers among older adults. *Psychoneuroendocrinology*, *36*(10), 1495–1504. <https://doi.org/10.1016/j.psyneuen.2011.04.003>
- Clapp, W. C., & Gazzaley, A. (2012). Distinct mechanisms for the impact of distraction and interruption on working memory in aging. *Neurobiology of Aging*, *33*(1), 134–148. <https://doi.org/10.1016/j.neurobiolaging.2010.01.012>
- Clay, O. J., Wadley, V. G., Edwards, J. D., Roth, D. L., Roenker, D. L., & Ball, K. K. (2005). Cumulative Meta-analysis of the Relationship Between Useful Field of View and Driving Performance in Older Adults: Current and Future Implications.

*Optometry and Vision Science*, 82(8), 724.

<https://doi.org/10.1097/01.opx.0000175009.08626.65>

Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural Systems for Visual Orienting and Their Relationships to Spatial Working Memory. *Journal of Cognitive Neuroscience*, 14(3), 508–523.

<https://doi.org/10.1162/089892902317362029>

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), Article 3.

<https://doi.org/10.1038/nrn755>

Cornu, V., Steinmetz, J.-P., & Federspiel, C. (2016). Deficits in Selective Attention Alter Gait in Frail Older Adults. *GeroPsych*, 29(1), 29–36. <https://doi.org/10.1024/1662-9647/a000137>

Cotier, F. A., Zhang, R., & Lee, T. M. C. (2017). A longitudinal study of the effect of short-term meditation training on functional network organization of the aging brain. *Scientific Reports*, 7(1), Article 1. <https://doi.org/10.1038/s41598-017-00678-8>

Coull, J. T., Nobre, A. C., & Frith, C. D. (2001). The Noradrenergic  $\alpha 2$  Agonist Clonidine Modulates Behavioural and Neuroanatomical Correlates of Human Attentional Orienting and Alerting. *Cerebral Cortex*, 11(1), 73–84.

<https://doi.org/10.1093/cercor/11.1.73>

Cox, R. W., & Hyde, J. S. (1997). Software tools for analysis and visualization of fMRI data. *NMR in Biomedicine*, 10(4–5), 171–178. [https://doi.org/10.1002/\(sici\)1099-1492\(199706/08\)10:4/5<171::aid-nbm453>3.0.co;2-l](https://doi.org/10.1002/(sici)1099-1492(199706/08)10:4/5<171::aid-nbm453>3.0.co;2-l)

Craik, F. I. M., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences*, 10(3), 131–138.

<https://doi.org/10.1016/j.tics.2006.01.007>

- Craik, F. I. M., & Byrd, M. (1982). Aging and Cognitive Deficits. In F. I. M. Craik & S. Trehub (Eds.), *Aging and Cognitive Processes* (pp. 191–211). Springer US.  
[https://doi.org/10.1007/978-1-4684-4178-9\\_11](https://doi.org/10.1007/978-1-4684-4178-9_11)
- Damoiseaux, J. S. (2017). Effects of aging on functional and structural brain connectivity. *NeuroImage*, *160*, 32–40.  
<https://doi.org/10.1016/j.neuroimage.2017.01.077>
- Dash, T., Berroir, P., Joannette, Y., & Ansaldò, A. I. (2019). Alerting, Orienting, and Executive Control: The Effect of Bilingualism and Age on the Subcomponents of Attention. *Frontiers in Neurology*, *10*.  
<https://www.frontiersin.org/article/10.3389/fneur.2019.01122>
- Davidson, D. J., Zacks, R. T., & Williams, C. C. (2003). Stroop Interference, Practice, and Aging. *Aging, Neuropsychology, and Cognition*, *10*(2), 85–98.  
<https://doi.org/10.1076/anec.10.2.85.14463>
- Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Que PASA? The posterior-anterior shift in aging. *Cerebral Cortex (New York, N.Y.: 1991)*, *18*(5), 1201–1209. <https://doi.org/10.1093/cercor/bhm155>
- De Brigard, F. (2012). The Role of Attention in Conscious Recollection. *Frontiers in Psychology*, *3*. <https://doi.org/10.3389/fpsyg.2012.00029>
- De Pue, S., Gillebert, C., Dierckx, E., Vanderhasselt, M.-A., De Raedt, R., & Van den Bussche, E. (2021). The impact of the COVID-19 pandemic on wellbeing and cognitive functioning of older adults. *Scientific Reports*, *11*(1), Article 1.  
<https://doi.org/10.1038/s41598-021-84127-7>
- de Souza Almeida, R., Faria-Jr, A., & Klein, R. M. (2021). On the origins and evolution of the Attention Network Tests. *Neuroscience & Biobehavioral Reviews*, *126*, 560–572. <https://doi.org/10.1016/j.neubiorev.2021.02.028>
- Deslauriers, J., Ansado, J., Marrelec, G., Provost, J.-S., & Joannette, Y. (2017). Increase of posterior connectivity in aging within the Ventral Attention Network: A



- functional connectivity analysis using independent component analysis. *Brain Research*, 1657, 288–296. <https://doi.org/10.1016/j.brainres.2016.12.017>
- Driver, J., Eimer, M., Macaluso, E., & Van Velzen, J. L. (2004). *The neurobiology of human spatial attention* (N. Kanwisher & J. Duncan, Eds.; pp. 267–300). Oxford University Press. <https://research.gold.ac.uk/id/eprint/5503/>
- Duda, B. M., & Sweet, L. H. (2019). Functional brain changes associated with cognitive training in healthy older adults: A preliminary ALE meta-analysis. *Brain Imaging and Behavior*. <https://doi.org/10.1007/s11682-019-00080-0>
- Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, 87(3), 272–300. <https://doi.org/10.1037/0033-295X.87.3.272>
- Edwards, J. D., Fausto, B. A., Tetlow, A. M., Corona, R. T., & Valdés, E. G. (2018). Systematic review and meta-analyses of useful field of view cognitive training. *Neuroscience and Biobehavioral Reviews*, 84, 72–91. <https://doi.org/10.1016/j.neubiorev.2017.11.004>
- Edwards, J. D., Xu, H., Clark, D. O., Guey, L. T., Ross, L. A., & Unverzagt, F. W. (2017). Speed of processing training results in lower risk of dementia. *Alzheimer's & Dementia : Translational Research & Clinical Interventions*, 3(4), 603–611. <https://doi.org/10.1016/j.trci.2017.09.002>
- Erel, H., & Levy, D. A. (2016). Orienting of visual attention in aging. *Neuroscience & Biobehavioral Reviews*, 69, 357–380. <https://doi.org/10.1016/j.neubiorev.2016.08.010>
- Eriksen, C. W., & Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics*, 12(2), 201–204. <https://doi.org/10.3758/BF03212870>
- Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, 25(4), 249–263. <https://doi.org/10.3758/BF03198804>

- Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479.  
<https://doi.org/10.1016/j.neuroimage.2005.02.004>
- Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. <https://doi.org/10.1162/089892902317361886>
- Fernandez-Duque, D., & Black, S. E. (2006). Attentional networks in normal aging and Alzheimer's disease. *Neuropsychology*, *20*(2), 133–143.  
<https://doi.org/10.1037/0894-4105.20.2.133>
- Festa-Martino, E., Ott, B. R., & Heindel, W. C. (2004). Interactions Between Phasic Alerting and Spatial Orienting: Effects of Normal Aging and Alzheimer's Disease. *Neuropsychology*, *18*(2), 258–268. <https://doi.org/10.1037/0894-4105.18.2.258>
- Festini, S. B. F. B., Zahodne, L. Z., & Reuter-Lorenz, P. A. R.-L. A. (2019). Theoretical Perspectives on Age Differences in Brain Activation: Harold, Pasa, Crunch—How Do They Stac Up? In *The Oxford Encyclopedia of Psychology and Aging*. Oxford University Press.  
<https://www.oxfordreference.com/view/10.1093/acref/9780190681852.001.0001/acref-9780190681852-e-400>
- Friedman, N. P., & Miyake, A. (2004). The Relations Among Inhibition and Interference Control Functions: A Latent-Variable Analysis. *Journal of Experimental Psychology: General*, *133*(1), 101–135. <https://doi.org/10.1037/0096-3445.133.1.101>
- Friesen, C. K., & Kingstone, A. (1998). The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic Bulletin & Review*, *5*(3), 490–495.  
<https://doi.org/10.3758/BF03208827>
- Fu, J., Yu, G., & Zhao, L. (2020). Effect of aging on visual attention: Evidence from the Attention Network Test. *Social Behavior and Personality*, *49*(3), checked.  
<https://doi.org/10.2224/sbp.9806>

- Gallen, C. L., Baniqued, P. L., Chapman, S. B., Aslan, S., Keebler, M., Didehbani, N., & D'Esposito, M. (2016). Modular Brain Network Organization Predicts Response to Cognitive Training in Older Adults. *PLOS ONE*, *11*(12), e0169015. <https://doi.org/10.1371/journal.pone.0169015>
- Gao, Y., Peng, H., & Wen, J. (2014). The Training Effect of Working Memory Based on Central Executive System Intervention in Older Adults: A Randomized Controlled Study. *Journal of Adult Development*, *21*(2), 80–88. <https://doi.org/10.1007/s10804-013-9181-7>
- Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., & D'Esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *Journal of Cognitive Neuroscience*, *17*(3), 507–517. <https://doi.org/10.1162/0898929053279522>
- Geerligs, L., Saliassi, E., Maurits, N. M., Renken, R. J., & Lorist, M. M. (2014). Brain mechanisms underlying the effects of aging on different aspects of selective attention. *NeuroImage*, *91*, 52–62. <https://doi.org/10.1016/j.neuroimage.2014.01.029>
- Getzmann, S., Golob, E. J., & Wascher, E. (2016). Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiology of Aging*, *41*, 138–149. <https://doi.org/10.1016/j.neurobiolaging.2016.02.018>
- Goldstein, J., Cajko, L., Oosterbroek, M., Michielsen, M., Van Houten, O., & Salverda, F. (1997). VIDEO GAMES AND THE ELDERLY. *Social Behavior and Personality: An International Journal*, *25*(4), 345–352. <https://doi.org/10.2224/sbp.1997.25.4.345>
- Grady, C. (2012). Trends in Neurocognitive Aging. *Nature Reviews. Neuroscience*, *13*(7), 491–505. <https://doi.org/10.1038/nrn3256>
- Grady, C., Sarraf, S., Saverino, C., & Campbell, K. (2016). Age differences in the functional interactions among the default, frontoparietal control, and dorsal

- attention networks. *Neurobiology of Aging*, *41*, 159–172.  
<https://doi.org/10.1016/j.neurobiolaging.2016.02.020>
- Gross, A. L., Payne, B. R., Casanova, R., Davoudzadeh, P., Dzierzewski, J. M., Farias, S., Giovannetti, T., Ip, E. H., Marsiske, M., Rebok, G. W., Schaie, K. W., Thomas, K., Willis, S., & Jones, R. N. (2018). The ACTIVE conceptual framework as a structural equation model. *Experimental Aging Research*, *44*(1), 1–17.  
<https://doi.org/10.1080/0361073X.2017.1398802>
- Guillaume, B., Hua, X., Thompson, P. M., Waldorp, L., Nichols, T. E., & Alzheimer's Disease Neuroimaging Initiative. (2014). Fast and accurate modelling of longitudinal and repeated measures neuroimaging data. *NeuroImage*, *94*, 287–302. <https://doi.org/10.1016/j.neuroimage.2014.03.029>
- Hahn, B., Ross, T. J., & Stein, E. A. (2006). Neuroanatomical dissociation between bottom-up and top-down processes of visuospatial selective attention. *NeuroImage*, *32*(2), 842–853. <https://doi.org/10.1016/j.neuroimage.2006.04.177>
- Hallquist, M. N., & Hillary, F. G. (2018). Graph theory approaches to functional network organization in brain disorders: A critique for a brave new small-world. *Network Neuroscience*, *3*(1), 1–26. [https://doi.org/10.1162/netn\\_a\\_00054](https://doi.org/10.1162/netn_a_00054)
- Hallquist, M. N., & Hillary, F. G. (2019). Graph theory approaches to functional network organization in brain disorders: A critique for a brave new small-world. *Network Neuroscience (Cambridge, Mass.)*, *3*(1), 1–26.  
[https://doi.org/10.1162/netn\\_a\\_00054](https://doi.org/10.1162/netn_a_00054)
- Hardcastle, C., Hausman, H. K., Kraft, J. N., Albizu, A., Evangelista, N. D., Boutzoukas, E. M., O'Shea, A., Langer, K., Van Van Etten, E., Bharadwaj, P. K., Song, H., Smith, S. G., Porges, E., DeKosky, S. T., Hishaw, G. A., Wu, S. S., Marsiske, M., Cohen, R., Alexander, G. E., & Woods, A. J. (2022). Higher-order resting state network association with the useful field of view task in older adults. *GeroScience*, *44*(1), 131–145. <https://doi.org/10.1007/s11357-021-00441-y>

- Hardcastle, C., Hausman, H. K., Kraft, J. N., Albizu, A., O'Shea, A., Boutzoukas, E. M., Evangelista, N. D., Langer, K., Van Etten, E. J., Bharadwaj, P. K., Song, H., Smith, S. G., Porges, E., DeKosky, S. T., Hishaw, G. A., Wu, S. S., Marsiske, M., Cohen, R., Alexander, G. E., & Woods, A. J. (2022). Proximal improvement and higher-order resting state network change after multidomain cognitive training intervention in healthy older adults. *GeroScience*. <https://doi.org/10.1007/s11357-022-00535-1>
- Harriger, L., van den Heuvel, M. P., & Sporns, O. (2012). Rich club organization of macaque cerebral cortex and its role in network communication. *PloS One*, *7*(9), e46497. <https://doi.org/10.1371/journal.pone.0046497>
- Hartley, A. A., Kieley, J., & McKenzie, C. R. (1992). Allocation of visual attention in younger and older adults. *Perception & Psychophysics*, *52*(2), 175–185. <https://doi.org/10.3758/BF03206771>
- Hasher, L., & Zacks, R. T. (1988). Working Memory, Comprehension, and Aging: A Review and a New View. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60041-9](https://doi.org/10.1016/S0079-7421(08)60041-9)
- Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (pp. 653–675). The MIT Press.
- Hazeltine, E., Poldrack, R., & Gabrieli, J. D. (2000). Neural activation during response competition. *Journal of Cognitive Neuroscience*, *12* Suppl 2, 118–129. <https://doi.org/10.1162/089892900563984>
- Heideman, S. G., Rohenkohl, G., Chauvin, J. J., Palmer, C. E., van Ede, F., & Nobre, A. C. (2018). Anticipatory neural dynamics of spatial-temporal orienting of attention in younger and older adults. *NeuroImage*, *178*, 46–56. <https://doi.org/10.1016/j.neuroimage.2018.05.002>

- Heilman, K. M., Valenstein, E., & Watson, R. T. (2000). Neglect and related disorders. *Seminars in Neurology*, *20*(4), 463–470. <https://doi.org/10.1055/s-2000-13179>
- Hillary, F. G., Genova, H. M., Chiaravalloti, N. D., Rypma, B., & DeLuca, J. (2006). Prefrontal modulation of working memory performance in brain injury and disease. *Human Brain Mapping*, *27*(11), 837–847. <https://doi.org/10.1002/hbm.20226>
- Hillyard, S. A., Russo, F. D., & Martinez, A. (n.d.). *The imaging of visual attention*. 8.
- Hopfinger, J. B., Buonocore, M. H., & Mangun, G. R. (2000). The neural mechanisms of top-down attentional control. *Nature Neuroscience*, *3*(3), Article 3. <https://doi.org/10.1038/72999>
- Huang, Y., Su, L., & Ma, Q. (2020). The Stroop effect: An activation likelihood estimation meta-analysis in healthy young adults. *Neuroscience Letters*, *716*, 134683. <https://doi.org/10.1016/j.neulet.2019.134683>
- Inzitari, M., Newman, A. B., Yaffe, K., Boudreau, R., de Rekeneire, N., Shorr, R., Harris, T. B., & Rosano, C. (2008). Gait Speed Predicts Decline in Attention and Psychomotor Speed in Older Adults: The Health Aging and Body Composition Study. *Neuroepidemiology*, *29*(3–4), 156–162. <https://doi.org/10.1159/000111577>
- Iordan, A. D., Cooke, K. A., Moored, K. D., Katz, B., Buschkuehl, M., Jaeggi, S. M., Polk, T. A., Peltier, S. J., Jonides, J., & Reuter-Lorenz, P. A. (2020). Neural correlates of working memory training: Evidence for plasticity in older adults. *NeuroImage*, *217*, 116887. <https://doi.org/10.1016/j.neuroimage.2020.116887>
- Iordan, A. D., Moored, K. D., Katz, B., Cooke, K. A., Buschkuehl, M., Jaeggi, S. M., Polk, T. A., Peltier, S. J., Jonides, J., & Reuter-Lorenz, P. A. (2021). Age differences in functional network reconfiguration with working memory training. *Human Brain Mapping*, *42*(6), 1888–1909. <https://doi.org/10.1002/hbm.25337>
- Ishigami, Y., Eskes, G. A., Tyndall, A. V., Longman, R. S., Drogos, L. L., & Poulin, M. J. (2016). The Attention Network Test-Interaction (ANT-I): Reliability and validity in

- healthy older adults. *Experimental Brain Research*, 234(3), 815–827.  
<https://doi.org/10.1007/s00221-015-4493-4>
- Ishigami, Y., & Klein, R. M. (2011). Repeated Measurement of the Components of Attention of Older Adults using the Two Versions of the Attention Network Test: Stability, Isolability, Robustness, and Reliability. *Frontiers in Aging Neuroscience*, 3, 17. <https://doi.org/10.3389/fnagi.2011.00017>
- Jaeggi, S. M., Buschkuhl, M., Jonides, J., & Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proceedings of the National Academy of Sciences*, 108(25), 10081–10086. <https://doi.org/10.1073/pnas.1103228108>
- James, W., & Burkhardt, F. H. (1983). The Principles of Psychology, the Works of William James. *Transactions of the Charles S. Peirce Society*, 19(2), 211–223.
- Jennings, J. M., Dagenbach, D., Engle, C. M., & Funke, L. J. (2007). Age-Related Changes and the Attention Network Task: An Examination of Alerting, Orienting, and Executive Function. *Aging, Neuropsychology, and Cognition*, 14(4), 353–369. <https://doi.org/10.1080/13825580600788837>
- Jockwitz, C., & Caspers, S. (2021). Resting-state networks in the course of aging—Differential insights from studies across the lifespan vs. Amongst the old. *Pflügers Archiv - European Journal of Physiology*, 473(5), 793–803.  
<https://doi.org/10.1007/s00424-021-02520-7>
- Johnson, K. A., Robertson, I. H., Barry, E., Mulligan, A., Dáibhis, A., Daly, M., Watchorn, A., Gill, M., & Bellgrove, M. A. (2008). Impaired conflict resolution and alerting in children with ADHD: Evidence from the Attention Network Task (ANT). *Journal of Child Psychology and Psychiatry*, 49(12), 1339–1347.  
<https://doi.org/10.1111/j.1469-7610.2008.01936.x>
- Jylhä, M. (2009). What is self-rated health and why does it predict mortality? Towards a unified conceptual model. *Social Science & Medicine (1982)*, 69(3), 307–316.  
<https://doi.org/10.1016/j.socscimed.2009.05.013>

- Kamboh, M. I., Fan, K.-H., Yan, Q., Beer, J. C., Snitz, B. E., Wang, X., Chang, C.-C. H., Demirci, F. Y., Feingold, E., & Ganguli, M. (2019). Population-based genome-wide association study of cognitive decline in older adults free of dementia: Identification of a novel locus for the attention domain. *Neurobiology of Aging, 84*, 239.e15-239.e24. <https://doi.org/10.1016/j.neurobiolaging.2019.02.024>
- Kaneko, R., Kuba, Y., Sakata, Y., & Kuchinomachi, Y. (2004). Aging and shifts of visual attention in saccadic eye movements. *Experimental Aging Research, 30*(2), 149–162. <https://doi.org/10.1080/03610730490274176>
- Karpouzian-Rogers, T., Heindel, W. C., Ott, B. R., Tremont, G., & Festa, E. K. (2020). Phasic alerting enhances spatial orienting in healthy aging but not in mild cognitive impairment. *Neuropsychology, 34*(2), 144–154. <https://doi.org/10.1037/neu0000593>
- Kawagoe, T. (2022). Overview of (f)MRI Studies of Cognitive Aging for Non-Experts: Looking through the Lens of Neuroimaging. *Life (Basel, Switzerland), 12*(3), 416. <https://doi.org/10.3390/life12030416>
- Kingstone, A., Klein, R., Morein-Zamir, S., Hunt, A., Fisk, J., & Maxner, C. (2002). Orienting Attention in Aging and Parkinson's Disease: Distinguishing Modes of Control. *Journal of Clinical and Experimental Neuropsychology, 24*(7), 951–967. <https://doi.org/10.1076/jcen.24.7.951.8387>
- Kivi, M., Hansson, I., & Bjälkebring, P. (2021). Up and About: Older Adults' Well-being During the COVID-19 Pandemic in a Swedish Longitudinal Study. *The Journals of Gerontology: Series B, 76*(2), e4–e9. <https://doi.org/10.1093/geronb/gbaa084>
- Konrad, K., Neufang, S., Thiel, C. M., Specht, K., Hanisch, C., Fan, J., Herpertz-Dahlmann, B., & Fink, G. R. (2005). Development of attentional networks: An fMRI study with children and adults. *NeuroImage, 28*(2), 429–439. <https://doi.org/10.1016/j.neuroimage.2005.06.065>



- Kueider, A. M., Parisi, J. M., Gross, A. L., & Rebok, G. W. (2012). Computerized Cognitive Training with Older Adults: A Systematic Review. *PLOS ONE*, *7*(7), e40588. <https://doi.org/10.1371/journal.pone.0040588>
- Lachat, F., Farroni, T., & George, N. (2012). Watch Out! Magnetoencephalographic Evidence for Early Modulation of Attention Orienting by Fearful Gaze Cueing. *PLOS ONE*, *7*(11), e50499. <https://doi.org/10.1371/journal.pone.0050499>
- Laird, A. R., McMillan, K. M., Lancaster, J. L., Kochunov, P., Turkeltaub, P. E., Pardo, J. V., & Fox, P. T. (2005). A comparison of label-based review and ALE meta-analysis in the Stroop task. *Human Brain Mapping*, *25*(1), 6–21. <https://doi.org/10.1002/hbm.20129>
- Lampit, A., Hallock, H., & Valenzuela, M. (2014). Computerized Cognitive Training in Cognitively Healthy Older Adults: A Systematic Review and Meta-Analysis of Effect Modifiers. *PLOS Medicine*, *11*(11), e1001756. <https://doi.org/10.1371/journal.pmed.1001756>
- Lawrence, N. S., Ross, T. J., Hoffmann, R., Garavan, H., & Stein, E. A. (2003). Multiple neuronal networks mediate sustained attention. *Journal of Cognitive Neuroscience*, *15*(7), 1028–1038. <https://doi.org/10.1162/089892903770007416>
- Lawrence, R. K., Edwards, M., & Goodhew, S. C. (2018). Changes in the spatial spread of attention with ageing. *Acta Psychologica*, *188*, 188–199. <https://doi.org/10.1016/j.actpsy.2018.06.009>
- Leskin, L. P., & White, P. M. (2007). Attentional networks reveal executive function deficits in posttraumatic stress disorder. *Neuropsychology*, *21*(3), 275–284. <https://doi.org/10.1037/0894-4105.21.3.275>
- Liu, X., Banich, M. T., Jacobson, B. L., & Tanabe, J. L. (2004). Common and distinct neural substrates of attentional control in an integrated Simon and spatial Stroop task as assessed by event-related fMRI. *NeuroImage*, *22*(3), 1097–1106. <https://doi.org/10.1016/j.neuroimage.2004.02.033>

- Logan, G. D., Van Zandt, T., Verbruggen, F., & Wagenmakers, E.-J. (2014). On the ability to inhibit thought and action: General and special theories of an act of control. *Psychological Review*, *121*(1), 66–95. <https://doi.org/10.1037/a0035230>
- Lorge, I. (1940). Old age and aging the present status of scientific knowledge: Section meeting, 1939: Psychometry: The evaluation of mental status as a function of the mental test. *American Journal of Orthopsychiatry*, *10*(1), 56–61. <https://doi.org/10.1111/j.1939-0025.1940.tb05660.x>
- Lövdén, M., Bäckman, L., Lindenberger, U., Schaefer, S., & Schmiedek, F. (2010). A theoretical framework for the study of adult cognitive plasticity. *Psychological Bulletin*, *136*(4), 659–676. <https://doi.org/10.1037/a0020080>
- Lu, H., Fung, A. W. T., Chan, S. S. M., & Lam, L. C. W. (2016). Disturbance of attention network functions in Chinese healthy older adults: An intra-individual perspective. *International Psychogeriatrics*, *28*(2), 291–301. <https://doi.org/10.1017/S1041610215001556>
- Lurie, D. J., Kessler, D., Bassett, D. S., Betzel, R. F., Breakspear, M., Kheilholz, S., Kucyi, A., Liégeois, R., Lindquist, M. A., McIntosh, A. R., Poldrack, R. A., Shine, J. M., Thompson, W. H., Bielczyk, N. Z., Douw, L., Kraft, D., Miller, R. L., Muthuraman, M., Pasquini, L., ... Calhoun, V. D. (2019). Questions and controversies in the study of time-varying functional connectivity in resting fMRI. *Network Neuroscience*, *4*(1), 30–69. [https://doi.org/10.1162/netn\\_a\\_00116](https://doi.org/10.1162/netn_a_00116)
- Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a “new view.” In *Inhibition in cognition* (pp. 145–162). American Psychological Association. <https://doi.org/10.1037/11587-008>
- Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: A review and future directions. *Neuropsychology Review*, *19*(4), 504–522. <https://doi.org/10.1007/s11065-009-9119-9>

- MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science (New York, N.Y.)*, *288*(5472), 1835–1838.  
<https://doi.org/10.1126/science.288.5472.1835>
- Madden, D. J. (2007). Aging and Visual Attention. *Current Directions in Psychological Science*, *16*(2), 70–74. <https://doi.org/10.1111/j.1467-8721.2007.00478.x>
- Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., White, L. E., & Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging*, *28*(3), 459–476. <https://doi.org/10.1016/j.neurobiolaging.2006.01.005>
- Madden, D. J., Whiting, W. L., Provenzale, J. M., & Huettel, S. A. (2004). Age-related Changes in Neural Activity during Visual Target Detection Measured by fMRI. *Cerebral Cortex*, *14*(2), 143–155. <https://doi.org/10.1093/cercor/bhg113>
- Madhyastha, T. M., Askren, M. K., Boord, P., & Grabowski, T. J. (2015). Dynamic Connectivity at Rest Predicts Attention Task Performance. *Brain Connectivity*, *5*(1), 45–59. <https://doi.org/10.1089/brain.2014.0248>
- Mahoney, J. R., Verghese, J., Goldin, Y., Lipton, R., & Holtzer, R. (2010). Alerting, orienting, and executive attention in older adults. *Journal of the International Neuropsychological Society: JINS*, *16*(5), 877–889.  
<https://doi.org/10.1017/S1355617710000767>
- Malagurski, B., Liem, F., Oswald, J., Mérillat, S., & Jäncke, L. (2020). Functional dedifferentiation of associative resting state networks in older adults – A longitudinal study. *NeuroImage*, *214*, 116680.  
<https://doi.org/10.1016/j.neuroimage.2020.116680>
- Mapstone, M., Rösler, A., Hays, A., Gitelman, D. R., & Weintraub, S. (2001). Dynamic Allocation of Attention in Aging and Alzheimer Disease: Uncoupling of the Eye and Mind. *Archives of Neurology*, *58*(9), 1443–1447.  
<https://doi.org/10.1001/archneur.58.9.1443>

- Markett, S., Reuter, M., Montag, C., Voigt, G., Lachmann, B., Rudolf, S., Elger, C. E., & Weber, B. (2014). Assessing the function of the fronto-parietal attention network: Insights from resting-state fMRI and the attentional network test. *Human Brain Mapping, 35*(4), 1700–1709. <https://doi.org/10.1002/hbm.22285>
- Martella, D., Manzanares, S., Campoy, G., Roca, J., Antúnez, C., & Fuentes, L. J. (2014). Phasic and tonic alerting in mild cognitive impairment: A preliminary study. *Experimental Gerontology, 49*, 35–39. <https://doi.org/10.1016/j.exger.2013.11.001>
- McDonough, I. M., Cervantes, S. N., Gray, S. J., & Gallo, D. A. (2014). Memory's aging echo: Age-related decline in neural reactivation of perceptual details during recollection. *NeuroImage, 98*, 346–358. <https://doi.org/10.1016/j.neuroimage.2014.05.012>
- McDonough, I. M., Wood, M. M., & Miller, Jr., W. S. (2019). A Review on the Trajectory of Attentional Mechanisms in Aging and the Alzheimer's Disease Continuum through the Attention Network Test. *The Yale Journal of Biology and Medicine, 92*(1), 37–51.
- McDowd, J. M. (1997). Inhibition in attention and aging. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 52*(6), P265-273. <https://doi.org/10.1093/geronb/52b.6.p265>
- McGaughy, J., & Eichenbaum, H. (2002). It's time to pay attention to attention in aging. *Learning & Memory (Cold Spring Harbor, N.Y.), 9*(4), 151–152. <https://doi.org/10.1101/lm.52902>
- Mozolic, J. L., Hayaska, S., & Laurienti, P. J. (2010). A cognitive training intervention increases resting cerebral blood flow in healthy older adults. *Frontiers in Human Neuroscience, 4*. <https://doi.org/10.3389/neuro.09.016.2010>
- Nee, D. E., Wager, T. D., & Jonides, J. (2007). Interference resolution: Insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective & Behavioral Neuroscience, 7*(1), 1–17. <https://doi.org/10.3758/cabn.7.1.1>

- Nestor, P. G., Kubicki, M., Spencer, K. M., Niznikiewicz, M., McCarley, R. W., & Shenton, M. E. (2007). Attentional networks and cingulum bundle in chronic schizophrenia. *Schizophrenia Research*, *90*(1), 308–315.  
<https://doi.org/10.1016/j.schres.2006.10.005>
- Nguyen, C. M., Copeland, C. T., Lowe, D. A., Heyanka, D. J., & Linck, J. F. (2020). Contribution of executive functioning to instrumental activities of daily living in older adults. *Applied Neuropsychology. Adult*, *27*(4), 326–333.  
<https://doi.org/10.1080/23279095.2018.1550408>
- Nithianantharajah, J., & Hannan, A. J. (2006). Enriched environments, experience-dependent plasticity and disorders of the nervous system. *Nature Reviews Neuroscience*, *7*(9), Article 9. <https://doi.org/10.1038/nrn1970>
- Nobre, A. C., Coull, J. T., Maquet, P., Frith, C. D., Vandenberghe, R., & Mesulam, M. M. (2004). Orienting attention to locations in perceptual versus mental representations. *Journal of Cognitive Neuroscience*, *16*(3), 363–373.  
<https://doi.org/10.1162/089892904322926700>
- Okonkwo, O. C., Crowe, M., Wadley, V. G., & Ball, K. (2008). Visual attention and self-regulation of driving among older adults. *International Psychogeriatrics*, *20*(1), 162–173. <https://doi.org/10.1017/S104161020700539X>
- Osaka, M., Otsuka, Y., & Osaka, N. (2012). Verbal to visual code switching improves working memory in older adults: An fMRI study. *Frontiers in Human Neuroscience*, *6*. <https://www.frontiersin.org/article/10.3389/fnhum.2012.00024>
- Pantoni, L., Poggesi, A., Diciotti, S., Valenti, R., Orsolini, S., Della Rocca, E., Inzitari, D., Mascalchi, M., & Salvadori, E. (2017). Effect of Attention Training in Mild Cognitive Impairment Patients with Subcortical Vascular Changes: The RehAtt Study. *Journal of Alzheimer's Disease*, *60*(2), 615–624.  
<https://doi.org/10.3233/JAD-170428>
- Parisi, G., Mazzi, C., [Link to external site, this link will open in a new window](#), Colombari, E., Chiarelli, A. M., [Link to external site, this link will open in a new](#)

- window, Metzger, B. A., Marzi, C. A., & Savazzi, S. (2020). Spatiotemporal dynamics of attentional orienting and reorienting revealed by fast optical imaging in occipital and parietal cortices. *NeuroImage*, 222. <https://doi.org/10.1016/j.neuroimage.2020.117244>
- Park, D. C., & Festini, S. B. (2017). Theories of Memory and Aging: A Look at the Past and a Glimpse of the Future. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 72(1), 82–90. <https://doi.org/10.1093/geronb/gbw066>
- Peelen, M. V., & Kastner, S. (2011). A neural basis for real-world visual search in human occipitotemporal cortex. *Proceedings of the National Academy of Sciences*, 108(29), 12125–12130. <https://doi.org/10.1073/pnas.1101042108>
- Peng, P., & Miller, A. C. (2016). Does attention training work? A selective meta-analysis to explore the effects of attention training and moderators. *Learning and Individual Differences*, 45, 77–87. <https://doi.org/10.1016/j.lindif.2015.11.012>
- Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, 35, 73–89. <https://doi.org/10.1146/annurev-neuro-062111-150525>
- Poldrack, R. A. (2015). Is “efficiency” a useful concept in cognitive neuroscience? *Developmental Cognitive Neuroscience*, 11, 12–17. <https://doi.org/10.1016/j.dcn.2014.06.001>
- Posner, M. I. (1978). *Chronometric explorations of mind* (pp. xiii, 271). Lawrence Erlbaum.
- Posner, M. I. (1988). Structures and function of selective attention. In *Clinical neuropsychology and brain function: Research, measurement, and practice* (pp. 173–202). American Psychological Association. <https://doi.org/10.1037/10063-005>
- Posner, M. I. (2012). Imaging attention networks. *NeuroImage*, 61(2), 450–456. <https://doi.org/10.1016/j.neuroimage.2011.12.040>

- Posner, M. I., Inhoff, A. W., Friedrich, F. J., & Cohen, A. (1987). Isolating attentional systems: A cognitive-anatomical analysis. *Psychobiology*, *15*(2), 107–121. <https://doi.org/10.3758/BF03333099>
- Posner, M. I., & Petersen, S. E. (1990). The Attention System of the Human Brain. *Annual Review of Neuroscience*, *13*(1), 25–42. <https://doi.org/10.1146/annurev.ne.13.030190.000325>
- Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1–23. <https://doi.org/10.1146/annurev.psych.58.110405.085516>
- Posner, M. I., Rothbart, M. K., & Tang, Y.-Y. (2015). Enhancing attention through training. *Current Opinion in Behavioral Sciences*, *4*, 1–5. <https://doi.org/10.1016/j.cobeha.2014.12.008>
- Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience*, *4*(7), 1863–1874. <https://doi.org/10.1523/JNEUROSCI.04-07-01863.1984>
- Rabbitt, P. (1965). An Age-decrement in the Ability to Ignore Irrelevant Information. *Journal of Gerontology*, *20*(2), 233–238. <https://doi.org/10.1093/geronj/20.2.233>
- Rebok, G. W., Ball, K., Guey, L. T., Jones, R. N., Kim, H.-Y., King, J. W., Marsiske, M., Morris, J. N., Tennstedt, S. L., Unverzagt, F. W., & Willis, S. L. (2014). Ten-Year Effects of the ACTIVE Cognitive Training Trial on Cognition and Everyday Functioning in Older Adults. *Journal of the American Geriatrics Society*, *62*(1), 16–24. <https://doi.org/10.1111/jgs.12607>
- Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive Aging and the Compensation Hypothesis. *Current Directions in Psychological Science*, *17*(3), 177–182. <https://doi.org/10.1111/j.1467-8721.2008.00570.x>
- Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review*, *25*(5), 1695–1716. <https://doi.org/10.3758/s13423-017-1384-7>

- Rosenberg, M. D., Finn, E. S., Scheinost, D., Constable, R. T., & Chun, M. M. (2017). Characterizing attention with predictive network models. *Trends in Cognitive Sciences*, 21(4), 290–302. <https://doi.org/10.1016/j.tics.2017.01.011>
- Rosenberg, M. D., Hsu, W.-T., Scheinost, D., Todd Constable, R., & Chun, M. M. (2018). Connectome-based Models Predict Separable Components of Attention in Novel Individuals. *Journal of Cognitive Neuroscience*, 30(2), 160–173. [https://doi.org/10.1162/jocn\\_a\\_01197](https://doi.org/10.1162/jocn_a_01197)
- Rösler, A., Mapstone, M., Hays-Wicklund, A., Gitelman, D. R., & Weintraub, S. (2005). The “zoom lens” of focal attention in visual search: Changes in aging and Alzheimer’s disease. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 41(4), 512–519. [https://doi.org/10.1016/s0010-9452\(08\)70191-6](https://doi.org/10.1016/s0010-9452(08)70191-6)
- Ross, L. A., Freed, S. A., Edwards, J. D., Phillips, C. B., & Ball, K. (2017). The Impact of Three Cognitive Training Programs on Driving Cessation Across 10 Years: A Randomized Controlled Trial. *The Gerontologist*, 57(5), 838–846. <https://doi.org/10.1093/geront/gnw143>
- Ross, L. A., Sprague, B. N., Phillips, C. B., O’Connor, M. L., & Dodson, J. E. (2018). The impact of three cognitive training interventions on older adults’ physical functioning across 5 years. *Journal of Aging and Health*, 30(3), 475–498.
- Ross, L. A., Webb, C. E., Whitaker, C., Hicks, J. M., Schmidt, E. L., Samimy, S., Dennis, N. A., & Visscher, K. M. (2018). The Effects of Useful Field of View Training on Brain Activity and Connectivity. *The Journals of Gerontology: Series B*. <https://doi.org/10.1093/geronb/gby041>
- Rushworth, M. F. S., Nixon, P. D., Renowden, S., Wade, D. T., & Passingham, R. E. (1997). The left parietal cortex and motor attention. *Neuropsychologia*, 35(9), 1261–1273. [https://doi.org/10.1016/S0028-3932\(97\)00050-X](https://doi.org/10.1016/S0028-3932(97)00050-X)
- Rusnáková, Š., Daniel, P., Chládek, J., Jurák, P., & Rektor, I. (2011). The Executive Functions in Frontal and Temporal Lobes: A Flanker Task Intracerebral



- Recording Study. *Journal of Clinical Neurophysiology*, 28(1), 30.  
<https://doi.org/10.1097/WNP.0b013e31820512d4>
- Sadaghiani, S., & D'Esposito, M. (2015). Functional Characterization of the Cingulo-Opercular Network in the Maintenance of Tonic Alertness. *Cerebral Cortex (New York, NY)*, 25(9), 2763–2773. <https://doi.org/10.1093/cercor/bhu072>
- Salomon, G., & Perkins, D. N. (1989). Rocky Roads to Transfer: Rethinking Mechanism of a Neglected Phenomenon. *Educational Psychologist*, 24(2), 113–142.  
[https://doi.org/10.1207/s15326985ep2402\\_1](https://doi.org/10.1207/s15326985ep2402_1)
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103(3), 403–428. <https://doi.org/10.1037/0033-295x.103.3.403>
- Salthouse, T. A. (2014). Correlates of cognitive change. *Journal of Experimental Psychology. General*, 143(3), 1026–1048. <https://doi.org/10.1037/a0034847>
- Salthouse, T. A. (2016). *Theoretical Perspectives on Cognitive Aging*. Psychology Press. <https://doi.org/10.4324/9781315785363>
- Schafer, R. J., & Moore, T. (2007). Attention governs action in the primate frontal eye field. *Neuron*, 56(3), 541–551. <https://doi.org/10.1016/j.neuron.2007.09.029>
- Serences, J. T., Yantis, S., Culberson, A., & Awh, E. (2004). Preparatory Activity in Visual Cortex Indexes Distractor Suppression During Covert Spatial Orienting. *Journal of Neurophysiology*, 92(6), 3538–3545.  
<https://doi.org/10.1152/jn.00435.2004>
- Shaw, J. S., & Hosseini, S. M. H. (2021). The Effect of Baseline Performance and Age on Cognitive Training Improvements in Older Adults: A Qualitative Review. *The Journal of Prevention of Alzheimer's Disease*, 8(1), 100–109.  
<https://doi.org/10.14283/jpad.2020.55>
- Sliwinski, M., & Buschke, H. (1999). Cross-sectional and longitudinal relationships among age, cognition, and processing speed. *Psychology and Aging*, 14(1), 18–33. <https://doi.org/10.1037/0882-7974.14.1.18>

- Sprague, B. N., Freed, S. A., Webb, C. E., Phillips, C. B., Hyun, J., & Ross, L. A. (2019). The impact of behavioral interventions on cognitive function in healthy older adults: A systematic review. *Ageing Research Reviews*, *52*, 32–52.  
<https://doi.org/10.1016/j.arr.2019.04.002>
- Spreng, R. N., Stevens, W. D., Viviano, J. D., & Schacter, D. L. (2016). Attenuated anticorrelation between the default and dorsal attention networks with aging: Evidence from task and rest. *Neurobiology of Aging*, *45*, 149–160.  
<https://doi.org/10.1016/j.neurobiolaging.2016.05.020>
- Staub, B., Doignon-Camus, N., Després, O., & Bonnefond, A. (2013). Sustained attention in the elderly: What do we know and what does it tell us about cognitive aging? *Ageing Research Reviews*, *12*(2), 459–468.  
<https://doi.org/10.1016/j.arr.2012.12.001>
- Stawski, R. S., Sliwinski, M. J., & Hofer, S. M. (2013). Between-person and within-person associations among processing speed, attention switching, and working memory in younger and older adults. *Experimental Aging Research*, *39*(2), 194–214. <https://doi.org/10.1080/0361073X.2013.761556>
- Strenziok, M., Parasuraman, R., Clarke, E., Cisler, D. S., Thompson, J. C., & Greenwood, P. M. (2014). Neurocognitive enhancement in older adults: Comparison of three cognitive training tasks to test a hypothesis of training transfer in brain connectivity. *NeuroImage*, *85*, 1027–1039.  
<https://doi.org/10.1016/j.neuroimage.2013.07.069>
- Sturm, W., Thimm, M., Küst, J., Karbe, H., & Fink, G. R. (2006). Alertness-training in neglect: Behavioral and imaging results. *Restorative Neurology and Neuroscience*, *24*(4–6), 371–384.
- Sutter, C., Zöllig, J., & Martin, M. (2013). Plasticity of Verbal Fluency in Older Adults: A 90-Minute Telephone-Based Intervention. *Gerontology*, *59*(1), 53–63.  
<https://doi.org/10.1159/000342199>

- Tales, A., Snowden, R. J., Brown, M., & Wilcock, G. (2006). Alerting and orienting in Alzheimer's disease. *Neuropsychology, 20*(6), 752–756.  
<https://doi.org/10.1037/0894-4105.20.6.752>
- Tang, Y.-Y., Tang, Y., Tang, R., & Lewis-Peacock, J. A. (2017). Brief Mental Training Reorganizes Large-Scale Brain Networks. *Frontiers in Systems Neuroscience, 11*. <https://doi.org/10.3389/fnsys.2017.00006>
- Taya, F., Sun, Y., Babiloni, F., Thakor, N., & Bezerianos, A. (2015). Brain enhancement through cognitive training: A new insight from brain connectome. *Frontiers in Systems Neuroscience, 9*.  
<https://www.frontiersin.org/article/10.3389/fnsys.2015.00044>
- Tennstedt, S. L., & Unverzagt, F. W. (2013). The ACTIVE Study: Study Overview and Major Findings. *Journal of Aging and Health, 25*(8 0), 3S-20S.  
<https://doi.org/10.1177/0898264313518133>
- Thiel, C. M., Zilles, K., & Fink, G. R. (2004). Cerebral correlates of alerting, orienting and reorienting of visuospatial attention: An event-related fMRI study. *NeuroImage, 21*(1), 318–328. <https://doi.org/10.1016/j.neuroimage.2003.08.044>
- Thompson, K. G., Biscoe, K. L., & Sato, T. R. (2005). Neuronal basis of covert spatial attention in the frontal eye field. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 25*(41), 9479–9487.  
<https://doi.org/10.1523/JNEUROSCI.0741-05.2005>
- Tomasi, D., & Volkow, N. D. (2012). Aging and Functional Brain Networks. *Molecular Psychiatry, 17*(5), 471–558. <https://doi.org/10.1038/mp.2011.81>
- Vallesi, A., Tronelli, V., Lomi, F., & Pezzetta, R. (2021). Age differences in sustained attention tasks: A meta-analysis. *Psychonomic Bulletin & Review, 28*(6), 1755–1775. <https://doi.org/10.3758/s13423-021-01908-x>
- Van Dam, N. T., Sano, M., Mitsis, E. M., Grossman, H. T., Gu, X., Park, Y., Hof, P. R., & Fan, J. (2013). Functional Neural Correlates of Attentional Deficits in Amnesic

- Mild Cognitive Impairment. *PLoS ONE*, 8(1), e54035.  
<https://doi.org/10.1371/journal.pone.0054035>
- Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience and Biobehavioral Reviews*, 26(7), 849–857.  
[https://doi.org/10.1016/s0149-7634\(02\)00071-4](https://doi.org/10.1016/s0149-7634(02)00071-4)
- Veríssimo, J., Verhaeghen, P., Goldman, N., Weinstein, M., & Ullman, M. T. (2022). Evidence that ageing yields improvements as well as declines across attention and executive functions. *Nature Human Behaviour*, 6(1), Article 1.  
<https://doi.org/10.1038/s41562-021-01169-7>
- Visintin, E., De Panfilis, C., Antonucci, C., Capecci, C., Marchesi, C., & Sambataro, F. (2015). Parsing the intrinsic networks underlying attention: A resting state study. *Behavioural Brain Research*, 278, 315–322.  
<https://doi.org/10.1016/j.bbr.2014.10.002>
- Wang, B., Zhang, J., Pan, W., Cao, S., Li, B., Bai, L., Hu, P., Tian, Y., Jiang, D., & Wang, K. (2020). Differential Influence of Location-Specific White-Matter Hyperintensities on Attention Subdomains Measured Using the Attention Network Test. *Medical Science Monitor : International Medical Journal of Experimental and Clinical Research*, 26, e921874-1-e921874-24.  
<https://doi.org/10.12659/MSM.921874>
- Waszak, F., Li, S.-C., & Hommel, B. (2010). The development of attentional networks: Cross-sectional findings from a life span sample. *Developmental Psychology*, 46(2), 337–349. <https://doi.org/10.1037/a0018541>
- Weaver, B., Bédard, M., McAuliffe, J., & Parkkari, M. (2009). Using the Attention Network Test to predict driving test scores. *Accident Analysis & Prevention*, 41(1), 76–83. <https://doi.org/10.1016/j.aap.2008.09.006>
- West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, 120(2), 272–292. <https://doi.org/10.1037/0033-2909.120.2.272>

- Westlye, L. T., Grydeland, H., Walhovd, K. B., & Fjell, A. M. (2011). Associations between Regional Cortical Thickness and Attentional Networks as Measured by the Attention Network Test. *Cerebral Cortex*, *21*(2), 345–356.  
<https://doi.org/10.1093/cercor/bhq101>
- Wilson, Beck, T. L., Bienias, J. L., & Bennett, D. A. (2007). Terminal cognitive decline: Accelerated loss of cognition in the last years of life. *Psychosomatic Medicine*, *69*(2), 131–137. <https://doi.org/10.1097/PSY.0b013e31803130ae>
- Woldorff, M. G., Hazlett, C. J., Fichtenholtz, H. M., Weissman, D. H., Dale, A. M., & Song, A. W. (2004). Functional Parcellation of Attentional Control Regions of the Brain. *Journal of Cognitive Neuroscience*, *16*(1), 149–165.  
<https://doi.org/10.1162/089892904322755638>
- Womelsdorf, T., Schoffelen, J.-M., Oostenveld, R., Singer, W., Desimone, R., Engel, A. K., & Fries, P. (2007). Modulation of neuronal interactions through neuronal synchronization. *Science (New York, N.Y.)*, *316*(5831), 1609–1612.  
<https://doi.org/10.1126/science.1139597>
- Wright, R. D., & Ward, L. M. (2008). *Orienting of Attention*. Oxford University Press.
- Xuan, B., Mackie, M.-A., Spagna, A., Wu, T., Tian, Y., Hof, P. R., & Fan, J. (2016). The activation of interactive attentional networks. *NeuroImage*, *129*, 308–319.  
<https://doi.org/10.1016/j.neuroimage.2016.01.017>
- Yam, A., & Marsiske, M. (2013). Cognitive Longitudinal Predictors of Older Adults' Self-Reported IADL Function. *Journal of Aging and Health*, *25*(8\_suppl), 163S-185S.  
<https://doi.org/10.1177/0898264313495560>
- Yang, H.-L., Chu, H., Kao, C.-C., Miao, N.-F., Chang, P.-C., Tseng, P., O'Brien, A. P., & Chou, K.-R. (2020). Construction and evaluation of multidomain attention training to improve alertness attention, sustained attention, and visual-spatial attention in older adults with mild cognitive impairment: A randomized controlled trial. *International Journal of Geriatric Psychiatry*, *35*(5), 537–546.  
<https://doi.org/10.1002/gps.5269>

- Yang, H.-L., Chu, H., Miao, N.-F., Chang, P.-C., Tseng, P., Chen, R., Chiu, H.-L., Banda, K. J., & Chou, K.-R. (2019). The Construction and Evaluation of Executive Attention Training to Improve Selective Attention, Focused Attention, and Divided Attention for Older Adults With Mild Cognitive Impairment: A Randomized Controlled Trial. *The American Journal of Geriatric Psychiatry: Official Journal of the American Association for Geriatric Psychiatry*, 27(11), 1257–1267. <https://doi.org/10.1016/j.jagp.2019.05.017>
- Zhang, R., Geng, X., & Lee, T. M. C. (2017). Large-scale functional neural network correlates of response inhibition: An fMRI meta-analysis. *Brain Structure and Function*, 222(9), 3973–3990. <https://doi.org/10.1007/s00429-017-1443-x>
- Zhang, Z., Zheng, H., Liang, K., Wang, H., Kong, S., Hu, J., Wu, F., & Sun, G. (2015). Functional degeneration in dorsal and ventral attention systems in amnesic mild cognitive impairment and Alzheimer's disease: An fMRI study. *Neuroscience Letters*, 585, 160–165. <https://doi.org/10.1016/j.neulet.2014.11.050>
- Zhu, D. C., Zacks, R. T., & Slade, J. M. (2010). Brain activation during interference resolution in young and older adults: An fMRI study. *NeuroImage*, 50(2), 810–817. <https://doi.org/10.1016/j.neuroimage.2009.12.087>

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## Education

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Biopsychology, Cognition, and Neuroscience

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## Select Peer-Reviewed Publications

**Chamberlain, J. D.,** Bowman, C. R., & Dennis, N. A. (2022). Age-related differences in encoding-retrieval similarity and their relationship to false memory. *Neurobiology of Aging*. <https://doi.org/10.1016/j.neurobiolaging.2022.01.011>

Dennis, N. A., **Chamberlain, J. D.,** Carpenter, C. (2022). False memories: What neuroimaging can tell us about how we mis-remember the past. *The SAGE Handbook of Cognitive and Systems Neuroscience. Vol. 2: Cognitive Systems, Development and Applications*. (PsyArXiv preprint <https://doi.org/10.31234/osf.io/hrj8v>)

**Chamberlain, J. D.,** Sprague, B. N., Ross, L. A. (2022). Age- and time-varying associations between subjective health and episodic memory in older adults. *The Journals of Gerontology: Series B: Psychological Sciences and Social Sciences*. <https://doi.org/10.1093/geronb/gbab142>

**Chamberlain, J. D.,** Turney, I. C., Goodman, J., Hakun, J., Dennis, N. A. (2021). Fornix white matter microstructure differentially predicts false recollection rates in older and younger adults. *Neuropsychologia*. <https://doi.org/10.1016/j.neuropsychologia.2021.107848>

**Chamberlain, J. D.,** Gagnon, H., Lalwani, P., Cassady, K., Simmonite, Seidler, R, Taylor, S., Weissman, D., Park, D. C., Polk, T. A. (2021). GABA levels in ventral visual cortex decline with age and are associated with neural distinctiveness. *Neurobiology of Aging*. <https://doi.org/10.1101/743674>

Bowman, C. R., **Chamberlain, J. D.,** & Dennis, N. A. (2019). Sensory Representations Supporting Memory Specificity: Age Effects on Behavioral and Neural Discriminability. *Journal of Neuroscience*, 39(12), 2265–2275. <https://doi.org/10.1523/JNEUROSCI.2022-18.2019>

Turney, I. C.\*, **Chamberlain, J. D.\*,** Hakun, J. G., Steinkraus, A. C., Ross, L. A., Kirchoff, B. A., Dennis, N.A. (revise & resubmit). Investigating neural effects of memory training to reduce false memories in older adults: Univariate and multivariate analyses. (bioRxiv preprint <https://doi.org/10.1101/2022.11.08.515495>)

**Chamberlain, J. D.,** & Dennis, N. A. (in prep). Systematically reducing schematic information during encoding differentially impacts true and false memory at retrieval in younger and older adults.

**Chamberlain, J. D.,** Fine, C., Solt, J., Troutman, S., Visscher, K., Dennis, N. A., Ross, L. A. (in prep). Attentional neural mechanisms associated with Useful Field of View cognitive training in healthy older adults.

## Select Honors & Awards

Penn State College of Liberal Arts Superior Teaching and Research (STAR) Award 2022

Penn State Research and Graduate Studies Office (RGSO) Dissertation Award 2022

Psi Chi Teaching Assistant of the Year 2021

Psi Chi Teaching Assistant of the Year 2019