Psychometric Properties and Age-Related Effects of the Combined Attention Systems Test

by

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Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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Abstract

Attention is a multifaceted cognitive process that is important for functioning in daily life. The study of attention commonly focuses on three networks: alerting, orienting, and executive control. Despite the rich literature surrounding attention, tools designed to independently assess the networks often conflate endogenous and exogenous modes of control. A novel measure, the Combined Attention Systems Test (CAST) was developed specifically to reflect this endogenous/exogenous distinction. This study aimed to 1) assess the psychometric properties of the CAST in a sample of healthy adults, and 2) explore whether attentional networks are affected by natural aging. Results from our study suggest that the CAST is a feasible, robust, and reliable measure of the attentional networks under both modes of control. Our assessment of aging effects on attention indicates that the endogenous mode of control is particularly vulnerable to aging, as all three endogenous networks showed a decline in performance with age.

List of Abbreviations and Symbols Used

ANT	Attention Network Test
ANT-C	Attention Network Test Child
ANT-I	Attention Network Test Interaction
ANT-R	Attention Network Test-Revised
ANTI-Vea	Attention Network Test for Interactions and Vigilance, Executive and Arousal Components
CAST	Combined Attention Systems Test
CI	Confidence Interval
Δ	Delta
EEG	Electroencephalogram
ER	Error Rate
ERP	Event-Related Potential
fMRI	Functional Magnetic Resonance Imaging
RT	Reaction Time
TMS	Transcranial Magnetic Stimulation

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CHAPTER 1 INTRODUCTION

1.1 Introduction to Attention

Attention is a multifaceted cognitive process that is important for functioning in almost every aspect of our daily lives. Whether we are completing tasks or socializing with others, our ability to focus our attention on specific stimuli or activities is essential for our success and well-being. On a day-to-day basis we use attention in a variety of ways. For example, directing our attention to find an item on the grocery store shelf, scanning for pedestrians on the street, or selecting who to listen to in a busy environment. Our attentional mechanisms are continuously at work, guiding our perception, decision-making, and behaviour. In this sense, attention can be thought of as a spotlight that illuminates specific aspects of our environment, allowing us to process information more efficiently and effectively. Understanding the nuances of our attentional processes is critical for improving our cognitive abilities and enhancing our overall quality of life.

1.2 Networks of Attention

Posner and Petersen (1990) identified three isolable networks of attention, namely, alerting, orienting, and executive control. The three networks of attention have different functions as well as neural substrates and show evidence of strong individual differences and relatively low correlations between network scores (Peterson & Posner, 2012; Fan et al., 2002; Callejas et al., 2004) (but see MacLeod et al., 2010). Although relatively independent, the networks of attention work cohesively together to allow us to perform a variety of tasks in everyday life.

1.2.1 *Alerting*

Alertness can be defined as achieving and maintaining an alert state. An alert state encourages an organism's receptiveness to stimuli as well as preparation for responding to events (Peterson & Posner, 2012). Alertness can be subdivided into two intrinsic states of alertness: tonic and phasic forms. Tonic alertness is involved in sustaining attention over longer periods, and is necessary for higher-level cognitive functions (Posner, 2008; Sturm et al., 1997). The ability to maintain a state of physiological readiness for the processing of information allows humans to continue to perform during long and boring sustained vigilance tasks by maintaining an optimal level of sensitivity to external stimuli; this is how tonic alertness is typically assessed (Posner & Boies, 1971; Peterson & Posner, 2012).

Conversely (and more relevant to the present investigation), phasic alertness is a rapidly changing alert state, often in response to external stimuli. A warning signal, a stimulus such as an auditory tone that indicates to the participant they should prepare for the target, is a commonly used catalyst to initiate change from a resting state to an alert state. The rapid change in alertness following a warning signal can improve reaction time (RT) for responding to stimuli. The warning signal triggers a state of preparation for stimulus detection, which results in a faster response initiation towards the stimuli, and subsequently responding. Although a warning signal results in quicker responses, it does not result in more accurate responses (Peterson & Posner, 2012). The typical timecourse of phasic alerting follows a U-shaped function, whereby reaction time decreases when the foreperiod between the warning signal and the stimulus is lengthened, between approximately 0 and 200 ms. However, with foreperiods of 400 ms or longer, the reaction time increases as the foreperiod increases (Posner et al., 1973; McCormick et al., 2019). The process of alertness relies on norepinephrine arising in the locus coeruleus. Tonic alertness is thought to be right-lateralized while research suggests that the effects of a warning signal inducing phasic alertness may rely on left cerebral hemisphere mechanisms (Posner & Peterson, 1990; Fan et al., 2002; Peterson & Posner, 2012).

1.2.2 *Orienting*

Orienting refers to the selection or prioritization of sensory information. This network prioritizes specific information by the selection of a modality or location (Posner & Petersen, 1990). There are two brain systems believed to be related to orienting. A more dorsal system is thought to be involved with rapid strategic control, such as the process of disengaging from a location invalidly cued to re-orient to the correct location. The more ventral network is thought to be involved in responsiveness to sensory events. For instance, the ventral network is active after the unexpected presentation of a target (Corbetta & Shulman, 2002; Peterson & Posner, 2012).

1.2.3 *Executive Control*

The executive control network is responsible for resolving conflict between competing information, which allows for the filtering of distracting information, and is involved in the regulation of thoughts, emotions, and actions (Peterson & Posner, 2012). There is evidence for multiple networks of executive control that may modulate different functions. A cingulo-opercular system appears to be related to understanding task instructions and maintaining task parameters, whereas a frontoparietal system may be more active during performance feedback (Peterson & Posner, 2012).

1.3 Measures of Attention

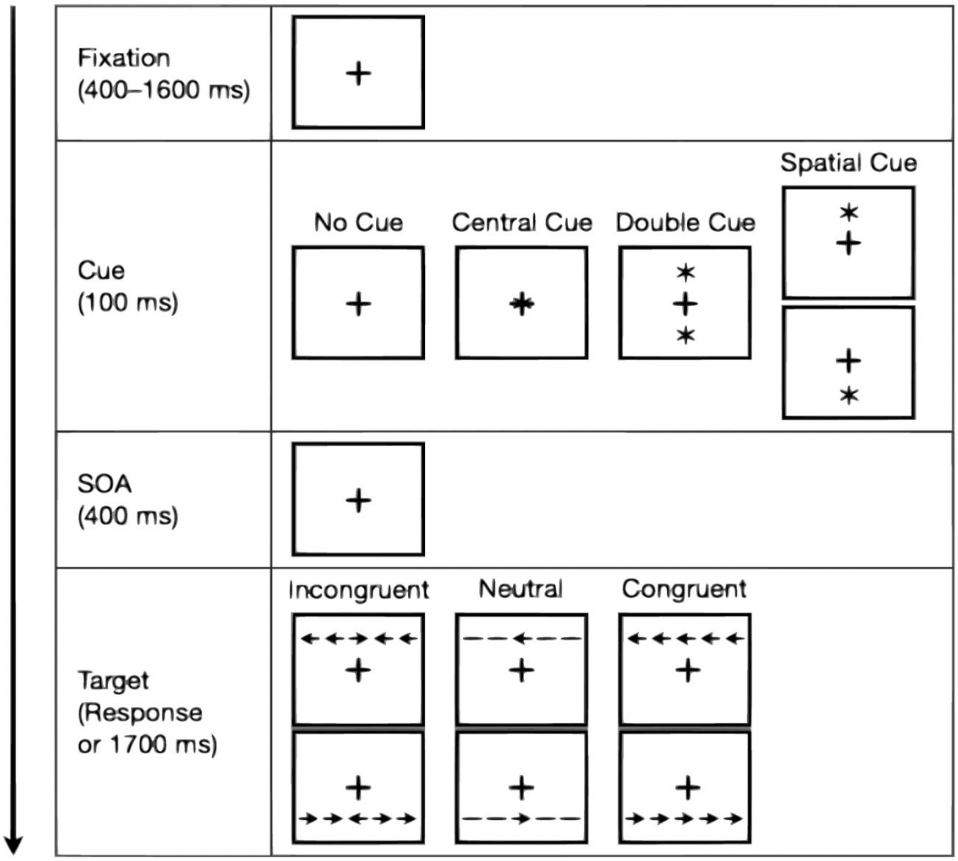
1.3.1 *Attention Network Tests*

Fan et al. (2002) designed the Attention Network Test (ANT) to measure the three networks of attention. The ANT has become a widely used cognitive neuropsychology tool for a variety of research questions (see Figure 13 in de Souza Almeida et al., 2021) and several variants have since been developed, including the child ANT (ANT-C) (Rueda et al., 2004), the ANT-Interaction (ANT-I) (Callejas et al., 2004), the lateralized ANT (Greene et al., 2008), the auditory ANT (Roberts et al., 2006), the ANT-Revised (ANT-R) (Fan et al., 2009), the AttentionTrip (Klein et al., 2017), and the Attentional Network Test for Interactions and Vigilance, Executive and Arousal Components (ANTI-Vea) (Luna et al., 2018) (for a review of the evolution of the ANT see de Souza Almeida et al., 2021).

The ANT combines Eriksen and Eriksen's flanker task (1974) and the Posner attentional cueing paradigm (Posner, 1980). Participants are asked to indicate the direction of a stimulus, a central target arrow, that points left or right. The target arrow appears either above or below a central fixation point and is accompanied by either neutral (non-directional bars), congruent (arrows pointing in the same direction as the target), or incongruent (arrows pointing in the opposite direction as the target) flankers on either side. The ANT has four cue conditions: no cue, center cue, double cue, or spatial cue. The spatial cue indicates the location of the upcoming target with 100% probability. See Figure 1 for the experimental procedure of the ANT.

Figure 1

Depiction of the Series of Events in the Experimental Procedure of the Attention Network Test (ANT)



Note. This image is reproduced from Arora et al. (2020).

A measure of alerting is calculated by subtracting the reaction time in the double cue condition from the reaction time in the no cue condition. The orienting effect is calculated by subtracting reaction time in the spatial cue condition from reaction time in the center cue condition. The central cue and the spatial cue both facilitate alerting and encourage orienting to one location, but only the spatial cue provides useful information about the upcoming target. The executive control network score is calculated by subtracting reaction time in the congruent flanker condition from reaction time in the incongruent flanker condition (flanker effect), which assesses the effect of distraction (Fan et al., 2002). See Table 1 for attentional network score formulas used in the ANT.

Table 1

Formulas for Calculating Attentional Network Scores from the ANT

Network	Calculation
Alerting	RT No Cue - RT Double Cue
Orienting	RT Central Cue - Spatial Cue Invalid
Executive Control	RT Incongruent – RT Congruent Flankers

Note. RT = reaction time

The ANT has proven to be an informative measure of attention over the last two decades that continues to be frequently used. However, Klein and Lawrence (2011) assert that the taxonomy upon which the ANT is based overlooks the fact that there are two modes of control of the allocation of limited processing resources. Not only do the ANT and many of its variants conflate endogenous (internally controlled) and exogenous (externally driven) modes of control (for detailed coverage of this distinction, see the next section), these measures are also limited by potential confounds in the alerting and orienting domains. The spatial cue used in the ANT provides reliable spatial information which engages endogenous modes of control, whereas the peripheral location of the appearing cue engages exogenous orienting (Klein et al., 2017; Lawrence, 2018). Additionally, both the alerting and orienting networks rely on the nature of the cue and therefore cannot be assessed for their interaction.

The ANT-I introduced an auditory warning signal that allows for the assessment of interaction between alerting and orienting. The ANT-I also modified the peripheral cues to be uninformative, rather than 100% informative in the original ANT (Callejas et al., 2004). The modification of the cues removes the conflation of endogenous and exogenous modes of control. However, the ANT-I only allows for measurement of a pure form of exogenous orienting, and no measurement of endogenous orienting.

1.3.2 *The Combined Attention Systems Test (CAST)*

Evolving from the ANT, its predecessors, and its variants, Lawrence (2018) developed the Combined Attention Systems Test (CAST). The CAST was designed to reflect a revised taxonomy of attention proposed by Klein and Lawrence (2011). The revised framework of attention consists of domains and modes. The domains include time, space, and task (or activity), and follow the three networks of attention identified by Posner and Petersen. The domains can be engaged through two control modes: endogenous or exogenous (Klein & Lawrence, 2011). A comparison of Posner and Peterson's (1990) original taxonomy of attentional networks and the revised taxonomy of attentional domains and modes of control by Klein and Lawrence can be seen in Table 2.

The endogenous mode of control is a top-down and more voluntary process, it is slow, effortful, and involves learning contingencies. Endogenous attention is driven by goals, intentions, or instructions, such as looking both ways before crossing the street. Conversely, the exogenous mode of control is seen as reflexive, fast, and more innate. Exogenous attention is driven by bottom-up processing, such as a salient event in the periphery catching one's attention, even when irrelevant (Jonides, 1981; Berger et al., 2005; Klein, 2009; Klein & Lawrence, 2011). The distinction between endogenous and exogenous modes of control has been proposed to represent competition between inner goals and external demands (Berger et al., 2005).

Table 2

Posner and Peterson's (1990) Original Taxonomy of Attention Networks and the Corresponding Revised Taxonomy by Klein and Lawrence (2011)

Original Taxonomy	Revised Taxonomy		
		Mode of Control	
Network	Domain	Endogenous	Exogenous
Alerting	Time	Expectancy	Capture
Orienting	Space	Arousal	Alertness
Executive Control	Task	Choice	Instinct/Habit

The CAST was designed to measure all domains and modes of Klein and Lawrence's novel framework. Whereas the ANT only produces three scores (one for each network), the CAST produces six: one for each combination of a domain of attention (3) under each mode of control (x2). Although the CAST is designed to reflect Klein and Lawrence's framework, we have chosen to maintain the original nomenclature of alerting, orienting, and executive control, for ease of comparison to previous literature.

In the CAST, participants are required to indicate the direction of a stimulus (a cartoon fish) that is amidst other congruent (facing the same direction) or incongruent (facing the opposite direction) fish. Auditory warning signals are manipulated to assess alerting, and spatial cues preceding the target are manipulated to assess orienting.

The CAST uses the flanker effect (difference in reaction time between congruent and incongruent flanker conditions) to assess endogenous executive control of attention. The spatial Stroop effect is used to assess exogenous executive control of attention.

Spatial Stroop is a version of the Simon effect and the Stroop effect. The Simon effect refers to the performance difference between trials for which the (task-irrelevant) spatial position of the response and the target correspond and do not correspond (Lu & Proctor, 1995). The Simon task requires participants to respond to non-spatial targets using the left and right keys. Participants are quicker to respond when the task-irrelevant target location matches the location of the correct response. For example, participants may be asked to respond to a green square with a left response and a red circle with a right response. Participants are typically faster to respond to the green square when it appears on the left side of the screen, compared to when it appears on the right. The Simon effect is thought to reflect the automatic activation of the spatial location of a stimulus and the subsequent interference with selecting and executing the appropriate response (Kawai et al., 2012).

In the Stroop task, participants are asked to name the ink color of a list of color words while ignoring the actual word itself. The colour and the word can be congruent (e.g., BLUE in blue ink), incongruent (e.g., RED in blue ink), or neutral (e.g., XXX in blue ink). The interference comes from automatic word reading and the effortful task of selectively attending to ink colour (Stroop, 1935). The Stroop task has been widely used to provide a simple and reliable behavioural measure for studying executive functioning. In particular, the task measures the ability to resolve conflict between competing information. The version of the Simon effect used in the CAST has been referred to as spatial Stroop because the task-relevant feature, an arrow, is itself spatial. The effect is Stroop-like in the sense that the interference is based on a shared property. In the classic Stroop effect, the property is colour, while in the spatial Stroop effect the shared property is spatial information. The conflict comes from the incongruence between the relevant spatial orientation of the target and the irrelevant spatial position.

Similar to the ANT's network calculations, the CAST assesses the function of each of the six networks by comparing reaction time and accuracy between one condition and the appropriate reference condition.

1.4 Attention and Aging

Continuous improvements in health care have increased life expectancy, and as a result the aging population is rapidly growing. According to Statistics Canada, only 7.6% of the population was aged 65 and older in 1961. While in 2021 that proportion had risen to 19%. The steady increase is expected to continue, with projections that older adults will make up 24.2% of the population by the year 2031 (Statistics Canada, 2022).

Along with an aging population comes a range of health and social issues, including cognitive decline. The decline in cognitive abilities as a result of natural aging can pose a significant threat to independence and safety, while also placing a strain on the healthcare system (Lunenfeld & Stratton, 2013). Age-related cognitive decline also affects life satisfaction and quality of life (St. John and Montgomery, 2010; Abrahamson et al., 2012).

Attention plays a crucial role in many daily activities. For instance, declines in perceptuomotor responses and temporal processing can be a result of attentional decline.

The weakening of these processes may make it more difficult to drive safely and judge speeds or distances, increasing the risk of motor vehicle accidents (Godefroy et al., 2010; Conlon & Herkes, 2008; Cantin et al., 2009; Myers et al., 2000; Okonkwo et al., 2008; Richardson & Marottoli, 2003; Sims et al., 2000). Impairments in visual spatial attention can also increase the risk of falls (Ambrose et al., 2013; Nagamatsu et al., 2009, 2013).

Although the networks of attention are known to be independent, they often work in coordination to complete activities. Thus, it is important to comprehensively explore the effects of aging on attentional processes to help us understand the underlying mechanisms of age-related cognitive decline and develop strategies to promote healthy aging. However, we have not yet elucidated the full impact of aging, as previous research in the field of attention and aging is inconclusive and inconsistent.

1.4.1 ***Aging and Alerting***

Results of studies looking at phasic alertness and the impacts of aging vary. Early studies suggest that alerting processes are preserved with age (Rabbitt, 1984; Talland & Cairnie, 1961). Tales et al. (2002a) found no effect of aging on phasic alertness when comparing response trials with and without the presence of a warning signal. In Tale's study there was a fixed stimulus onset asynchrony (SOA), which is the time between the presentation of the warning signal and the subsequent presentation of a target. Conversely, Festa-Martino et al. (2004) varied the SOA in their study and reported smaller alerting effects for older adults compared to younger adults. Other behavioural studies have concluded that the efficiency of the alerting network declines with age, even when reaction time is corrected for age-related slowing (Gamboz et al., 2010; Jennings et al., 2007; Mahoney et al., 2010). However, another study reported that the alerting network was actually enhanced by aging (Fernandez-Duque et al., 2006).

More recently, Williams et al. (2016) paired behavioural data from the Attention Network Test with measures of brain activity using an electroencephalogram (EEG). Initial results suggested an age-related enhancement of orienting and a decline in alerting and executive control. However, further analysis that involved correcting for age-related slowing resulted in no differences in the orienting or executive control networks, but a significant decline in the alerting network (Williams et al., 2016). Considering the neural data, event-related potential (ERP) components related to executive control showed age-related differences, but similar modulation was found in ERP markers for the alerting network between young and old adults. They suggested that differences in behavioural data may stem from an interaction between alerting and executive control networks based on age-different response strategies and prioritization (speed versus accuracy), rather than an actual deficit in the alerting network (Williams et al., 2016).

Erel et al. (2020) reported that differences in the alerting network may depend on the modality of the alerting cue; in their study, older adults were able to use an auditory warning signal as efficiently as younger adults, but a visual warning signal was less beneficial to the older group (Erel et al., 2020).

1.4.2 *Aging and Orienting*

The orienting network appears to have somewhat consistent findings, which suggest that the efficiency of the orienting network is preserved with age (Folk & Hoyer, 1992; Fernandez-Duque et al., 2006; Gamboz et al., 2010; Jennings et al., 2007; Williams et al., 2016). Although, like the other networks, there are conflicting findings in the literature and different conditions elicit different results (see Erel & Levy, 2016 for a comprehensive review of orienting and aging). One issue with studying orienting and aging is that orienting is not a singular process. Seminal work by Posner suggests there are at least three components of attentional orienting: disengaging, shifting, and engaging attention (Posner, 1988; Posner & Peterson, 1990). Variations in the nature of the cues employed, the mode of control (endogenous or exogenous), type of attending (overt or covert), orienting benefits or re-orienting costs, SOAs, the social aspect of cues, etc., may all contribute to inconsistencies in orienting and aging effects (Erel & Levy, 2016).

Overt orienting is accompanied by eye or head movements whereas covert attending is without accompanying movement. Overt and covert attending may be differentially affected by aging (Erel & Levy, 2016). Kingstone et al. (2002) found that older adults showed deficits in all forms of overt orienting, but an absence of aging effects on both endogenous and exogenous covert orienting. Other research on covert orienting suggests that exogenously engaged shifts of spatial attention are preserved with age, whereas endogenous orienting is vulnerable to decline. Consequently, older adults may have less efficient endogenous but not exogenous orienting (Folk &Hoyer, 1992; Brodeur & Enns, 1997; Tales et al., 2002b; Waszak et al., 2010). Although, some researchers have not found this dissociation (Slessor et al., 2014). Juola et al. (2000) found that older adults had difficulty with inhibiting orienting to abrupt onset cues and disengaging attention from invalid cues compared to younger adults, suggesting that there may be an interaction between orienting and executive networks under exogenous control.

1.4.3 *Aging and Executive Control*

There is evidence that aging affects the executive control network. Several top-down cognitive processes work together to allow us to selectively focus our attention, maintain and integrate relevant information, and filter irrelevant information to achieve current goals throughout our daily lives (West, 1999). Previous research using both behavioural and neuroimaging data has suggested that top-down attentional control may deteriorate with natural aging (Lustig & Jantz, 2015).

The literature on aging and top-down processes largely surrounds inhibitory control and memory processes (West & Baylis, 1998; West, 1999; Milham et al., 2002; Gazzaley & D'esposito, 2007; Reuter-Lorenz & Park, 2010; Lustig & Jantz, 2015). Older adults are worse at inhibiting irrelevant information than younger adults (Borella et al., 2008; Gazzaley et al., 2005; Hasher and Zacks, 1988; Zanto et al., 2010; Mahoney et al., 2010; Waszak et al., 2010). For instance, Milham et al. (2002) found increased interference in the Stroop task in older adults as measured by reaction time and accuracy. The researchers also used functional magnetic resonance imaging (fMRI) and found activation in areas that were suggestive of impairments in inhibiting task-irrelevant information (Milham et al., 2002). Gazzaley & D'esposito (2007) reported converging evidence from fMRI, EEG, and transcranial magnetic stimulation (TMS), exhibiting that older adults could not suppress neural activity with distracting information. Although other studies have found no effects of age on conflict resolution (Kramer et al., 1994; Fernandez-Duque & Black, 2006). Jennings et al. (2007) and Gamboz et al. (2010) found a significant effect of age on the executive control network when using raw data, however, these effects were not significant following transformation.

Kawai et al. (2012) used the flanker task and the Simon task to study aging effects on inhibitory processes. The researchers found greater Simon effects for older adults than for younger adults. However, they reported no differences in the flanker task. They concluded that older adults have difficulties in response inhibition, but not in stimulus interference suppression (Kawai et al., 2012). More recently, Servant and Evans (2020) found increased reaction time and larger flanker congruency effects in older adults when the spacing between targets and flankers was small. Kubo-Kawai and Kawai (2010) also found a greater magnitude Simon effect for older adults compared to younger adults.

Some researchers argue that factors such as stimulus characteristics, aging differences in perceptual load, processing capacity, and inhibitory processes can account for age-related effects in conflict tasks (Kramer & Kray, 2006). D'Aloisio and Klein (1990) used the flanker paradigm to study aging and suggested that age-related differences may be a result of differences in task prioritization rather than differences in conflict resolution ability. Older adults were slower to respond, however, when accuracy was accounted for there were no differences in interference. It is possible that younger adults focus on speed and older adults prioritize accuracy (D'Aloisio & Klein, 1990).

1.5 Present Research

The CAST has been developed to provide a more detailed and comprehensive view of attentional functioning compared to previous assessment tools. The CAST considers all domains and modes of control as well as their interactions. Although it provides a promising measure of attention's components, the psychometric properties of the CAST have yet to be established across the lifespan. Previously, the psychometric properties have been assessed with middle-to-older children (age 8-16) and young adults (18-24), wherein Lawrence (2018) demonstrated that the six scores produced were robust and reliable. No research to date has included an older population in assessment using the CAST. Thus, the primary goal of our research was to assess healthy young to older adults with the CAST and evaluate the reliability of the measure as well as the feasibility of using the CAST for data collection.Validating the CAST would open the door for an effective and more exhaustive measure of attention to be available for future research.

If the CAST were found to produce robust measures of attention, our secondary goal was to explore the effects of aging on attentional processes. Attention in older adults might be expected to diminish with cognitive aging, as mental processes slow (Salthouse, 1996), concentration and attention may not be as well sustained. Although there is evidence to support changes in attention with age, the literature is inconsistent regarding the specific aspects and degree to which attentional processes are affected. We hope that the CAST may be able to provide additional evidence, as the CAST de-confounds the modes of attention across the domains.

Research with a sample from the middle to older adult population is essential to assess the generalizability of the CAST as a psychometric test and to further assess changes in attentional processes across the lifespan.

1.5.1 ***Objective One***

Our first objective was to examine the feasibility of the CAST for data collection and its psychometric properties. For feasibility we focused on measures of compliance/usability (i.e., how many participants can comply with the instructions and complete the entire testing procedure). To assess the psychometric properties of the test, we explored whether the CAST would produce robust and reliable measures of the six networks of attention, that are implied by the three domains of attention and two modes of control. Test-retest reliability was assessed by using multiple testing sessions, to evaluate if results were consistent over time.

1.5.2 *Objective Two*

Our second objective was to explore age-related changes in attentional processes. By comparing network scores between younger and older adults, we hoped to explore how attention may change as a result of normal aging. We believe that endogenous and exogenous modes of control may be differentially affected by aging, with the endogenous mode being more vulnerable to age-related decline. Based on this assumption, and previous research on aging and attention networks, we expect to find differences in endogenously controlled networks. Specifically, we expect to find reduced network efficacy in the endogenous alerting, orienting, and executive control networks. We also believe that the exogenous executive control network may show reduced network efficacy, in line with previous research on aging and the Simon effect. On the other hand, we expect the exogenous alerting and orienting networks will be relatively preserved with age.

CHAPTER 2 METHODS

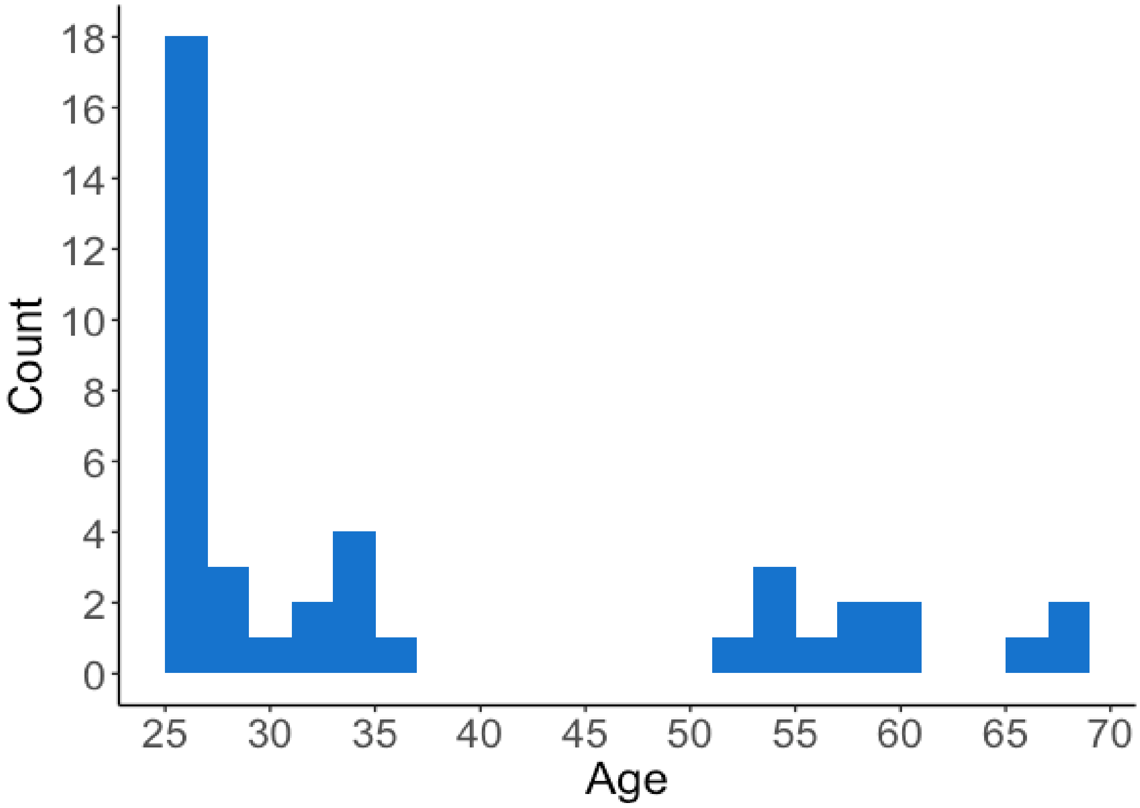
This study was preregistered at the Open Science Forum prior to the collection of any data. The preregistration includes a description of the methodology, hypotheses, and analysis plan for the primary goal of the study (assessing the psychometric properties of the CAST). The preregistration can be viewed at: https://osf.io/9qkg2. Inclusion criteria for the study were normal or corrected-to-normal vision and hearing, and no physical problems that would interfere with participation (e.g., limb injury). Participants who self-reported diagnoses of neurological disorders (e.g., Parkinson's disease, dementia) or any cognitive deficits affecting attention (e.g., ADHD, short-term memory deficits) were excluded from participation. All study procedures were approved by the Dalhousie Research Ethics Board before study onset.

2.1 Participants

We recruited 42 healthy adults (age 25+) for this study from Dalhousie University and the community of Halifax, Nova Scotia, Canada. One participant was removed for failing to complete the task. After exclusions, the participants consisted of 23 females, 17 males, and one person who identified as non-binary between the ages of 25 and 68 (*Mdn* = 29). See Figure 2 for a histogram illustrating the distribution of participants' ages. Thirty-eight participants reported being right-handed, three were ambidextrous, and zero were left-handed. In lieu of guaranteed compensation, all participants were entered in a draw to win one of three $150 honoraria.

Figure 2

Histogram Showing the Distribution of Participants' Ages



2.2 Materials

The CAST was coded in the Python programming language and run on an Apple MacBook Air computer (13.3-inch display, resolution of 2560 x 1600). Participants sat at a distance of approximately 100 cm from the screen. To complete the task, an Xbox360 gamepad was used. Participants made responses on the gamepad by pressing on the triggers using their left and right index fingers. For a response to be counted for feedback, participants had to meet a threshold of at least half the possible trigger depression level. Otherwise, the response would be considered an error if the 1200 ms response window elapsed, without another response being made that met the threshold. The gamepad was chosen because it can record the full-time course of the response, including partial responses that do not meet the threshold.

2.2.1 ***The Combined Attention Systems Test (CAST)***

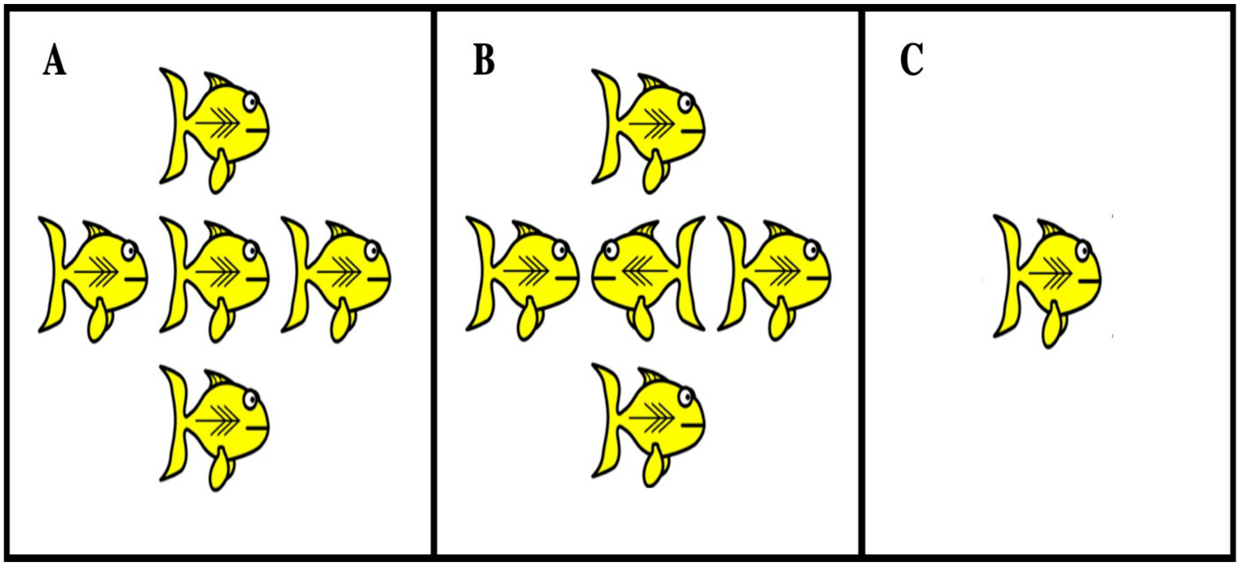
Participation in the CAST involved two sessions on two separate days (usually within one week of each other). Each session required completing each subtest (endogenous, exogenous) and then repeating each. The order of administration of the endogenous and exogenous subtests of the CAST were counterbalanced across participants, as well as within and between participant sessions (e.g., Session 1: Endo, Exo, Endo, Exo; Session 2: Exo, Endo, Exo, Endo).

The main task of the CAST consists of the original flanker task from the ANT, in which participants must indicate the direction of a stimulus that is either alone or embedded amongst distractors. Rather than implementing the arrows used in the ANT, the CAST employs the colourful fish of the ANT-C, making the task child friendly and more engaging for all ages. Participants were informed that the target fish would either be alone or surrounded by friends. The distractor fish appeared both above/below and to the left/right of the target fish. A measure of endogenous executive attention comes from manipulating the school of flanking fish to be either congruent or incongruent with the target fish (the flanker effect). The CAST presents the array of fish to the left or right of fixation (counter to the ANT which presented the target above or below). The lateralization of the targets and the responses made using left and right fingers on the gamepad make it possible to observe spatial Stroop, which provides a measure of exogenous executive attention. An example of the stimulus in the CAST can be seen in Figure 3.

Figure 3

The Array of Cartoon Fish Stimuli Used in Both Subtests of the CAST.

A) Congruent Flankers; B) Incongruent Flankers; C No Flankers



To begin the task, participants were first presented with general instructions applicable to both subtests, as well as endogenous or exogenous task-specific instructions. The specific instructions are repeated to participants at the onset of each subtest and participants were given a chance to practice the task each time. Throughout the task, participants were provided with breaks between subtests, as well as after every 24 trials. Breaks were self-terminated by the participant.

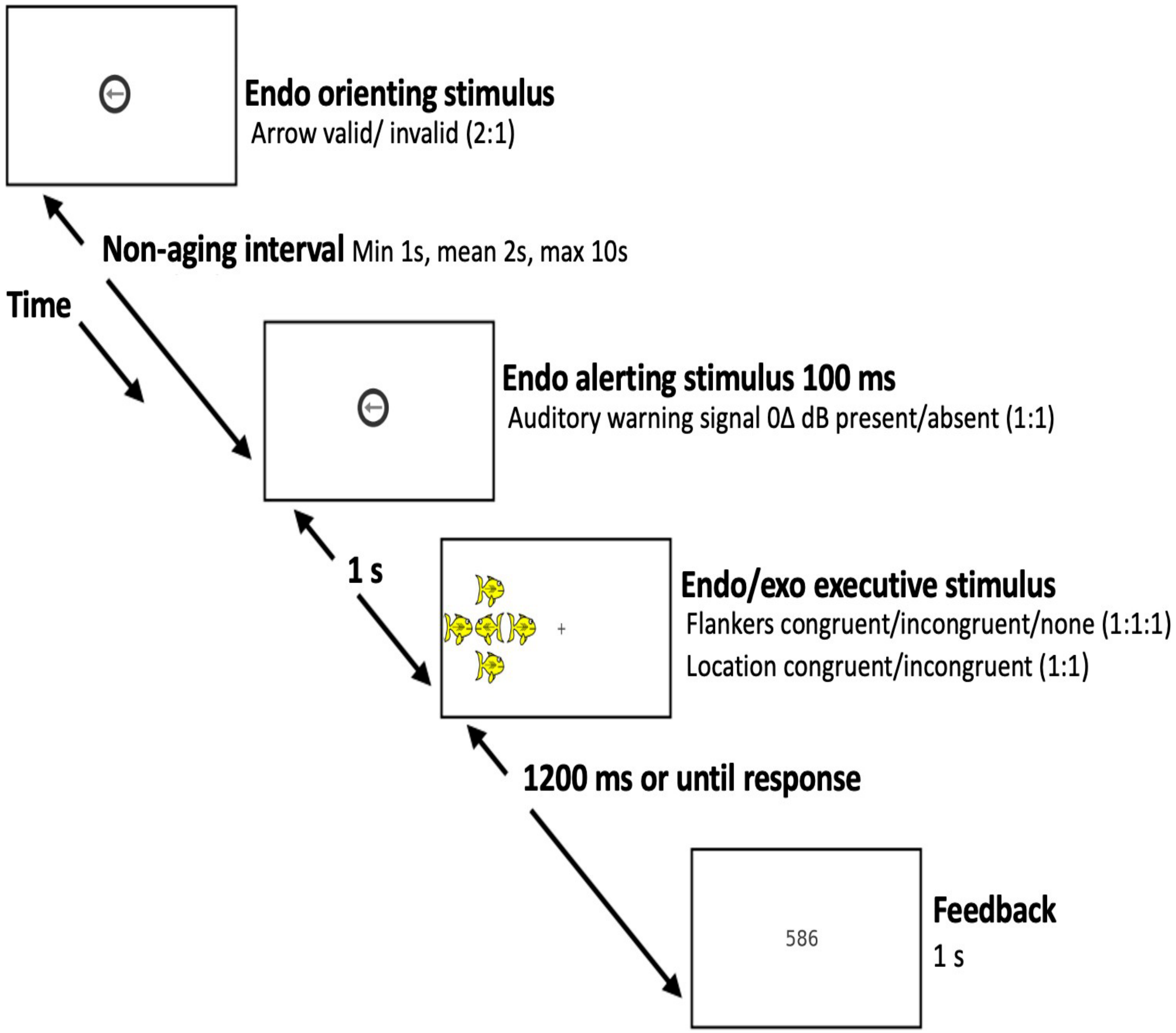
One full session of the CAST consists of 576 trials including 96 practice trials (24 practice trials before each of the 4 subtest blocks). One speculation regarding inconsistent behavioural findings of age differences in attentional network scores, is that the scores may be affected by the number of trials used in studies. Previous research has shown that the reliability of the size of the network effects derived from the ANT are improved with larger data sets (Ishigami & Klein, 2010; Ishigami & Klein, 2011). Previous studies that implemented a small number of experimental tasks may not have been accurate reflections of aging effects (Williams et al., 2016).

2.2.2 *The CAST: Endogenous Subtest*

We included two blocks of the endogenous subtest. Each block was approximately 15 minutes and consisted of 144 trials. Every trial begins with a variable duration fixation arrow (mean 2 s). The fixation arrow is also used as the orienting cue and points to the left or right, predicting with 66% accuracy the location of the subsequent target. The target appears one second after the cue. Participants are informed that the cue is not always accurate but is accurate “more often than not”. A measure of endogenous spatial attention comes from the comparison of validly and invalidly cued trials. At the end of the fixation interval, 50% of trials include an isointense warning signal that consists of a switch from the presentation of diotic (mono/ same sound presented to each ear) white noise to dichotic (stereo, different sound in each ear) white noise for 100 ms, with no change in volume (0Δ dB). The fixation arrow is surrounded by a circle on trials with a warning signal, and a square on trials without a warning signal, to account for the influence of uncertainty. A measure of endogenous alerting comes from the comparison of trials with and without a warning signal. See Figure 4 for a depiction of the series of events in the endogenous subtest of the CAST.

Figure 4

Series of Events in the Endogenous Subtest of the CAST.

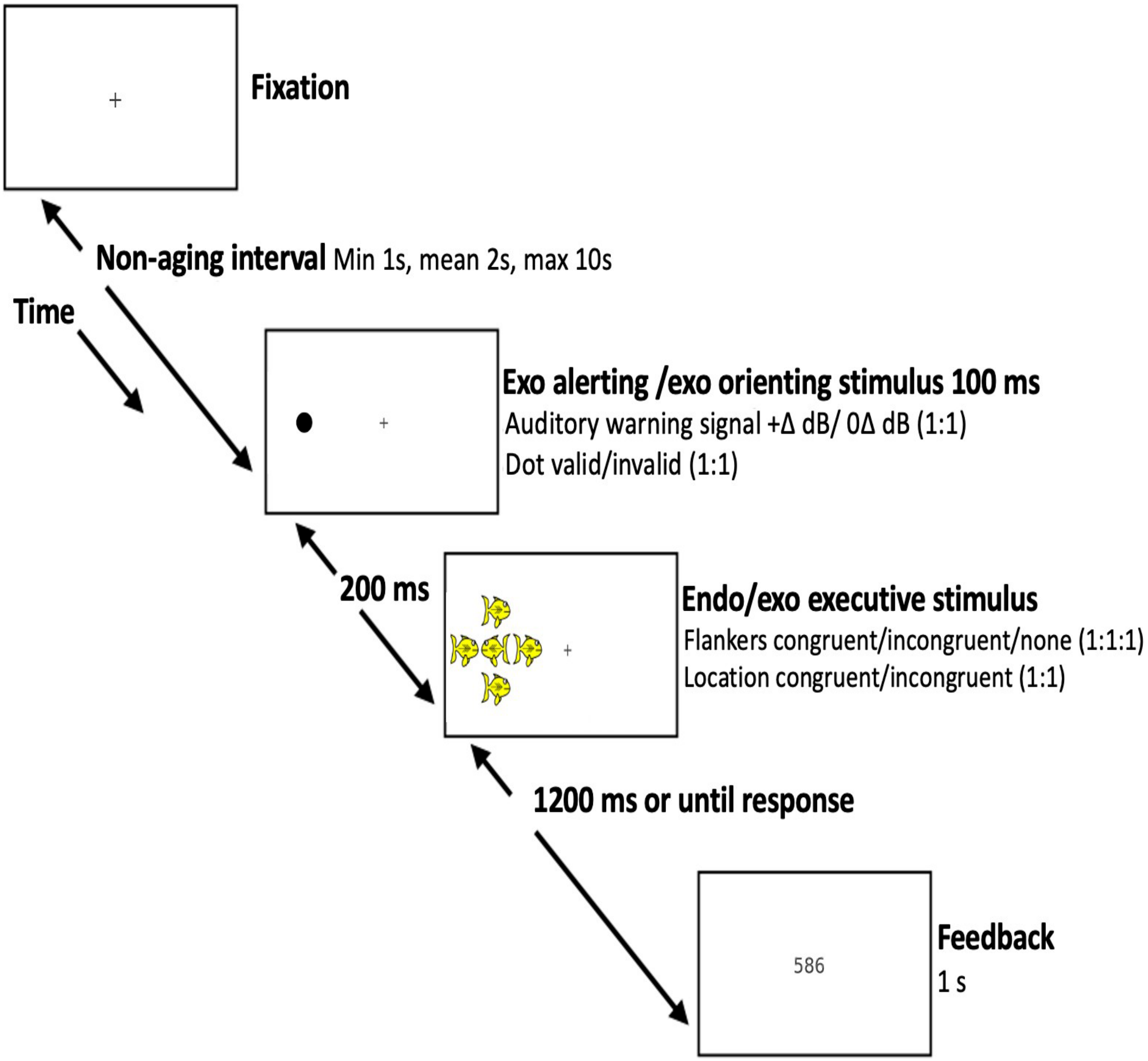


2.2.3 *The CAST: Exogenous Subtest*

We included two blocks of the exogenous subtest. One block takes approximately 7 minutes to complete and consists of 96 trials. The subtest begins with the presentation of a black fixation cross for a variable duration (mean 2 s). Following fixation, a 100ms cue (a black dot) is presented randomly to the left or right of fixation and is not reliably predictive of the upcoming location of the target. The target appears 200 ms after the cue. A measure of exogenous spatial attention comes from a comparison between trials that are validly cued (the target appears at the same location as the cue) and trials that are invalidly cued (the target appears at the location opposite the cue). Throughout the task, the participant is presented with continuous white noise. When the cue is presented, the diotic white noise simultaneously switches to dichotic white noise for 100 ms, that is either with an increase in volume intensity (+Δ dB, 50% of trials) or without any change in volume (0Δ dB, 50% of trials). A measure of exogenous alerting comes from comparing warning signal trials that are with and without an increase in volume. See Figure 5 for a depiction of the series of events in the endogenous subtest of the CAST.

Figure 5

Series of Events in the Exogenous Subtest of the CAST.



All trials in the CAST begin with a random fixation interval, at least one second long and no longer than 10 seconds, to minimize temporal information. Reaction time and error rate are recorded. When participants make a response their reaction time is presented on the screen before proceeding to the next trial. If a participant does not respond within 1200 ms “Miss!” is presented on the screen and the trial ends. If the participant makes an anticipatory response, before the appearance of a target, “Too soon!” is presented on the screen and the trial ends. During the practice blocks only, the feedback “Incorrect response! Please pull the trigger on the same side as the middle fish is facing” is given to participants. All feedback is presented for one second.

2.3 Procedure

Participants had the option of either attending the lab on the Dalhousie campus, or of having the study brought to their residence to complete the sessions. We hoped that providing the option of bringing the task directly to the participants would make the study more accessible and encourage people to volunteer. Particularly, we thought it may increase the recruitment of elderly participants. To bring the CAST to participants we asked that they have a quiet and comfortable location with a table and chair for us to set up our apparatus. Twenty participants completed the task in an off-campus space. The research study always began with informed consent, followed by a brief demographic questionnaire. Next, participants completed the CAST, including both endogenous and exogenous subtests twice. Following a break of at least 24 hours, participants then completed the full CAST again, in the opposite order of their first session.

2.4 Statistical Analyses

All statistical analyses were conducted using the open-source software package R Studio. Although the entire time course of each response was recorded, we only looked at gamepad responses that met the criterion for response feedback. Data was preprocessed and we excluded trials for which participants did not respond before the trial timed out, trials for which participants did not meet the threshold for response, trials for which participants pressed both triggers at once on the gamepad, and trials with very quick response times indicative of anticipatory responses (which do not reflect accurate processing time). Reaction time analyses only included trials in which participants made the correct response, while accuracy analyses include all non-excluded responses.

Attentional network scores were calculated for each combination of network (3) under each mode of control (x2). Both reaction time and error rate scores were computed. The six network scores were calculated as illustrated in Table 3:

Table 3

Formulas for Calculating Attentional Network Scores in the CAST

Network	Calculation
Endogenous Alerting	Warning signal absent – warning signal present (0Δ dB)
Endogenous Orienting	Invalidly cued trials – validly cued trials
Endogenous Executive	Incongruent flanker trials – congruent flanker trials
Exogenous Alerting	Warning signal present: (0Δ dB) – (+Δ dB)
Exogenous Orienting	Invalidly cued trials – validly cued trials
Exogenous Executive	Incongruent target location – congruent target location

Note. Endogenous executive = the flanker effect; exogenous executive = spatial Stroop

For our first objective, we ran mixed effects models for reaction time and accuracy, to look at the effect of session on each of the network scores. Pearson's correlations were used to assess test-retest reliability between session one and session two. For our second objective, exploring age-related effects, we split the dataset into younger (age 25-44) and older (age 45+) adult groups based on the distribution of ages in our overall sample. Linear mixed effects models were run separately for reaction time and accuracy, to look at the effect of age on network scores. We considered $p < .05$ as statistically significant for our analyses.

CHAPTER 3 RESULTS

3.1 Data Exclusions

We first removed all trials on which participants either failed to make a response before the trial timed out or did not meet the response threshold (.58% of trials), trials where participants pressed both triggers at once (.24%), and trials for which the reaction time was faster than 300 ms (.32%). Among the remaining, non-excluded trials, errors made up 5.11% of all responses. Analyses of reaction time were based only on trials with correct responses. Trials with response competition (meaning participants pressed the incorrect trigger first but did not meet the threshold before switching to the correct response) made up 2.7% of all responses. Older adults are generally slower than younger adults when responding to stimuli. Consequently, and based on the distribution of reaction times, we chose a 300 ms value for the fast reaction time cut-off, rather than the 200 ms cut-off used in the children and young adult samples from Lawrence (2018).

3.2 Objective One: Psychometric Assessment

Our first objective was to examine the feasibility of the CAST for data collection and its psychometric properties. To examine the feasibility, we focused on measures of compliance/usability (i.e., how many participants were able to comply with the instructions and complete the entire testing procedure). From our sample of 42 participants, only one participant failed to complete both sessions of the CAST. However, the participant was removed from the study for reasons unrelated to the methodology and therefore was not included in our assessment of objective one. Based on the remaining sample, we had 100% compliance with the task.

We explored whether the CAST would produce robust and reliable measures of the six networks of attention, that are implied by three domains of attention and two modes of control. Although we analyzed and report both accuracy and reaction time, we will focus primarily on reaction time as the ANT literature focuses almost exclusively on reaction time. However, accuracy levels are considered and discussed when pertinent. Considering both metrics allows for a more complete picture, due to the possibility of participants trading off speed for accuracy.

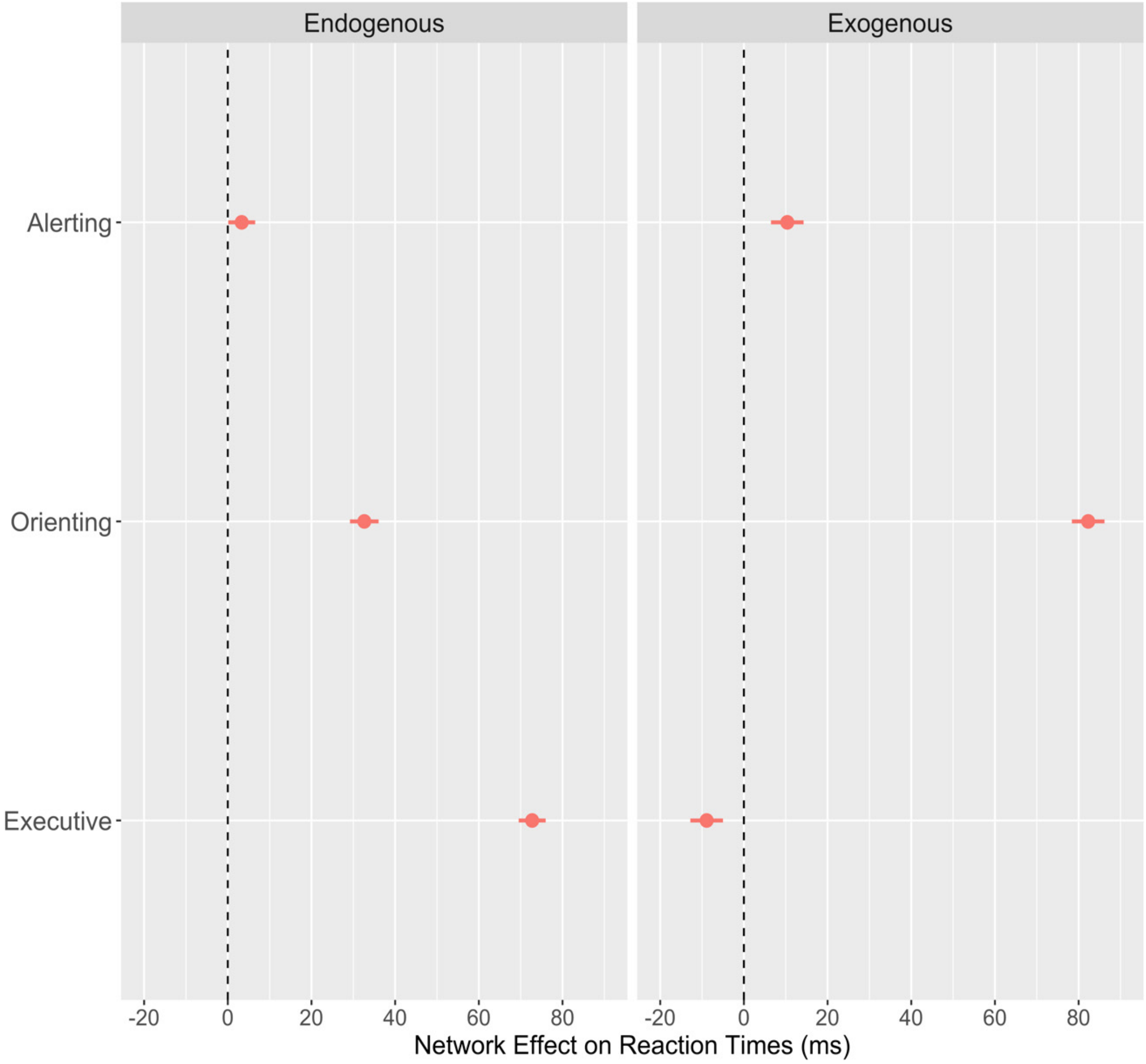
3.2.1 *Psychometrics: Overall Network Scores*

Considering reaction time, the overall network scores (i.e., across both sessions) in the endogenous subtest were: alerting = 3.32 ms, 95% CI [.10, 6.53]; orienting = 32.62 ms; [29.20, 36.05]); executive control (flanker effect) = 72.75 ms [69.52, 75.97]. In the exogenous subtest, the scores were: alerting = 10.37 ms [6.48,14.27]; orienting = 82.29 ms [78.39, 86.18]; executive control (spatial Stroop) = -8.90 ms [-12.79, -5.00].

For accuracy (% errors) the overall network scores in the endogenous subtest were: alerting = -.30%, 95% CI = [-.85, .24]; orienting = 1.76% [1.03, 2.49]); executive control (flanker effect) = 6.07%, [4.34, 7.79]. In the exogenous subtest the scores were: alerting = -.17% [-1.0, 0.67]; orienting = 3.09%, [1.99, 4.18]); executive control (spatial Stroop) = 1.54 % [.64, 2.44]. See Figures 6 (reaction time) and 7 (% errors) for the overall network scores across sessions.

Figure 6

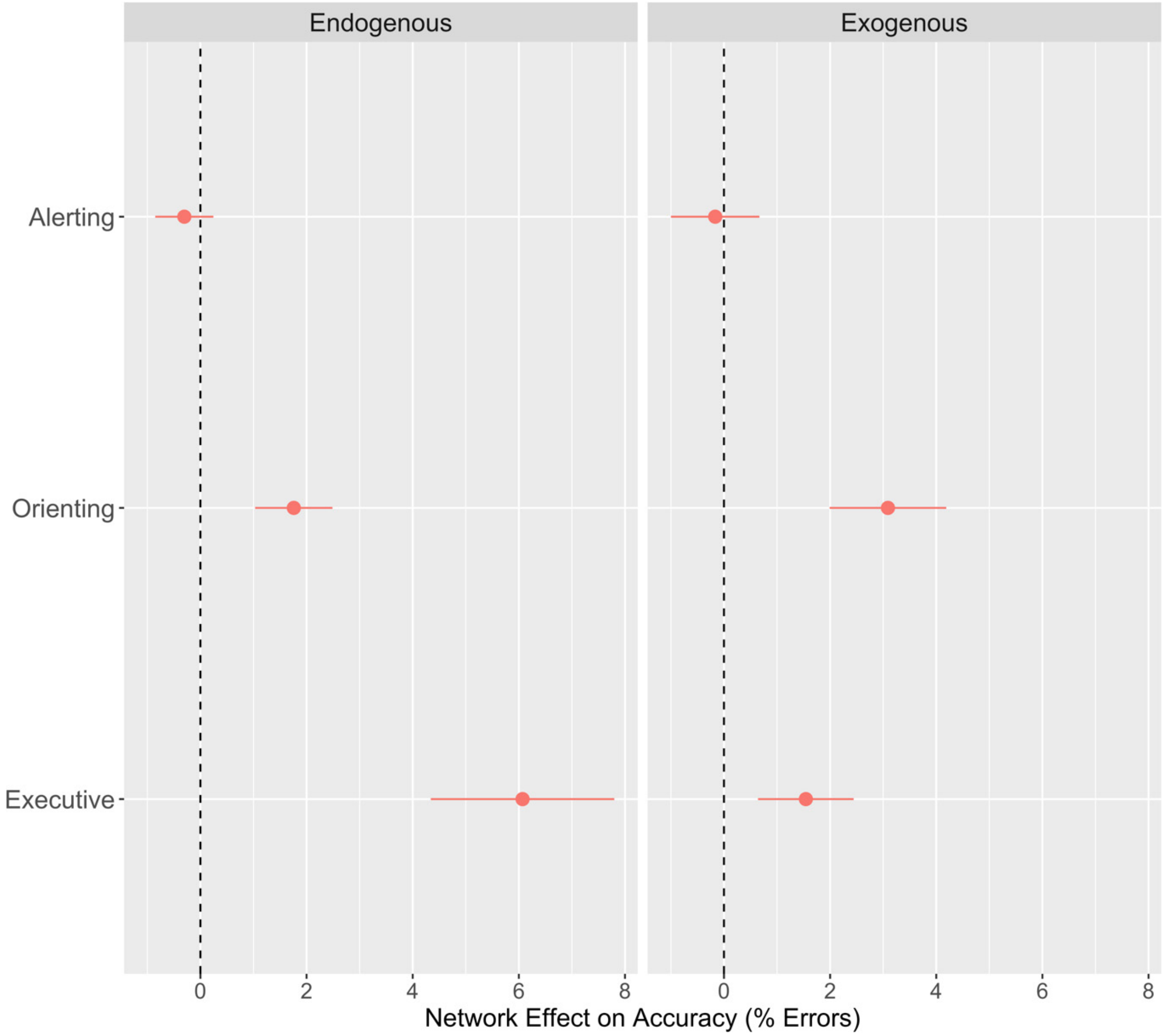
Overall Network Effects (RT) in the Endogenous and Exogenous Subtests of the CAST



Note. This plot displays the reaction time (ms) network scores collapsed across sessions. Each point represents the mean reaction time for a given network and error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in RT.

Figure 7

Overall Network Effects (% Errors) in the Endogenous and Exogenous Subtests of the CAST



Note. This plot displays the overall network scores collapsed across sessions in accuracy (% errors). Each point represents the mean reaction time for a given network and error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in accuracy.

The average reaction time and accuracy for each condition that is used in the alerting, orienting, and executive control network scores are reported in Tables 4 through 9.

Table 4

Average Reaction Time (ms) in Each Alerting Condition Between Subtests

Alerting Condition	*M* (SE)	
	Signal Absent/ Isointense	Signal Present/ Intense
Endogenous	674 (8.97)	674 (8.97)
Exogenous	633 (6.78)	622 (6.78)

Table 5

Average Reaction Time (ms) in Each Orienting Condition Between Subtests

Orienting Condition	*M* (SE)	
	Invalid	Valid
Endogenous	690 (9.01)	659 (8.94)
Exogenous	671 (6.78)	584 (6.77)

Table 6

Average Reaction Time (ms) in Each Executive Control Condition Between Subtests

Executive Control Condition	*M* (SE)	
	Incongruent	Congruent
Endogenous (Flankers)	712 (8.98)	636 (8.97)
Exogenous (Spatial Stroop)	623 (6.78)	632 (6.78)

Note. The values in this table represent the estimated marginal means from our generalized mixed model which did not include the no-flanker condition, therefore the no-distractor column has not been estimated.

Table 7

Average Accuracy (% Correct) in Each Alerting Condition Between Subtests

Alerting Condition	*M* (SE)	
	Signal Absent / Isointense	Signal Present / Intense
Endogenous	97 (.43)	96 (.47)
Exogenous	94 (.63)	94 (.64)

Table 8

Average Accuracy (% Correct) in Each Orienting Condition Between Subtests

Orienting Condition	*M* (SE)	
	Invalid	Valid
Endogenous	95 (.55)	97 (.35)
Exogenous	93 (.76)	96 (.52)

Table 9

Average Accuracy (% Correct) in Each Executive Control Condition Between Subtests

Executive Control Condition	*M* (SE)	
	Incongruent	Congruent
Endogenous (Flankers)	93 (.76)	99 (.14)
Exogenous (Spatial Stroop)	94 (.69)	95 (.59)

3.2.2 *Psychometrics: Robustness*

Average network scores and corresponding standard errors (SE) of all networks in each subtest (endogenous, exogenous) and between the two sessions are reported for both reaction time and accuracy in Tables 10 through 13. Alerting network scores were found to be atypically small in both subtests and across sessions.

Table 10

Average Network Scores (RT) Between Sessions of the Endogenous Subtest

	M (SE)	
Endogenous Control	Session One	Session Two
Alerting	2.39 (2.32)	4.25 (2.31)
Orienting	34.67 (2.47)	30.58 (2.46)
Executive (Flankers)	72.35 (2.32)	73.14 (2.32)

Table 11

Average Network Scores (RT) Between Sessions of the Exogenous Subtest

	M (SE)	
Exogenous Control	Session One	Session Two
Alerting	12.06 (2.81)	8.69 (2.81)
Orienting	79.62 (2.81)	84.96 (2.81)
Executive (Spatial Stroop)	-10.37 (2.81)	-7.42 (2.81)

Note. Although there is variation in the standard errors calculated, the differences are small and therefore all rounded to 2.81.

Table 12

Average Network Scores (% Errors) Between Sessions of the Endogenous Subtest

	M (*SE*)	
Endogenous Network	Session One	Session Two
Alerting	- .40 (.42)	-.21(.37)
Orienting	1.96 (.51)	1.56 (.46)
Executive (Flankers)	6.05 (.89)	6.09 (1.11)

Table 13

Average Network Scores (% Errors) Between Sessions of the Exogenous Subtest

	M (*SE*)	
Exogenous Network	Session One	Session Two
Alerting	0.24 (.61)	-.57 (.60)
Orienting	2.27 (0.66)	3.91 (0.78)
Executive (spatial Stroop)	1.51 (.63)	1.57 (.62)

Linear mixed effects models were run separately for reaction time and accuracy, to look at the effect of session on network scores. The reaction time model included alerting, orienting, and executive control as predictors and included random intercepts and slopes for the variable "session" for each participant. For accuracy we ran a logistic generalized mixed effects model that included alerting, orienting, and executive control as predictors and included random intercepts and slopes for the variable "session" for each participant.

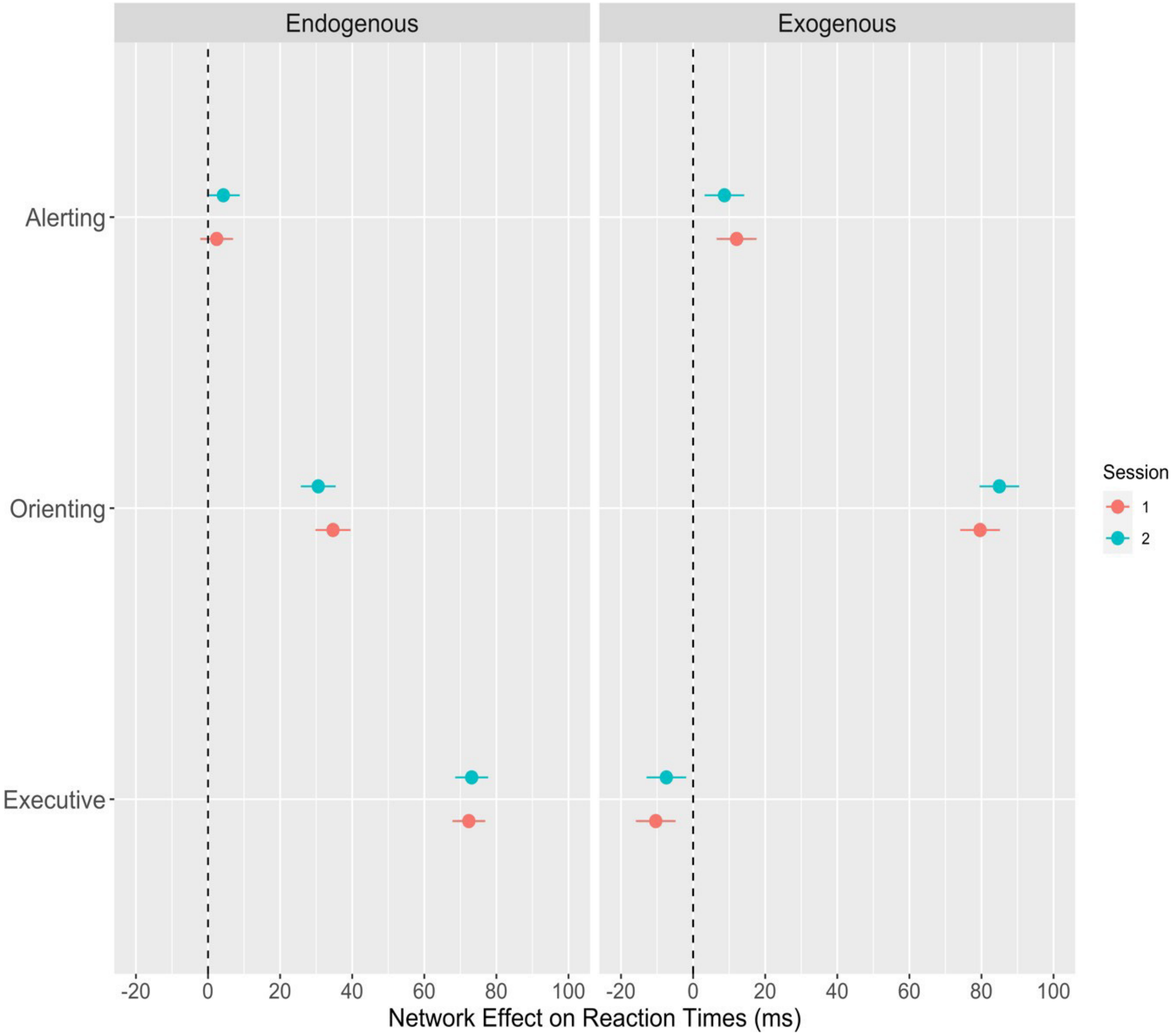
For the endogenous subtest, the main effect of session was significant ($B = 27.45$, $SE = 5.53$, $t = 4.96$, $p < .001$), indicating that reaction time differed between sessions. On average, participants were approximately 27 ms faster in their second session compared to the first, as would be expected due to practice effects and becoming familiar with the task. Among the predictors, alerting ($B = -3.32$, $SE = 1.64$, $t = -2.02$, $p = .043$), orienting ($B = -32.62$, $SE = 1.75$, $t = -18.67$, $p < .001$), and executive control (flanker effect) ($B = -72.75$, $SE = 1.64$, $t = -44.25$, $p < .001$) had significant main effects on reaction time. None of the interaction terms were significant (all $p > .05$).

For the exogenous subtest, the main effect of session was significant ($B = 27.74$, $SE = 6.17$, $t = 4.49$, $p < .001$). On average, participants were approximately 28 ms faster in their second session compared to their first. Among the predictors, alerting ($B = -10.37$, $SE = 1.99$, $t = -5.22$, $p < .001$), orienting ($B = -82.29$, $SE = 1.99$, $t = -41.41$, $p < .001$), and executive control (spatial Stroop) ($B = -90$, $SE = 1.99$, $t = 4.48$, $p < .001$) had significant main effects on reaction time. None of the interaction terms were found to be significant (all $p > .05$).

While all network measured by the CAST produced scores significantly different from zero (as measured by reaction time), the alerting scores are relatively small, and the exogenous executive control score is unexpectedly negative. However, the endogenous orienting and executive control network, as well as the exogenous orienting network, are significantly robust and consistent between sessions. See Figure 8 for network scores (reaction time) between sessions in the endogenous and exogenous subtests.

Figure 8

Network Scores in the Endogenous and Exogenous Subtests (RT) Between Sessions



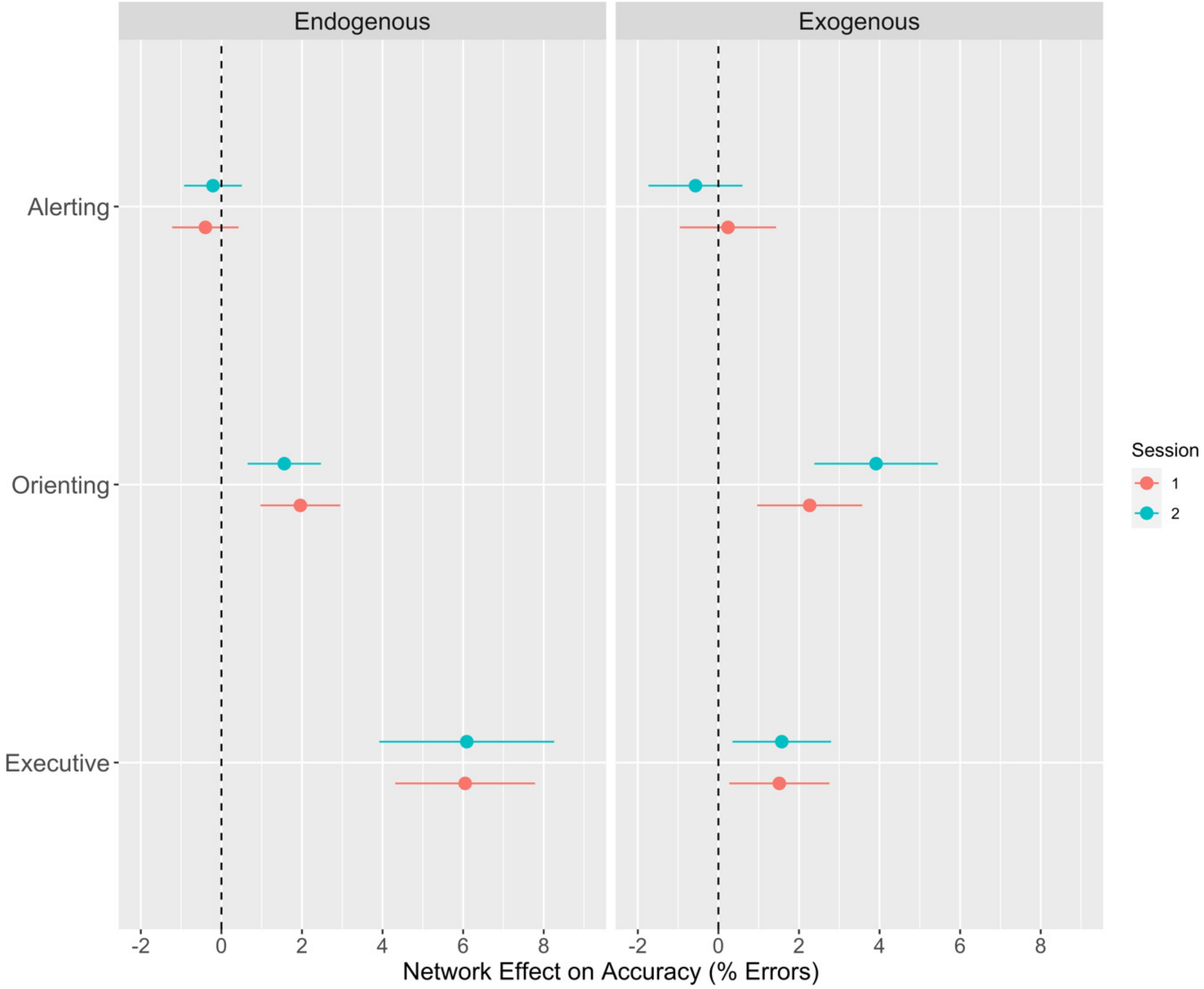
Note. This plot displays the average network scores in reaction time (ms). The session is indicated by colour and error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in reaction time.

Considering accuracy, under the endogenous mode of control, there was a significant main effect of session (*B* = -.48, *SE* = .18, z = -2.61, *p* < .01). On average, participants were .48% less accurate in their second session compared to their first. Among the predictors, orienting (*B* = .49, *SE* = .08 , z = 6.33, *p* < .001) and executive control (flanker effect) (*B* = 2.28, *SE* = .12, z = 19.55, *p* < .001) had significant main effects on accuracy. Alerting was not significant (*B* = -.08, *SE* = .08, z = -1.07, *p* = .28). There were no significant interactions (all *p* > .05).

Under the exogenous mode of control there was a significant main effect of session (*B* = -.38, *SE* = 0.18, z = -2.05, *p* < .05), indicating accuracy differed between sessions. On average, participants were .38% less accurate in their second session compared to their first. Among the predictors, orienting (*B* = .58, *SE* = .08, z = 7.30, *p* < .001), and executive control (spatial Stroop) (*B* = .29, *SE* = .08, z = 3.63, *p* < .001) had significant main effects on accuracy. Alerting was not significant (*B* = -.03, *SE* = .08, z = -.41, *p* = .68). There was a significant interaction between session and orienting (*B* = -.35, *SE* = .16, z = -2.16, *p* < .05). The were no other significant interactions (all *p* > .05). See Figure 9 for network scores (accuracy) between sessions in the endogenous and exogenous subtests.

Figure 9

Network Scores in the Endogenous and Exogenous Subtests (% Errors) Between Sessions



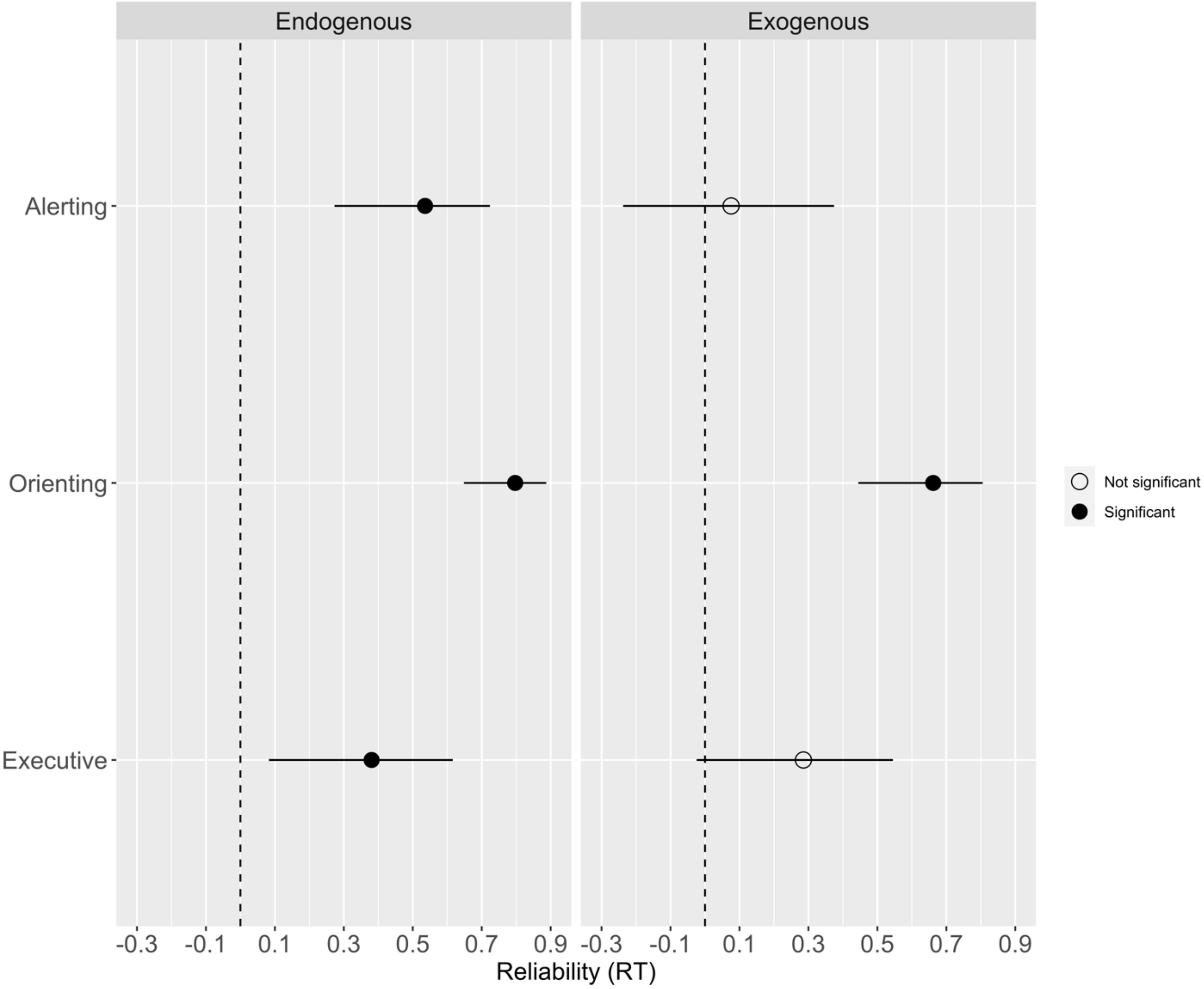
Note. This plot displays the network scores represented as the percentage of errors. Each point represents the mean score for a given network, the session is indicated by colour, and error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in accuracy.

3.2.3 *Psychometrics: Reliability*

Every participant completed two testing sessions on separate days to evaluate if the results were consistent over time. We conducted Pearson's correlations to look at the test-retest reliability between session one and session two of the CAST. Correlational analyses of the six network scores showed that all test-retest reliabilities were significant in the endogenous subtest regarding reaction. Reliabilities were *r* (39) alerting = .54, orienting = .80, and executive control = .39. In the exogenous subtest, only orienting was significant at *r* (39) = .66. See Figure 10 for Pearson's correlations of reaction time network scores between sessions.

Figure 10

Pearson's Correlations of Network Scores Between Sessions of the CAST (RT)



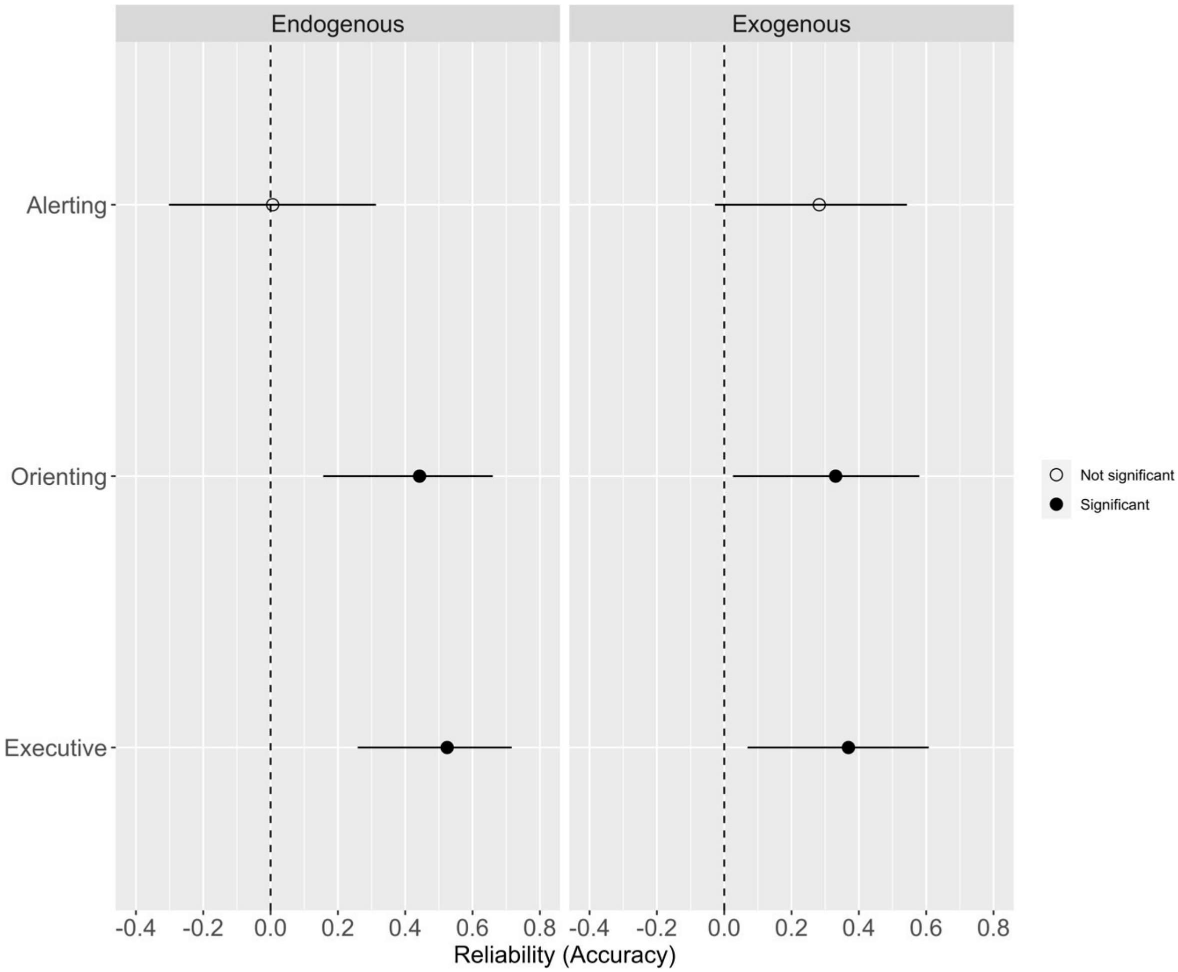
Note. This graph shows correlations for network scores calculated with reaction time. The plot includes a vertical dashed line at 0. Significance is indicated by the solid black circles.

Correlational analyses of the six network scores showed that the test-retest reliabilities were significant for orienting and executive control in both subtests regarding accuracy.

Reliabilities for the endogenous subtest were *r* (39) orienting = .44, executive control = .52. Reliabilities for the exogenous subtest were *r* (39) orienting = .33, executive control = .37. Correlations were not significant for the alerting network in either subtest. See Figure 11 for Pearson's correlations of accuracy network scores between sessions.

Figure 11

Pearson's Correlations of Network Scores Between Sessions of the CAST (Accuracy)



Note. This graph shows correlations for network scores calculated with accuracy. The plot includes a vertical dashed line at 0. Significance is indicated by the solid black circles.

3.3 Objective Two: Aging Effects on Attention

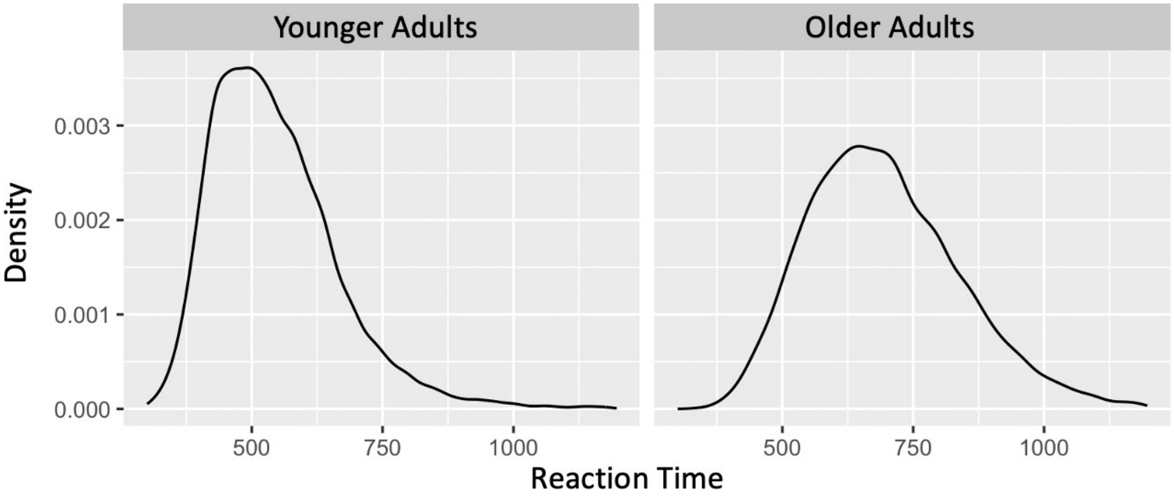
Based on the distribution of ages in our participant sample, we chose 44 as the cutoff for our younger adult sample (see Figure 2 in section 2.1). Our resulting groups ranged in age from 25 to 36 and 52 to 68.

3.3.1 *Aging: Overall Reaction Time and Error Rates*

We first compared the younger and older adult samples on their overall mean reaction time and error rates. Older adults are known to have a slower processing speed than younger adults (Salthouse, 1996). Consistent with previous research we found a slower overall reaction time in the older adult sample (*M* = 694.55 ms) compared to the younger adults (*M* = 542.73 ms). However, older adults were more accurate on average (97%) than younger adults (94%). Whereas it is unlikely that this difference in accuracy is completely responsible for the 150 ms difference in reaction time, it does suggest that as we age, we become more conservative and averse to errors. See Figure 12 for the distribution of reaction times between age groups.

Figure 12

Density Plot of Reaction Time Between Age Groups



3.3.2 *Aging: Network Score Comparison (Rection Time)*

Linear mixed effects models were run separately for reaction time and accuracy, to look at the effect of age on network scores. The reaction time model included alerting, orienting, and executive control as predictors. The model included random intercepts for the variable "age" for each participant. For accuracy we ran a logistic generalized mixed effects model that included alerting, orienting, and executive control as predictors and included random intercepts for the variable "age" for each participant.

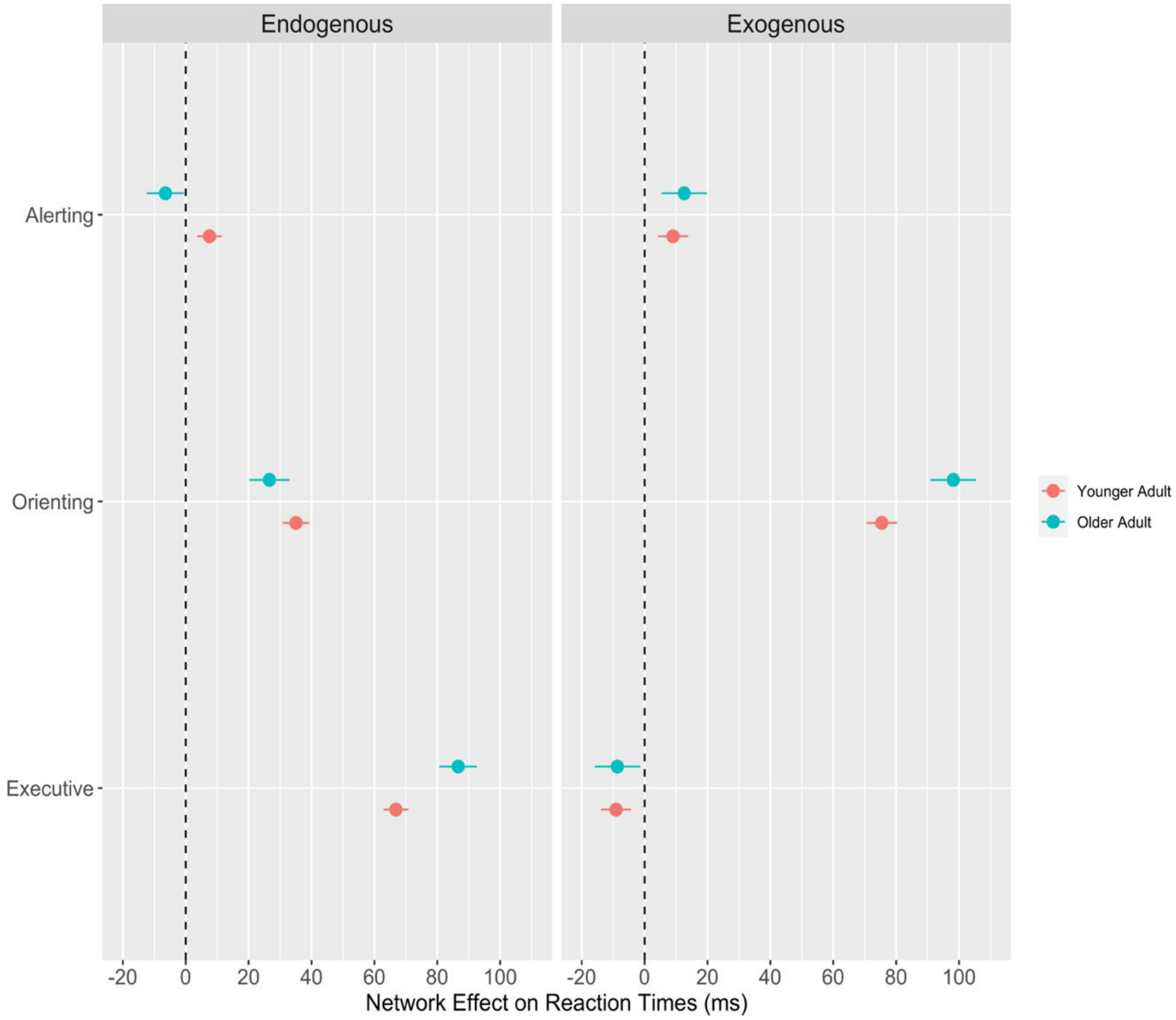
Examining the relationship between age group and attention networks in the endogenous subtest, results indicated a significant effect of age group on reaction time ($B = -149.25$, $t(39.10) = -8.36$, $p < .001$). Older adults had significantly longer reaction times compared to younger adults, confirming overall reaction time effects reported previously. The interaction between age and alerting ($B = -14.0$, $t(14718.07) = -3.83$, $p < .001$), orienting, ($B = - 8.46$, $t(14718.30) = 5.42$, $p < .05$), and executive control (flankers) ($B = 19.83$, $t(14718) = -2.18$, $p <. 001$) were all significant. See the left panel of Figure 13.

Examining the relationship between age group and attention networks in the exogenous subtest, results indicated a significant effect of age group ($B = -151.17$, $t(38.96) = -11.31$, $p <.001$). Older adults had significantly longer reaction times compared to younger adults, again confirming the overall reaction time effects. The interaction between age and orienting was significant ($B = 22.77$, $t(9509.18) = 5.14$, $p < .001$). There were no other significant interactions between age group and attention networks (all $p > .05$). See the right panel of Figure 13.

The results suggest that attention networks change with age. Under the endogenous mode of control, older adults differed from younger adults in all three attention networks. Under the exogenous mode of control, the age groups only differed on the orienting network.

Figure 13

Network Scores (RT) Between Younger and Older Adults in Each Subtest of the CAST



Note. This plot displays the interaction of age group and network in reaction time (ms). Each point represents the mean reaction time for a given network, and the age group is indicated by colour. Error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in reaction time.

A significant difference was found in the alerting network between age groups under the endogenous mode of control. Older adults had a negative altering network score of -6.46 ms, suggesting they did not benefit from an isointense warning tone. Younger adults showed an alerting network score in the expected direction. However, the network score for younger adults was also small at 7.54 ms. There were no significant differences between groups on alerting under the exogenous mode of control, and these scores were also relatively small (older adults 12.60 ms; younger adults 9.04 ms).

There were differences between age groups in the orienting network for both modes of control. Older adults had a smaller endogenous orienting network score of 26.6 ms, 95% CI [20.24, 32.96], whereas younger adults had a network score of 35.07 ms, 95% CI [30.88, 39.25], an approximately 8.5 ms difference in scores. Compared to the endogenous network, differences were larger under the exogenous mode of control (approximately 23 ms) and found in the opposite direction. Older adults showed a larger network score of 98.19 ms, 95% CI [90.97, 105.41], whereas younger adults showed a network score of 75.42 ms, 95% CI [70.61, 80.24]. The endogenous orienting result, which is derived from comparing the difference between valid and invalid informative central cues, may suggest older adults were less efficient than younger adults at using an endogenous spatial cue to respond quicker to targets. In contrast, the exogenous orienting results may suggest that older adults were less efficient at avoiding capture by uninformative stimuli in the periphery.

Age groups were found to differ on the endogenous but not exogenous executive control network. For the endogenous network (flankers), older adults had a larger network score of 86.66 ms, whereas younger adults had a network score of 66.83 ms. These results may suggest that older adults are more affected by competing information than younger adults on the flanker task. However, further consideration of accuracy is necessary and reported in section 3.3.3. There were no differences between age groups on the exogenous executive control network when calculating the spatial Stroop effect across flanker conditions, and network scores were found to be small and negative for both groups (older adults -8.67 ms; younger adults -9.07 ms). Further consideration using the no-flanker condition is reported in section 4.1.2.

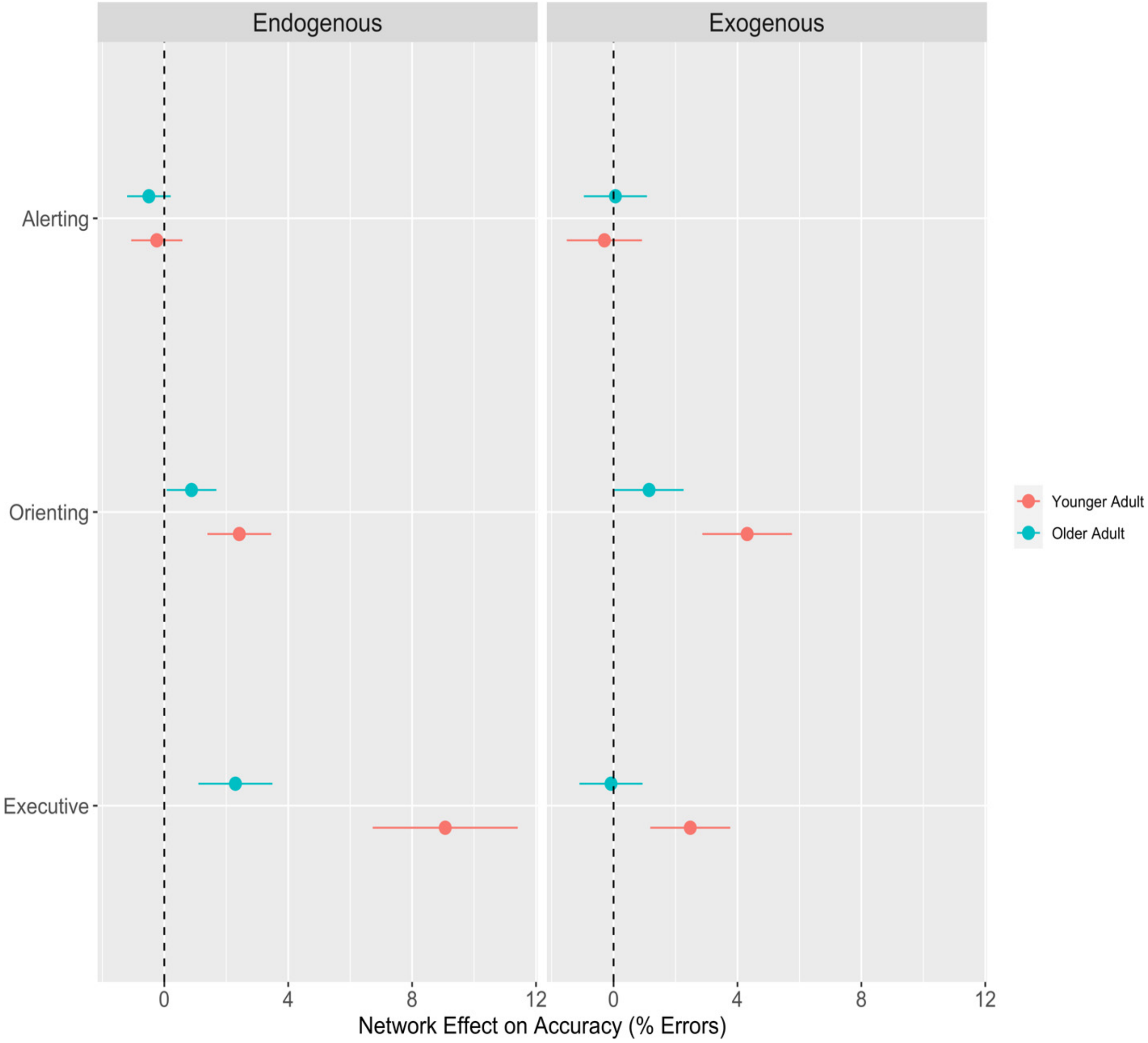
3.3.3 *Aging: Network Score Comparison (Accuracy)*

Examining the relationship between age group and attention networks on the endogenous subtest, results indicated a significant effect of age on accuracy ($B = -1.23$, $z = -3.91$, $p < .001$). Younger adults were less accurate on average than older adults. None of the interactions were significant ($p > .05$). For the exogenous subtest, results indicated a significant effect of age group ($B = -.75$, $z = -2.52$, $p < .05$), indicating that younger adults were less accurate on average. None of the interactions were significant ($p > .05$). See Figure 14 for accuracy network scores between age groups.

Although the results of our model did not find a significant interaction, there is an obvious difference in accuracy between younger and older adults for the endogenous executive control network. We believe the non-significant findings are due to ceiling effects. In the congruent flanker condition younger adults averaged 98.8% accuracy, whereas in the incongruent condition their accuracy was 89.8%. On the other hand, older adults were 99.5% accurate in the congruent condition, and 97% accurate in the incongruent condition. We ran a follow-up test on the original model, having back-transformed the log-odds to regular accuracy, and found a significant interaction. Younger adults showed an average network score of 9%, whereas older adults' network score was 2% ($z = 5.06$, $p < .0001$). Therefore, even though older adults had a larger reaction time network score, their accuracy score was smaller than younger adults. These results suggest a speed-accuracy-trade-off between age groups.

Figure 14

Network Scores (Accuracy) Between Younger and Older Adults in Each Subtest



Note. This plot displays the interaction of age group and network in accuracy (% errors). Each point represents the mean accuracy for a given network, and the age group is indicated by colour. Error bars represent 95% confidence intervals. The plot also includes a vertical dashed line at 0 to indicate no change in accuracy.

CHAPTER 4 DISCUSSION

Common measures of attention, such as the ANT and its many variants, have added rich value to the study of attention over the last couple of decades. However, these tools have been limited by confounds in their methodology, including the conflation of endogenous and exogenous modes of attentional control. Evolving from the tools which came before it, the CAST was developed as a novel method to rectify these methodological issues and provide a more comprehensive assessment of attention. The present study aimed to assess the psychometric properties of the CAST in a sample of young and older adults (age 25+). Our primary goal was to determine the feasibility and usefulness of the CAST, as a measure of all the domains (alerting, orienting, and executive control) and modes (endogenous, exogenous) of Klein and Lawrence's (2011) framework of attention.

4.1 Objective One: Psychometric Assessment

Our first objective was to examine the feasibility of the CAST for data collection and to assess the psychometric properties of our novel tool.

4.1.1 *Psychometric Assessment: Feasibility*

To examine the feasibility, we focused on measures of compliance/usability. We found 100% compliance with the task; all participants successfully completed both sessions. Notably, participants often reported the sessions of the experiment were too long, and they felt fatigued by the end of each session. However, the present study consisted of test-retest both within the session and on separate days. In future research, the CAST could be implemented in single-session research, and completed in half the length of the sessions in the present experiment (approximately 25 minutes). These findings are highly supportive of the accessibility of the CAST for future research with young to older adults. Considering also the findings of Lawrence (2018), our combined research suggests that the CAST is a feasible tool to be used to measure attention across the lifespan.

4.1.2 *Psychometric Assessment: Robustness*

To assess the psychometric properties of the CAST, we looked at whether the tool would produce robust and reliable measures of the six networks of attention (that are implied by three domains of attention and two modes of control) over time. Considering reaction time, the overall network scores (i.e., collapsed across both sessions) were all significantly different from zero. Refer to the average network scores plotted in Figure 6 in section 3.2.1.

The only network that did not show an effect in the expected direction was the exogenous executive control network. The assessment of the exogenous executive control network comes from the measure of the spatial Stroop effect, which refers to the performance difference between trials for which the (task-irrelevant) spatial position of the response and the target correspond and do not correspond (Lu & Proctor, 1995). We expected that participants would be faster to respond when the location of the target stimuli matched the correct response (e.g., responding to a left-facing target that is presented on the left side of the screen, where the correct response is the left trigger), compared to when there was a mismatch between the target response and the location (e.g., responding to a left facing target that is presented on the right side of the screen, where the correct response is the left trigger). Instead, our results suggest that participants were faster when the correct response did not align with the stimulus location, although this effect was small (between 5 and 13 ms). Using the ANT-R Fan et al. (2009) also found a similar unexpected pattern of results, suggesting quicker reaction times to incongruent rather than congruent locations (approximately -11 ms).

Lawrence (2018) found an interaction between the exogenous executive control network (spatial Stroop) and the endogenous executive control network (flankers). In the no-flanker condition, Lawrence observed the largest exogenous executive control network score, with the expected pattern of behaviour, i.e., participants responding faster to targets in the congruent location rather than incongruent location. In the congruent flanker condition, the exogenous executive control network score was found to be smaller than the no-flanker condition. Looking at the incongruent flanker condition the pattern of results reversed, with participants responding faster to incongruent locations rather than congruent conditions (Lawrence, 2018). Based on the previous research of Lawrence (2018) and Fan et al. (2009), we suspect that the inclusion of both incongruent and congruent flankers in our assessment of the spatial Stroop effect led to our unexpected results. To test this theory, we calculated the spatial Stroop effect from the raw means and found a negative spatial Stroop effect of approximately -20 ms in the incongruent flanker condition. In the congruent flanker condition there was no effect, and in the no-flanker condition we found effects in the expected direction of approximately 30 ms.

Interestingly, it seems that the endogenous demands of the flanker conflict override the reflexive nature of the task-irrelevant stimuli location (location conflict) and reverse the spatial Stroop effect. We suggest that future research implementing the CAST use the no-flanker condition for the truest measure of exogenous executive control.

We further explored robustness by looking at whether the network effects were consistent over sessions. In general, participants were faster during their second testing session of the CAST compared to their first, by approximately 27-28 ms. These results were expected due to practice effects as participants became more familiar with the task across sessions. Despite participants improving on reaction time in their second session, they were less accurate on average compared to their first session, although this effect was small (approximately .5 %). The decline in accuracy that accompanied faster reaction time possibly suggests a speed-accuracy-tradeoff.

Linear mixed effect models used to explore the effect of session on reaction time network scores showed that all six networks were significant. The results suggest that the robustness of the network scores were consistent over time. Refer to Figure 8 in section 3.2.2. Although the alerting network was found to be significant overall and between sessions, the confidence interval for the endogenous alerting effect in the first session was not significant, with the interval spanning -2.16 to 6.94 ms. Based on the small alerting network scores, that were produced under both endogenous and exogenous modes of control, we suspect that variability in audio levels may have affected the results of our study. Typically, in younger adults than were tested here, an alerting effect of approximately 40 ms can be observed using the ANT or its variants (e.g., Fan et al., 2002; Callejas et al., 2004; Klein et al., 2017).

4.1.3 *Psychometric Assessment: Reliability*

Test-retest reliability was assessed by using multiple testing sessions, to evaluate if results were consistent over time. Considering reaction time, correlational analyses of the endogenous subtest found significant reliability for all three networks (alerting, orienting, executive control). As for the exogenous subtest, only the orienting network showed significant reliability.

We suspect that the non-significant reliability between the two sessions for the exogenous alerting network, and the non-significant findings for the first session of the endogenous alerting network mentioned previously, might be due to differences in audio volume between participants. As participants were instructed to "adjust the volume to a comfortable level", there was not consistency. The white noise used throughout the experiment may not have been pleasurable to participants and they may have chosen to turn down the volume as a result. The endogenous warning signal involves voluntary listening since there is no change in intensity from baseline, meaning sufficient audio volume is necessary to benefit from the signal. It may be the case that most participants simply could not hear the auditory warning signal and therefore there was almost no benefit of the signal found. On the other hand, the exogenous warning signal has an increase in volume, which should add an attention-grabbing component. However, the reliability between sessions was not significant, and high variability compared to other network scores suggests there may have been differences in volume which affected the results. We believe that a fixed volume level for participants and shorter testing sessions will make the alerting network more reliable in future research.

Overall, reliability was variable across networks (refer to Figure 10 in section 3.2.3). The highest reliability was found in the endogenous orienting network at $r = .8$, indicative of good reliability. Moderate reliability was found in the endogenous alerting network at $r = .54$, and poor reliability in the endogenous executive control network (flankers) at $r = .39$. In the exogenous subtest only orienting was significant at $r\ (39) = .66$, indicative of moderate reliability. However, based on our findings of the spatial Stroop effect using the no-flanker condition, we decided to test the reliability of this effect and found a correlation of $r\ (39) = .67$. This moderate reliability provides further support for using the no-flanker condition in future research.

Previous research on the ANT has generally found the executive control network to be the most reliable, followed by orienting, with alerting commonly reported as the least reliable. Macleod (2010) reviewed the psychometric properties of the ANT including 15 studies (N =1,129) and reported split-half reliabilities using Spearman–Brown prophecy formula, the results were r = .38 for alerting, r = .55 for orienting, and r = .81 for the executive network. Ishigami et al. 2015 assessed the psychometric properties of the ANT-I in a sample of 173 healthy older adults (65+), also finding similar split-half reliabilities of r = .29 for alerting, r = .7 for orienting, and r = .68 for executive control.

The low and moderate reliabilities associated with the CAST, like the ANT, may be a consequence of the nature of the network calculations. The correlation between the two variables used to calculate a difference score can affect the reliability, and therefore difference scores tend to have low levels of reliability. When a subtraction score reduces the between-participant variance it increases the proportion of measurement error (see Salthouse & Hedden, 2002 and Hedge et al., 2018). As well, it is important to consider whether components of attention are states or traits. If a network, such as alerting, is thought to be a state, then it likely will vary across measurements and produce low reliability (Macleod et al., 2010).

4.1.4 *Psychometric Assessment: Conclusion*

For our first objective, we considered whether the CAST was a feasible measure of the six networks of attention that produced robust and reliable scores. We found 100% compliance with the task, all six network scores were significantly different from zero, and all scores were consistent over time at a group level. We also used Pearson's correlations to assess test-retest reliability, and although we found correlations ranging from poor to good, we recognize that correlational analyses may not be the best metric on which to base our assessment, due to the nature of the difference scores that are used for the CAST. Comparing our results to previous research that implements the ANT and its variants, we also find similarities in network scores suggestive of construct validity for the CAST. Except for the alerting network, our network scores were generally comparable to previous literature. Typically reaction time network scores tend to fall in the approximate ranges of: alerting 20 – 50 ms, orienting 30 – 70 ms, and executive control (flanker effect) 70 – 120 ms (e.g., Fan et al., 2002; Callejas et al., 2004; Klein et al., 2017; Neuhaus et al., 2010; Gamboz et al., 2010; Zhou et al., 2011; Brunyé et al., 2010; Mahoney et al., 2010; Ishigami & Klein, 2011; MacLeod et al., 2010; Ishigami et al., 2015). Taken together, we believe that these results generally show strong support for the utility of the CAST in attentional assessment. We believe that a fixed minimum for the auditory stimuli in future research may produce larger alerting scores, although this theory remains to be tested in future research.

4.2 Objective Two: Aging

Having found evidence that the CAST produced robust and relatively reliable measures of the six networks of attention, and that our findings were consistent with previous research suggesting sufficient construct validity, our final objective was to explore age-related changes in attentional processes. By comparing scores between younger and older adults we hoped to explore how the attention networks are affected by healthy aging in adulthood. Based on the distribution of ages in our participant sample, we chose 45 as the cutoff for our groups. Our resulting groups ranged in age from 25 to 36 and 52 to 68.

4.2.1 *Aging: Alerting*

We hypothesized that reduced network scores would be seen in the endogenous alerting network but not the exogenous alerting network. In line with our hypotheses, the alerting network showed no differences between younger and older adults under the exogenous mode of control. Differences were found between age groups under the endogenous mode of control. Older adults showed a small negative alerting effect in reaction time, suggesting participants were faster to respond to targets on warning signal absent trials (-6.46 ms) compared to trials with an endogenous warning signal (+0Δ dB). Younger adults also showed a small alerting effect. However, this effect was in the expected direction, with participants faster to respond to targets following an endogenous warning signal compared to trials with no warning signal (7.54 ms). These results suggest older adults did not benefit from an isointense warning tone.

Previous research with the ANT has found similar results suggesting that the efficiency of the alerting network declines with age (Gamboz et al., 2010; Jennings et al., 2007; Mahoney et al., 2010; Westlye et al., 2011). However, due to the results found above in objective one and the small alerting network scores for both age groups, we believe it is possible that our adult sample may not have been able to reliably hear the warning signal in our experiment. Therefore, although our results support our hypotheses, we are not confident in our findings and believe further research needs to be conducted on age-based differences in endogenous and exogenous alerting.

4.2.2 *Aging: Orienting*

We hypothesized that the exogenous orienting network would be preserved with age, but reduced orienting would be seen in the endogenous network. In partial support of our hypotheses, we found an interaction between age and orienting under both endogenous and exogenous modes of control. Under endogenous control older adults exhibited a smaller orienting score (the difference between invalidly cued and validly cued trials) compared to younger adults. Under exogenous control, older adults exhibited a larger orienting network score than younger adults. These findings suggest that older adults did not benefit as much as younger adults from a valid endogenous spatial cue to respond quicker to targets. However, they may be more efficient at avoiding capture by uninformative exogenous cues.

Previous research using the ANT to study aging effects on attentional networks have found no differences in the orienting network between younger and older adults (Gamboz, et al., 2010; Jennings, et al., 2007; Zhou et al., 2011; Williams et al., 2016). However, the ANT conflates endogenous and exogenous modes of orienting, and there is research which suggests that these modes of control may be differentially affected by age. Aging literature suggests that top-down processes are generally more vulnerable to age-related effects (Lustig & Jantz, 2015). Consequently, it has been theorized that endogenous orienting is more likely to deteriorate with older age (Zivony et al., 2020). In support of this theory, there are studies of orienting which suggest that exogenously induced shifts of spatial attention are preserved with age, whereas endogenous orienting may become less efficient with aging (Folk & Hoyer, 1992; Brodeur & Enns, 1997; Tales et al., 2002b; Waszak et al., 2010; Erel & Levy, 2016). However, despite this prevalent belief, aging effects on endogenous orienting are not always observed.

Conventionally, two versions of the cueing paradigm have been implemented to study endogenous and exogenous modes of orienting. A salient peripheral cue to engage exogenous processes, and a centrally located predictive cue to engage endogenous processes. Facilitative effects on reaction time following the centrally presented endogenous cue have been attributed to the cue's spatial predictivity. However, research has revealed that some forms of cues have a learned association which engages reflexive orienting, such as arrows, finger pointing, and spatially informative words such as “left” or “right” (Ristic et al., 2002; Ristic and Kingtone, 2006; Langton & Bruce, 2000; Hommel et al., 2001). This research suggests that centrally placed directional cues used to engage endogenous orienting may be engaging exogenous control as well, depending on the nature of the cue. Therefore, it is possible that some studies which have failed to find differences in endogenous orienting may be due to the conflation of endogenous and exogenous modes of control. As a result, aging effects on endogenous orienting may be underrepresented.

Although we used a predictive cue in the shape of an arrow to engage endogenous orienting, we believe that the timing of our stimuli hinders the contribution of the exogenous component of the cue. It has been observed that performance enhancement following an exogenous cue occurs within 100 ms of cue onset (Ristic & Kingstone, 2006). The cue-target SOA of one second in the CAST’s endogenous subtest allows for the reflexive nature of the cue to elapse, and therefore any benefits of the cue are likely to be due to endogenous control of spatial orienting.

Whereas we did not expect to find differences in the exogenous orienting network between age groups, these results are not unheard of (Lincourt et al., 1997; Poliakoff et al., 2007; Langley et al., 2011). Despite the opposing direction of effects for the endogenous and exogenous orienting networks between groups, both differences may suggest orienting deficits for older adults. A smaller orienting network score (as the older sample shows with endogenous orienting) may suggest that participants were less able to take advantage of a cue to attend to the likely location of a target. A larger orienting network score (as the older sample shows with exogenous orienting), could be rooted in a greater difficulty disengaging from an invalidly cued location, in order to reorient to the proper location. Considering previous research, we believe that the age difference in the exogenous alerting network may reflect slower disengagement from an invalid cue, rather than faster engagement of a valid cue.

4.2.3 *Aging: Executive Control*

We hypothesized that older adults would show deficits in the endogenous and exogenous executive control networks. In partial support of our prediction, age groups were found to differ in the endogenous executive control network. There were no differences between age groups in the exogenous executive control network when we calculated the spatial Stroop effect across flanker conditions.

For the endogenous executive control network (flankers) older adults had an average network score approximately 20 ms larger than younger adults. These results may suggest that older adults are more affected by competing information than younger adults on the flanker task. These findings are in line with previous research implementing the ANT and its variants to study aging, in which older adults were found to exhibit larger network scores compared to younger adults (Mahoney et al., 2010; Zhou et al., 2011). However, we want to draw attention to differences in accuracy between younger and older adults. While older adults had a larger reaction time network score, their accuracy score was smaller than younger adults. In line with the findings of D'Aloisio and Klein (1990), we believe that the differences in network scores represent differences in priority. Whereas younger adults focus on being fast, older adults seem to prioritize being accurate.

We initially assessed the exogenous executive control network across flanker conditions and found no differences between age groups. We then re-evaluated this network using only the no-flanker condition based on our findings mentioned previously. When the spatial Stroop effect was calculated from the no-flanker condition, younger adults were found to have an average network score of 26.2 ms, whereas older adults had a mathematically higher network score of 36.4 ms. Although this difference was not significant (p =.082), it was nevertheless supportive of Kawai et al. (2012) who also found greater Simon effects for older adults compared to younger adults.

4.2.4 Aging: Conclusion

The impact that natural aging has on cognitive function and safety presents significant challenges for society. The results of this study have provided valuable insight into the effects of natural aging on attentional networks and show support for the theory that endogenous control may be more vulnerable to age-related decline. However, there was evidence for age-related differences under the exogenous mode of control as well. It is crucial to continue research into aging effects, in hopes of developing strategies to promote healthy aging, support older adults in maintaining their independence and quality of life, and address the needs of caregivers and the healthcare system.

4.3 Limitations and Future Directions

This study was not without limitations. First, older adults found the time-out parameter for a trial (1200 ms) to be too quick, particularly when they were first becoming accustomed to the task. Despite this, our practice session allowed participants to become accustomed to the task and time-out trials only accounted for a very small portion of responses (.58% of overall trials). Overall younger and older adults also had a similar amount of excluded trials, 1.07% and 1.31%, respectively. Refer to Figure 12 in section 3.3.1 to see the distribution of reaction times between age groups. Participants often reported that the study was too long, resulting in boredom and fatigue. However, this limitation can be mitigated in future research with shorter testing sessions and single day sessions.

Another limitation of this study is that we were not able to recruit any participants who were in their 40s or who were 70 years of age or older. These gaps in age groups may affect the generalizability of our findings and it is still possible that the CAST may not be as feasible for use with older adults, particularly 70+. It is also possible that more pronounced differences between younger and older adults would have been found with an older sample of participants.

While the CAST's portability and the option to bring the experiment to the participants made the study more accessible and increased data collection, it also resulted in less methodological control over the setup of the experiment. In some situations, the home environment included distractions that would not have been present in the lab (e.g., a participant's dog occasionally barking in the other room). These environmental differences may have affected the results of our study, especially the alerting network.

Another consideration is that we did not control for the time of day. Previous research has suggested that younger and older adults have different performance patterns based on the time of day. For instance, the time of day has been shown to affect alerting performance on the ANT, with performance enhanced by alerting cues in off- peak times. Older adults benefit most from alerting cues in the afternoon, whereas younger adults benefit more from alerting cues earlier in the day (Knight & Mather, 2013). In future research, testing participant age groups with a consideration of the time of day may help to elucidate effects.

Our results, as well as previous research, suggest an interaction between endogenous and exogenous executive control. In the no-flanker condition we found a positive spatial Stroop effect, however, this effect is overridden by the congruent/incongruent flankers. Therefore, the negative spatial Stroop scores we reported are likely not reflecting the true exogenous executive control network we intended to measure, but rather a confounded effect due to the flankers. In future research we believe that assessment of the exogenous executive control network should use the no-flanker condition, rather than the incongruent and congruent flanker conditions, in order to produce more robust and reliable results.

We have the least confidence in our findings on the alerting network and speculate that the participant-controlled audio level may largely account for our small alerting network scores and insignificant test-retest correlations. Therefore, we also believe future testing should control the minimum audio level heard by participants throughout the experiment.

4.4 General Conclusion

Overall, the findings from this study suggest that the Combined Attention Systems Test is a feasible tool for assessing attention in healthy adults. Our assessment of the psychometric properties showed robust results significantly different from zero for all six networks. Considering multiple testing sessions, the robustness of all networks were also significant over time. However, we believe future research should maintain a fixed audio level and use only the no-flanker condition to improve measures of the alerting networks and the exogenous executive control network, respectively. Although we found variability in correlations between the first and second testing sessions ranging from not significant to good, we believe these results may be due to the nature of the difference scores.

Regarding aging, our results support the theory that the endogenous mode of control is particularly vulnerable to age-related decline. We found diminished network scores in alerting and orienting under endogenous control. We also found differences in the endogenous executive control network. However, this may reflect a speed-accuracy-trade-off, rather than the reduced ability to ignore conflict. Under the exogenous mode of control, there were differences in the orienting network that may also suggest a decline in performance with age.

We believe the results of our study suggest that the CAST could be a useful tool in the comprehensive assessment of attention, which could have important implications for our future understanding of both typical and disordered states of attention. The results of our study also further our knowledge of cognitive aging and attention, information which could be useful in promoting the maintenance of the domains and modes of attention across the lifespan.

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