CUEING VISUAL SPATIAL WORKING MEMORY: EFFECTS OF CUE MODALITY, CUE TYPE, AND AGE

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Abstract

In general, attentional control and spatial working memory (WM) decline with increasing age. It is well known that relative to non-cued targets, spatially informative visual (uni-modal) cues quicken response time in target detection attention tasks, and improve feature and spatial WM performance. Spatially informative auditory and vibrotactile (cross-modal) cues provide additional benefit in more difficult attention tasks, but their effects on spatial location WM are unknown. This dissertation presents two studies that investigated effects of uni-modal visual cues and cross-modal auditory and vibrotactile cues on visual spatial location WM in younger adults (YA) and older adults (OA), and under various conditions that modulated WM task demands. In study one, we found that both spatially informative uni-modal and cross-modal cues improved spatial location WM performance to a similar degree for YA and OA. This benefit was generally greater under higher WM load (i.e., six-item vs. four-item memory arrays) and longer maintenance delays, whereas centrally presented alerting cues generally impaired performance. Individuals with lower spatial spans also benefitted most from spatially informative cross-modal cues. Study two assessed the impact of maintenance interference on spatially informative cue effects. In contrast to study one, we found age-related cue effects, which were moderated by WM maintenance interference type. When interference was to be ignored, OA benefitted from visual, auditory, and vibrotactile cues for lower WM loads (i.e., four-item arrays), whereas YA only benefitted from vibrotactile cues at higher WM loads (i.e., six-item arrays). When interference was to be compared, OA showed increased benefit to WM performance from cross-modal auditory and vibrotactile cues, whereas YA benefitted from all cue modalities. Taken together, these findings suggest spatially informative cross-modal cues can improve spatial location WM in both YA and OA, particularly when demands on spatial attention and attentional control are high. Furthermore, OA show more consistent benefit from cross-modal cues in resource demanding conditions. These results provide insight into cognitive underpinnings of cross-modal cue effects, and age-related differences in use of environmental support. They also provide a rationale for real world applications using cross-modal cues, aimed at improving cognitive function in complex visual environments, particularly for OA.

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Table of Contents

List of Tables

Tables for Study 1

Tables for Study 2

List of Figures

Figures for Study 1

Figures for Study 2

Chapter 1: Introduction

General Introduction

In our visually complex world, it is becoming more important to utilize strategies to help focus and maintain our attention on the most relevant information. Using cues to help us direct our attention can help reduce the time it takes to respond to information, which could have beneficial effects in real world tasks, such as driving, and locating important items or landmarks. Older adults (OA), who are vulnerable to environmental distraction (e.g., Sekuler, Bennett, & Mamelak, 2000), can likely benefit most from cue utilization or other methods to help facilitate their cognitive abilities. One such cognitive ability is visual spatial working memory (WM), in particular visual spatial *location* WM or the short term memory for object locations. This type of memory is used in various real world tasks, and a common complaint of OA is forgetting the location of household items (e.g., Fairchild & Scogin, 2010). Furthermore, visual spatial location WM is thought to be particularly important during driving for OA, as baseline performance on tasks that measure this type of memory are associated with performance in simulated driving scenarios (Cassavaugh, & Kramer, 2009). Therefore, by investigating ways to help improve the focus of attention during spatial location working memory tasks in the laboratory, we can help inform the design of real world paradigms, which tap into common cognitive complaints of OA and general deficits observed in driving simulations. The most beneficial strategies that help ameliorate memory decline, at least in the short term, could assist OA in their daily activities, with the ultimate goal of helping them to live independently longer.

The aim of this dissertation was to investigate how different types of cues, across various sensory modalities, can influence visual spatial location WM, and determine whether cross-modal cues (cues that differ in modality from items to be remembered in a spatial WM task) provide any additional benefit relative to uni-modal cues (cues in the same modality as items to be remembered). We also sought to determine whether cue benefits were greater for OA relative to younger adults (YA). A second goal of this dissertation was to investigate the nature of the cue benefit to visual spatial location WM. The research studies conducted help shed light on the specific processes of WM that might be facilitated, which will ultimately inform the future design of the most optimal cueing paradigm.

The rest of Chapter 1 presents a literature review that provides a background of the relevant research pertaining to this dissertation. Theoretical cognitive models of attention and visual spatial (both feature and spatial location) WM are discussed. Behavioural findings from facilitation paradigms such as cueing are also summarized. Additionally, theoretical accounts of cognitive aging are addressed, and a rationale for the current research is presented. Finally, our overarching research aims, specific research questions, and predictions are described.

Chapters 2 and 3 include the manuscripts for study one and study two, respectively. Study one assessed the impact of and age differences of cross-modal and uni-modal cues on visual spatial location WM performance without interference. Study two assessed the impact and age effects of these cues under the presence of WM interference. Both chapters include brief background introductions, methods, results, and discussions. Additional procedural details, participant data, and statistical analyses are presented in the appendices, and summarized at the end of each manuscript as a sub-chapter.

Chapter 4 is a general discussion of the dissertation research. An integrative interpretation of results and possible applications from both studies are presented. Finally, limitations of the current research and suggestions for future research are discussed.

Literature Review

Attention

Cognitive Models. Attention can be broadly defined as a control system, which prioritizes incoming sensory information, and selects the information to which we respond (Posner & Peterson, 1990). Early analogies described attention as a "spotlight" that "illuminates" the high priority information for further cognitive processing (Posner, 1980). The spotlight analogy was modified by Ericksen and St. James (1986), and in their theoretical account, attention was described as a "zoom lens". It was posited that the spotlight can increase or decrease in size, and this in turn changes the efficiency of attentional processing (Ericksen & St. James, 1986). For example, if the spotlight is bigger in diameter, attentional resources are more dispersed across the entire illuminated area, leading to shallower processing of items that fall within the spotlight. In contrast, when the zoom lens is more focused, and the spotlight is consequently smaller in diameter, resources are more focused and this leads to more efficient or deeper processing of the illuminated area (Ericksen & St James, 1986).

Selective attention essentially refers to the cognitive mechanism mediating the zoom lens, and describes the process of focusing all attentional resources on one part of the environment or one internal mental representation, while ignoring other environmental inputs or mental representations (Treisman, 1969). Selective attention can be further subdivided into attention for visual features, or spatial locations, termed selective visual and selective *spatial attention*, respectively (e.g., Clark & Hillyard, 1996; Posner & Dehaaene, 1994). Selective attention differs from *divided attention*, where resources are distributed across different aspects of the external environment or internal representations (Treisman, 1969).

Attentional processes have been alternatively described as constituting three main cognitive systems: alerting, orienting, and executive (e.g., Posner & Peterson, 1990; Posner & Rothbart, 2007). The alerting system is responsible for maintaining a vigilant state of arousal, or sustaining a low threshold for response to incoming sensory information (Posner & Peterson, 1990). This system is analogous with *sustained attention*, which is necessary during tasks with a longer duration such as listening to a lecture or reading a book.

The orienting system shifts our attentional resources to a spatial region and is analogous with spatial attention described previously (Posner & Peterson, 1990). This shift can occur with or without awareness (Mahoney, Verghese, Goldin, Lipton, &

Holtzer, 2010), described as endogenous and exogenous orienting, respectively (Theewes, 1991).

Finally, the executive attention system is responsible for control of focal, conscious attention, as well as the coordination of attentional processing, and has a limited capacity (Petersen & Posner, 2012). This conscious coordinating of attentional resources is termed *executive attention* (Kane & Engle, 2002; Posner & Peterson, 1990). This type of attention is often utilized in tasks where there are more than one stimuli competing for an individual's attention. A real world example involving this type of attention would be if you were driving and trying to pay attention to the physical environmental (e.g., the road, traffic, traffic signs, etc.) while also paying attention to a global positioning system (GPS) digital map. This situation would have different stimuli that would compete to grab your attention. Your executive attention network would help coordinate your attentional resources to pay more attention to the road while driving in more complex scenarios (e.g., during a cluttered high way scenario), and less attention to the GPS system (e.g., the visual cues on the screen, and the auditory voice that tells you directions) which would become less important in a more complex driving situation.

Summary. Cognitive models of attention have likened it to a spotlight or zoom lens that allows selective, focal processing on certain aspects of the environment or internal representations. Spatial attention refers to the focusing of cognitive resources on regions of space. Attention has been alternatively described as involving three main systems, orienting, alerting, and executive, responsible for spatial, sustaining, and executive attention, respectively.

The next section will discuss ways in which attentional processes can be facilitated through the use of cues.

Facilitating Attention

Cueing Attention. It has long been established that visual cues that predict the location of an upcoming visual stimulus can facilitate attention by decreasing response time in target detection tasks (Driver & Spence, 1998; Mcdonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Posner, 1980; Spence & Driver, 1997). However, there are several factors (e.g., cue-target temporal intervals, Martens & Johnson, 2005; to what degree a cue is predictive of an upcoming target or "cue validity", Schmidt, Postma, & de Haan, 2000; cue-target spatial proximity, Ferris & Sarter, 2008; etc.) that affect the degree of overall cue benefit. Two additional factors of relevance to the present research are cue type and cue modality. These factors will be discussed in more detail next.

Cue Type. The type of cue impacts the magnitude of attentional facilitation. The two cue types of interest in the present work are alerting and spatially informative (orienting) cues. Alerting cues are considered preparatory cues, and are meant to facilitate sustained attention or the alerting system (Fernandez-Duque & Posner, 1997). They simply prepare someone for the imminent presentation of a visual target. An example would be a non-directional (i.e., centrally presented) "beeping" sound that alerts an individual to pay attention or prepare for upcoming targets. In contrast, spatially informative cues activate the orienting network of attention and direct spatial attention to a certain region of internal mental or external (environmental) space (Fernandez-Duque & Posner, 1997). An example would be a sound cue that is directional (presented to the left or right), and indicates to the individual where to focus their attention (e.g., pay attention to the left or right side of a computer screen). Although alerting cues have been shown to enhance target detection and discrimination by quickening response time, spatially informative cues have been shown to provide greater cue benefit in similar tasks (Luca & Murtha, 2009). However, the effects of alerting cues on higher order cognitive abilities such as WM remain unknown. In the present research, both alerting and spatially informative cues were used. We were particularly interested in whether or not spatially informative and alerting cues show similar benefits to visual spatial WM. This information is important, as it affects the interpretation of cueing effects (Weinback & Heinik, 2012). For example, if spatially informative cues provide additional benefit to WM performance, greater than what is seen for alerting cues, this allows more certainty in attributing the cueing effects of a spatially informative cue to its ability to orient attention, instead of simply alerting an individual to respond.

Spatially informative cues can also be characterized by their ability to reflexively or strategically orient attention. When these cues automatically orient spatial attention to a certain visual area, they are called exogenous (e.g., Jesus Funes, Lupianez, & Milliken, 2007; Posner, 1980). An example of this type of exogenous cue would be a “beeping” sound that is presented in the periphery and directs your attention in an automatic, reflexive, or a “bottom-up” fashion to the cued location. On the other hand, strategic spatially informative cues are called endogenous cues, since they provide information about where a target is going to appear, but the individual must orient attention in a self-initiated or “top-down” fashion (Posner, 1980). An example of an endogenous cue would be a centrally located visual arrow that points to the direction of where a visual target is going to appear.

Exogenous cues can be both informative and valid (i.e., spatially predictive of an upcoming target) or uninformative and invalid (i.e., non-predictive of an upcoming target). Likewise, endogenous cues that are informative and valid correctly predict the location of a target (i.e., an arrow points left and a subsequent target appears on the left). If they are invalid, they would incorrectly predict the target location. The cues employed in the current research are both exogenous and valid. They are exogenous in nature, in that they are presented in the periphery and are thought to automatically orient attention to the left or right region of space. However, they can also be considered valid, since they are always spatially informative, and participants are encouraged to use the cues to help direct their attention.

Cue modality. Cue modality is another important factor to consider when designing appropriate cueing paradigms that aim to maximize behavioural performance across cognitive tasks. The cues of interest in the present research are those that are in the same modality as the target (uni-modal cues), or those in a different modality as the target (cross-modal cues). An example of a uni-modal cue would be a flashing light that cues a visual target, whereas a cross-modal cue could be a “beeping” sound (auditory cue) or a vibrating sensor (vibrotactile cue) placed on the body that cues a visual target.

Cross-modal cues have shown both similar as well as increased benefits in attention tasks, relative to uni-modal cues. Visual and auditory cues have been shown to quicken visual target detection (McDonald et al., 2003; Schmidt et al., 2000; 2001) to a similar degree. For visual target localization, where an individual must detect and discriminate between two areas where a target could appear, cue effects depend on the informative nature of the cue. While visual cues that do not predict the location of a visual target (i.e., invalid cues) have been shown to provide a greater cue benefit relative to invalid auditory cues in a target localization task (Spence & Driver, 1997), a different pattern occurs for predictive (i.e., valid) cues. In a similar target localization task, spatially predictive auditory cues have been shown to quicken response time to a similar degree as visual cues (Schmidt et al., 2001). On the other hand, vibrotactile cues have quickened response time to a greater degree than visual cues in a visual change detection task, where individuals indicate when they detect a change between two rapidly presented visual scenes (Sklar & Sarter, 1999).

The benefit of cross-modal cues has also been shown in real world scenarios such as driving (Ho, Tan, & Spence, 2005), where engaging visual attention is particularly challenging due to the wide variety of visual distracters competing to grab one’s attention (i.e., billboards, traffic lights, and signs). In driving simulator studies, where participants perform an attention task, indicating the presence of a visual obstacle in their field of view, findings have shown a greater benefit of spatially predictive auditory cues over spatially predictive vibrotactile cues in terms of quickening response time (Ferris, Penfold, Hameed, & Sarter, 2006). Taken together, these results suggest that task demands play a role in cue benefits. For more difficult or higher order cognitive tasks, (e.g., target discrimination, change detection, or a complex driving scenario), cross-modal cues appear to provide a greater benefit relative to uni-modal cues.

An additional benefit of cross-modal cues, particularly, auditory and vibrotactile cues, is their ability to exert their effects on visual target detection over a larger region of space, by presumably broadening the window of attentional focus (Gray, Mohebbi, & Tan, 2009). Spatial separation between the cue and target location is much more critical for visual cues. For instance, as visual cue-visual target separation increases, response time to target detection increases monotonically (Gray et al., 2009). For auditory and vibrotactile cues, although maximal cue benefit is achieved when the cue and target location are coincident, this benefit does not decrease monotonically as the cue-target separation increases (Gray et al., 2009).

Summary. It is well known that cues can facilitate attentional processing, by quickening response time across a variety of attention tasks. This benefit is moderated by factors such as cue type and cue modality. Overall, cues that are spatially informative appear to provide the greatest benefit, relative to alerting cues. Whether this pattern is observed in cognitive abilities such as WM remains to be established. In simple target detection tasks, cross-modal and uni-modal cues provide similar benefit. However, when task demands increase, as seen in localization discrimination or change detection tasks, auditory and vibrotactile cues provide greater benefit over visual cues. Cross-modal cues also exert their cue effects over a wider region of visual space, thus strengthening the rationale for implementing these cues in a real world application, which could be more flexible in their design.

The next section will discuss the other cognitive ability of interest to the present work: visual spatial WM. The relatively limited research on cueing visual spatial WM will also be summarized.

Visual Spatial Working Memory

Cognitive Models. Visual spatial WM is part of the broader WM system which can be defined as the short term active maintenance and manipulation of information held "online" (Baddeley, 1981; Hitch & Baddeley, 1976; Kiyonaga & Egner, 2012). Within Baddeley's *multicomponent* WM model, the "central executive" controls and directs two "slave systems" called the phonological loop and visuospatial sketchpad. The phonological loop maintains auditory/verbal information, and the visuospatial sketchpad stores visual features and spatial locations. Within this visual storage system, the capacity for objects is thought to be approximately three to four (Todd & Marois, 2005; Xu & Chun, 2005), whereas the capacity for spatial locations is thought to be approximately five (Simons, 1996). For the purpose of this research we are interested in visual spatial location WM, therefore, according to Baddeley (1981), this information would be stored within the visuospatial sketchpad, and occupy the spatial storage component. More recently, Baddeley updated his WM model to include storage of haptic or vibrotactile information within the visuospatial sketchpad and added another component called the episodic buffer (Baddeley, Allan, & Hitch, 2011). He proposed that the episodic buffer interacted with the phonological loop, visuospatial sketchpad, and central executive to bind items from different modalities in WM into coherent representations. For example, it can bind visual features such as color to an object location, so that this information is stored as a unitary object in the episodic buffer. It can also bind information from different sensory modalities, such as auditory and visual information (Baddeley et al., 2011). It remains to be determined the extent to which the episodic buffer is controlled by the central executive (Baddeley et al., 2011). That is, it is unclear whether the binding is automatic or relies on processing resources in WM.

Although other WM models have also been developed, such as *capacity theory* (Daneman & Carpenter, 1980), and the *embedded-process model* (Cowan, 1999), they all acknowledge the active processing of information within WM. WM is not a passive storage system; rather it involves effortful cognitive processing of items to be remembered. These items are actively kept within the focus of attention, a process that Cowan's (1999) model equates with the definition of WM. In Baddeley's (1981), and Cowan's (1999) models, the active component can be considered the central executive. However, in Daneman & Carpenter's model (1980), they describe the active component as a computation production system that modulates activation thresholds of incoming stimuli, which must be exceeded in order for a memory item to be maintained in WM.

WM phases. Within the WM system, there are three phases in which information is processed and/or remembered: encoding, maintenance, and retrieval/response. Prior to encoding into WM, target items must be encoded perceptually, which refers to the initial translation of sensory stimuli into perceptual representations (e.g., Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002). Encoding in WM refers to the consolidation of target stimuli into constructs that can be temporarily stored (Mainy, Kahane, Minotti, Hoffmann, Bertrand, & Lachaux, 2007). The encoding specific to WM consolidation, and of interest to the present work, differs from the early perceptual encoding in that it is not automatic (Macpherson et al., 2014; Todd, Han, Harrison, & Marois, 2011).

WM maintenance refers to the short term active storage of encoded mental representations. The duration of WM maintenance is in the order of seconds (Baddeley, 2003), after which information can be lost due to temporal decay of the mental representations. Successful WM maintenance can also be disrupted due to interference of irrelevant items, which can displace part or all of the contents that are currently being actively stored (Reitman, 1974). It has been suggested that these two forms of maintenance disruption (decay and interference) are not necessarily mutually exclusive, and that both time and interference can concurrently contribute to memory loss during maintenance (Barrouillet & Camos, 2001).

WM retrieval occurs during the response phase of a WM task and refers to the search of encoded memory representations, and allocation of attention to a particular item of interest (Öztekin, McElree, Staresina, & Davachi, 2009). WM retrieval can be recall or recognition based. Recall is considered to use more processing resources since the entire contents of WM are searched in the absence of a visual probe (Craik & McDowd, 1987). Recognition tasks, on the other hand, involve comparison of a probe item to the contents of WM, thus utilize fewer cognitive resources during retrieval (Craik & McDowd, 1987).

Interactions Between Attention and Working Memory. It has been suggested that attention and WM are overlapping cognitive processes. However, the role of attention in WM has not been definitively established. It is unclear whether attention facilitates encoding, maintenance, or both stages of WM. For example, in general, selective attention (visual or spatial) has been proposed as a “gatekeeper” that prioritizes relevant information to be encoded in WM (Awh, Vogel, & Oh, 2006; Murray, Nobre, & Stokes, 2011). It has also been posited that selective spatial attention acts as a rehearsal mechanism that helps to maintain a durable memory store (Awh, Anllo-Vento, & Hillyard, 2000; Awh, Jonides, & Reuter-Lorenz, 1998). However, this view has also been challenged. For example, in one study it was found that visual spatial location WM accuracy was not disrupted or impaired when a secondary visual spatial attention task (i.e., visual search) was performed during spatial WM maintenance (Chan, Hayward, and Theewes, 2009). The authors concluded that spatial attention is not an important component of WM maintenance. We provide insight into these discrepant viewpoints in our current work. For example, study one of this dissertation uses spatially informative pre-cues (presented prior to encoding) that engage spatial attention prior to WM encoding, and compares their effects on memory for spatial locations, across short and long delay periods. If different cueing effects are observed between delay periods, this would lend support to the hypothesis (Awh et al., 2000) that spatial attention plays an important role in WM maintenance.

The overlap between attention and WM is further evidenced by theoretical cognitive accounts. For example, the central executive component of visual WM has been called a “pure attentional system” (Baddeley, 1981). The central executive is essentially a cognitive control mechanism, distributing the appropriate amount of attentional resources to cognitive processes, according to task demands (Baddeley, 1981).

More recently, visual WM has also been called “internal attention” (Kiyonaga & Egner, 2012). This account suggests that this internal selective attention competes with external selective attention that responds to information presented in the environment. Given that both processes share limited cognitive resources, there is a give and take relationship that prioritizes the information to be either internally or external attended. Thus, external stimuli can interfere with the maintenance of encoded information within WM if it gains the focus of attention, and vice versa (Kiyonaga & Egner, 2012).

Summary. According to Baddeley (1981), WM contains a central control process called the central executive that coordinates two storage systems called the visuospatial sketchpad and phonological loop that encode visual features, haptic information, verbal information, and spatial locations. The episodic buffer is a fourth component that was later added to the WM model (Baddely et al., 2011), which might be controlled by the central executive and stores multimodal information as coherent memory representations. However, the role of the episodic buffer in WM is still not fully established. Interactions between attention and WM have been frequently suggested. In more recent theoretical accounts, the central processor overlaps with executive attention, and has been labelled “internal attention”. The overlap between executive attention and WM processes warrants investigation of cue effects on visual spatial WM, that have to date been largely examined in attention tasks. The following section will summarize the fairly limited research in this area.

Facilitating Visuospatial WM

Cueing Visuospatial WM.

Cognitive evidence. Despite the proposed strong interactions between attention and WM, the research on cueing WM is limited, and mostly restricted to uni-modal paradigms (i.e., visual cue, visual memory targets). Behavioural studies have shown that spatially informative visual cues can improve the accuracy of remembering simple colored shapes (Schmidt, Vogel, Woodman, & Luck, 2002; Souza, 2016), and letters (Belopolsky, Kramer, & Godijn, 2008; Ruff, Kristjánsson, & Driver, 2007). A possible explanation for this cue benefit is given by Bays and Husain (2008), who showed that both spatial location and item orientation memory performance decrease when attention is distributed across an increasing number of target items. Thus, the authors suggest that when attention is selectively focused, more resources are devoted to the creation of a memory representation, thus more information (i.e., more feature or location detail) is stored and recalled (Bays &Husain, 2008). Similarly, in a study by Murray and colleagues (2011), the visual cue showed a marginally significant trend for increasing the quality of the stored stimulus representation (Murray et al., 2011). By similar logic, it is likely that increasing WM load will decrease the precision of a stored memory item representation, as resources must be distributed across all the items within WM. It is also possible that a cue might ameliorate the decline in memory item precision to a greater degree with increasing memory load, by more efficiently allocating attentional resources within WM. To explore this further in visual spatial location WM, different memory array sizes are presented in the current research, in order to help elucidate the differential effects of cues across varying memory loads.

There are only a few studies that have investigated cross-modal cueing of WM. Initially, spatially informative auditory cues were shown to provide no benefit to visual feature WM, failing to improve the memory of color of a cued stimulus (Botta, Santangelo, Raffone, Lupianez, & Belardinella, 2011). It was later revealed that auditory cues are only beneficial to visual WM when they cue spatially distinct visual stimuli (Botta, Lupianez, & Sanabria, 2013). The authors suggested that a common perceptual grouping that associates the location of the auditory cue automatically with the location of the visual target is necessary to elicit a cue effect that enhances visual WM (Botta et al., 2013). Therefore in experimental paradigms, it is important to have a distinct spatial dissociation between stimuli presented in right and left space, so that cues and targets can be perceptually grouped. In the present work, we achieved this by presenting items in the memory task in distinct regions of left and right visual space in our experimental paradigm (e.g., in the computerized task, visual stimuli were presented at a reasonable distance from the center of the computer screen, occupying distinct “left hemifield” and “right hemifield” space).

Neural evidence. Regarding neural evidence on cueing of visuospatial WM, the mechanisms involved in spatial attention and WM appear to interact. Moreover, cues that elicit neural activity in attention and WM brain areas ultimately impact recall and recognition. For example, it was found that a visual endogenous cue (central arrow) that predicts the region of space (left or right of fixation) in which a to be remembered target subsequently appears activates the posterior parietal cortex, and suppresses activation of feature detectors in WM brain areas: superior frontal gyrus and occipital areas (Soto et al., 2011). It was posited that spatially informative visual cues might exert their cue benefit by attenuating the visual response of attention grabbing salient items, thereby helping to maintain the focus of attention on the relevant items in WM. A previous study (Pan & Soto, 2010) also found that a similar endogenous visual cue that is spatially informative diminishes the effect of a feature WM cue (where the color or shape of a to be remembered item is flashed briefly during maintenance). Similarly, Murray and colleagues (2011) found that a centrally presented visual cue increases the probability that cued targets (arrows with varying orientations) are encoded into WM and subsequently recalled. Additionally, it was discovered via electroencephalogram (EEG) recordings that early neural markers of selective attention modulate recall accuracy (Murray et al., 2011). In the presence of a cue, participants who display higher mean amplitudes of an early attention directing negativity elicited by occipital cortices, and anterior attention directing negativity produced by the fronto-parietal network, show higher recall of cued targets (arrows in varying orientations, Murray et al., 2011).

Temporal cue order. Research has also investigated the effects of temporal order of cues in WM tasks, and interfering stimuli presented during maintenance, on visual WM recall accuracy. Makovski and Jiang (2007) found that when participants were asked to remember the color of simple target items (colored disks), central “retro-cues” that pointed towards the target location in WM (presented after encoding, indicating the to be remembered item that would later be probed) increased recognition accuracy, compared to a no-cue condition. Furthermore, the authors found that interference from an irrelevant “mask” array during the delay period/maintenance phase does not impair performance when a cue is present (accuracy was the same for cue before interference and no-cue condition). Thus, it was suggested that visual retro-cues protect WM from interference. Peripheral cues that briefly occupied the spatial location of to be remembered items in WM had similar effects, but order of cue presentation and numbers of cues used were important (Makovski & Jiang, 2007). Cues presented before encoding provided more widespread benefit, as cueing one to three locations increased WM accuracy compared to a no-cue condition or an “alerting” condition where all target positions were cued. Retro-cues, however, only effectively increased WM accuracy when one item was cued (Makovski & Jiang, 2007). Therefore, it appears that spatial attention can be more extensively oriented prior to WM encoding.

A follow up study investigated the nature of the retro-cue benefit (Makovski, Sussman, & Jiang, 2008). It was proposed that the cue could exert its effects on WM by either protecting memory items from decay, reducing interference of irrelevant items, simplifying the comparison between the probe item and the memory array, or making the stored information resistant to subsequent input of the probe. Results showed that the retro-cue improved WM accuracy for both simple feature (color) and complex feature (shape) recognition in a change detection task, compared to a no-cue or simultaneous cue (cue presented at probe/response phase). Given that the retro-cue had a longer retention interval before the probe array was presented, compared to the no cue or simultaneous cue condition, the authors concluded that the cue is not simply protecting items in WM from decay (Makovski et al., 2008). Additionally, when the probe array was reduced to a single item, thereby simplifying the comparison process across all cue conditions, the retro-cue benefit to WM performance remained. While the cue increased memory performance across all array sizes (one to six), it only showed an increased advantage for loads of two compared to one, and there were no differences in cue benefits between loads two to six. Given that the cue benefit generally did not increase with memory load, the authors proposed that the cue likely does not reduce interference from other items initially encoded (Makovski et al., 2008). Instead, it appears that the retro-cue acts to help maintain the durability of the information stored in WM, and increase its resistance to subsequent input (i.e., from probe items).

Taken together, these studies suggest that once spatial attention has been deployed, subsequently presented irrelevant information becomes less intrusive to WM performance. Pre-cues also seem to provide more widespread benefit for WM encoding and/or maintenance. It remains to be determined how spatially informative cues can facilitate spatial components of WM (e.g., memory for spatial locations), and whether or not cross-modal cues (e.g., auditory and vibrotactile) can provide benefit to this type of WM, and if so, whether the benefit is similar or greater to that observed for visual cues.

Summary. Research on cueing WM is relatively limited. Uni-modal (visual) cues that are spatially informative improve memory of target features and orientations. Auditory cues provide similar benefit to feature WM, but their effects, as well as the effects of vibrotactile cues on visual spatial WM have not been established. The temporal order of the cue is important, and research shows that pre-cues presented at encoding are more beneficial to WM accuracy than retro-cues, presented during maintenance.

Cognitive and Neural Models of Cueing

There have been several theories put forth that attempt to explain why cues that facilitate spatial attention enhance perception, attention, and WM. The first is a neural model proposed by Driver and Spence (1998) called the *supramodal* attentional theory, which posits that once spatial attention is deployed in one sensory modality, spatial attention systems in other modalities are automatically activated. For example, according to this theory, an auditory cue emanating from the right side of space will enhance or facilitate visual spatial attention networks and quicken response time to detect a visual target in the right side of space. Evidence supporting the supramodal theory has been provided by neuroimaging studies where the temporal sequence of activation in frontal-parietal networks was similar for visual and auditory spatial attention (Green, Doesburg, Ward, & MacDonald, 2011). Specific brain regions or networks are thought to mediate this supramodal system. It has been suggested that the superior colliculus, a midbrain structure, might mediate supramodal attention by activating sensory cortices in a top-down manner (Alvarado, Vaughan, Stanford, & Stein, 2007; Macaluso, 2010). Furthermore, superior intraparietal-frontal networks have been found to mediate shifts of spatial attention following cross-modal cueing (Macaluso et al., 2002). Overall, research suggests that modality specific spatial attention systems use overlapping resources in the same overarching supramodal system.

The supramodal theory does not account for the impact of task demands, nor does it explain how cross-modal cues could be more beneficial than uni-modal cues under certain conditions. The *multiple resource theory* proposed by Wickens (1998) is a cognitive account that provides additional insight into how cross-modal cues might work. This theory posits that there are separate dimensions in which cognitive resources can be divided. It suggests that resource stores are separate for each sensory modality (e.g., visual, auditory, vibrotactile), and further separated into how information is stored or coded (e.g., verbal or spatial). The multiple resource theory also proposes that within each modality, channels of cognitive processing share available cognitive resources (e.g., perception or memory resources are shared with resources utilized during a response phase). The degree to which resources must be shared by separate channels (i.e., visual sensory resources and cognitive resources) determines the magnitude of task interference. For example, in a visual WM task, visual sensory stores and cognitive processing stores will share resources. Therefore, if the visual sensory channel is overloaded in a high load WM task or a visual search task with multiple distracters, then there will be fewer resources available for concurrent visual tasks. By this logic if you wanted to facilitate cognitive performance through the use of a spatially informative cue, this could be better achieved by presenting a cue in a nonvisual modality, such as auditory or vibrotactile cue, as these cross-modal cues would utilize separate resources from those in the visual WM task. Indeed, this was found to be true in a visual change detection task performed by pilots in a simulated cockpit, where vibrotactile cues improved detection rates and quickened response time to a greater degree than visual cues (Sklar & Sarter, 1999).

Summary. Two main models accounting for cross-modal cue benefits have been put forth. The cognitive model is called the multiple resource theory, which accounts for changing task demands or competition for processing resources. The neural model is called the supramodal attention theory, and it suggests that there is an overarching brain region or network within the superior colliculus and/or the superior parietal cortex that is the site of spatial attention facilitation and integration. Thus, these two theories might not be mutually exclusive, and be applicable to interpretations of cross-modal cueing effects under varying task demands.

The next sections will describe the main age-related changes in attention and WM, and then summarize the main cognitive models of aging. The research regarding age differences in the facilitation of attention and WM through the use of cueing paradigms will also be described.

Cognitive Aging

Attention. In term of attention networks, some research has shown that alerting and orienting networks remain relatively stable with age (Mahoney et al., 2010), while other findings have suggested an intact orienting network and age-related decline in alerting mechanisms (Fernandez-Duque & Black, 2006; Festa-Martino, Ott, & Heindel, 2004; Gamboz, Zamarian, & Cavallero, 2010; Jennings, Dagenbach, Engle, & Funke, 2007). The consensus for the executive attention network is that it declines substantially with increasing age (Mahoney et al., 2010; Milham et al., 2002) and this deficit will be described in more detail next. Considering the favourable impact of cueing on attention suggests that it would be more helpful to utilize attention networks that remain intact with age, in order to facilitate some types of cognitive processing. It remains to be determined if it would be more beneficial to use spatially informative and/or alerting cues to facilitate the executive network.

Cognitive task related studies have shown that OA display impairment in visual attention processes relative to YA, namely a deficit in executive control or top down suppression of task irrelevant information (Darowski, Helder, Zacks, Hasher, & Hambrick, 2008; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Madden, 2007). This interferes with the ability to focus on a target and simultaneously inhibit distracter stimuli. As a result, OA display impaired reaction time, relative to YA, on visual target detection tasks in the laboratory, and this impairment is exacerbated with increasing task difficulty or distraction (Hasher & Zacks, 1979).

Aging and WM

Attentional impairments experienced by older adults also affect WM performance. Attentional control is thought to be one of the main cognitive mechanisms mediating the WM deficits (e.g., Craik & Bialystok, 2006; Vaughan, Basak, Hartman, & Verhaeghen, 2008). As a result, OA have been shown to have decreased WM capacity, for both spatial information such as object location (e.g., Kessels, Meulenbroek, Fernández, & Olde Rikkert, 2010; Naveh-Benjamin, 1988; Schmiedek, Li, & Lindenberger, 2009; Light & Zelinski, 1983), spatial routes (e.g., Moffat, Zonderman, & Resnik, 2001) and feature information such as color and object identity (Gilchrist, Duarte, & Verhaeghen, 2016; Vaughan & Hartman, 2009). These declines are attributed to difficulties in storing or maintaining information "online" in their respective WM store (e.g., Kessels et al., 2010, Gilchrist et al., 2016). This decreased maintenance ability of OA is exacerbated in the presence of distracting, task irrelevant information, due to their reduced attentional control (i.e., top down effortful, self-initiated processing; (Beigneux, Plaie, & Isingrini, 2007; Craik, 1994; Kessels et al., 2010; McIntosh et al., 1999).

Clapp and Gazzaley (2010) provide further insight into the cognitive and neural mechanisms responsible for the negative impact distracting information has on WM performance. They found that when OA were instructed to ignore information presented during the maintenance period of a face recognition WM task, they devoted more attentional resources than YA to the “distracting” item. Furthermore, OA also showed decreased WM accuracy relative to YA in face recognition when no distracting stimuli were presented during the maintenance phase. Therefore, decreased maintenance abilities caused by decreased attentional focus could make OA even more vulnerable to the impact of distracters (Clapp & Gazzaley, 2012). While these results might reflect general improvement across all types of WM when attention is focused during maintenance, their results were specific to face processing, which falls under visual feature WM, and is thought to be mediated by separate neural mechanisms than visual spatial WM (Courtney, Ungerleider,, Keil, & Haxby, 1996). Therefore it is unknown if facilitating attentional focus (e.g., cueing attention) in OA will subsequently improve visual spatial WM performance relative to an uncued condition.

In terms of WM response or retrieval mechanisms, while OA show impairments in both recognition (where they must compare a probe item or array to contents in WM) and recall (where no probe item is presented and they must freely retrieve contents in

WM) tasks, it has been proposed that they have more impairment in the recall tasks, due to the increased reliance on attention and WM processing resources (Craik & McDowd, 1987). However, this view has also been challenged, as increasing task demands by presenting higher WM loads and distracting participants during WM maintenance leads to a greater deficit in recognition WM performance of OA, relative to YA (Gazzaley, Sheridan, Cooney, & D'esposito, 2007). We selected a recognition task in the present studies because binary responses (yes/no) could be easily and accurately recorded. Additionally, the nature of our cueing paradigm, and manipulated factors within our WM task were also best suited to a recognition task, similar to experimental procedures that have been previously employed (e.g., Schmidt et al., 2002; Gazzaley et al., 2005).

Cognitive Models of Aging.

Speed of Processing. Salthouse (1979; 1996) originally proposed that all age differences in cognition could be accounted for by a generalized deficit in processing speed. For example, in a WM task, he suggested that if OA were given ample time to complete a task, such as given more time for encoding, or more time to rehearse information in WM, age deficits in memory accuracy would disappear. Generalized slowing in processing speed has been shown to account for certain age-related changes in attention networks (e.g., Mahoney et al., 2010), however, this theory has also been challenged. For example, studies have shown that after accounting for differences in processing speed, age-related slowing remained in tasks that measured visual search target identification (Foster, Behrmann, & Stuss, 1995; McLaughlin et al., 2010), and context processing of a cued target (Rush, Barch, & Braver, 2006). Therefore it has been suggested that the cognitive decline experienced with aging is functional in nature, and not simply due to slowing of neuronal processing.

***Inhibition*.** Hasher and Zacks (1979) posit that the primary age-related deficit in cognition is inefficient inhibition. For example, OA have problems inhibiting prepotent motor responses (Butler & Zacks, 2006), and inhibiting irrelevant task information such as non-targets in attention or WM tasks (Gazzaley et al., 2005; Padgaonkar, Zanto, Bollinger, & Gazzaley, 2017). Attending to irrelevant stimuli is also associated with increased activation of the orienting fronto-parietal network (Geerligs, Saliasi, Maurits, Renken, & Lorist, 2014), as well as feature processing areas (Padgaonkar, Zanto, Bollinger, & Gazzaley, 2017), relative to the activity shown in YA.

Cognitive Control. The cognitive control theory builds on the inhibition theory by suggesting that inhibition deficits can be considered under the broad cognitive aging deficit in executive control (Braver & Barch, 2002), thought to be the main cause of age-related decline across most cognitive domains. This theory posits that there is age-related loss of dopamine receptors in the striatum (Erixon-Lindroth et al., 2005), and extrastriate areas (Kaasinen et al., 2000) that either project to or disrupt the function of the pre-frontal cortex. This in turn can lead to declines in context learning and keeping task goals in mind (Paxton, Barch, Racine, & Braver, 2008), important components of cognitive control. Whereas YA are able to engage in strategic self-initiated proactive cognitive control (e.g., the use of a cue prior to encoding in a WM task), OA are more likely to exhibit reactive (e.g., during the response phase of a WM task where a probe is presented) cognitive control (Paxton et al., 2008; Townsend, Adamo, & Haist, 2006). This reactive control is a type of compensation, and is mediated by increased levels of frontal cortical activation in the proactive phase and response phase for YA and OA, respectively (e.g., Cabeza, Anderson, Locantore, & McIntosh, 2002; Paxton et al., 2008). Similarly, relative to YA, OA require a greater amount of cognitive control to keep attention focused on relevant targets in the presence of distracting irrelevant information (Geerligs et al., 2014). OA are worse at exhibiting cognitive control due to their reliance on more reactive, compensatory mechanisms. Thus, facilitating top down, strategic control would presumably be of greater benefit to cognitive performance of OA, compared to YA.

Facilitating Cognition in Older Adults. Research shows that OA can benefit from different types of environmental support that help facilitate top-down attentional processes. The negative effect of visual distracters on attentional focusing (represented by slower reaction time in target detection or visual search tasks) can be reduced by cue utilization (Pesce, Guidetti, Baldari, Tessitore, & Capranica, 2005), which appears to remain intact for older adults as it involves the posterior neural mechanisms that require the more automatic attentional processes of alerting and orienting. In fact, studies have shown a favorable effect of cueing in healthy OA, relative to YA, resulting in faster reaction times on visual target detection tests (Thornton & Raz, 2006), and greater cue benefit as task complexity increases (McLaughlin & Murtha, 2010). However, contextual cues can sometimes overload cognitive mechanisms such as WM, particularly when task demands or memory load are already high, and hinder performance (Kessels et al., 2010). The cues used in the present study are primarily exogenous, reflexive cues, which will be presented prior to memory encoding, thereby presumably maximizing any potential benefit to WM performance.

To the best of our knowledge, there have been only a few studies beyond the preliminary work conducted in our lab (Curtis & Murtha, 2010), that examined cueing of WM in OA. In our preliminary work, unfamiliar or “novel” objects were presented and participants were asked to remember their location, or their object identity. We found that compared to non-cued trials, spatially informative auditory cues improved visual spatial location WM accuracy at memory arrays with the fewest number of items (two-item arrays) and an intermediate number of items (four-item arrays), and did not improve visual spatial location WM at array sizes with the greatest number of items (eight-item arrays). In the object identity task, cues were only helpful to visual feature (object identity) WM performance at intermediate array sizes (four-item arrays). Additionally increased cue benefit for OA relative to YA was only observed for visual spatial location WM, and at four-item array sizes, whereas the cue benefit was similar for both age groups in the visual object identity WM task. Our results suggested that spatially informative cross-modal cues might be most helpful to OA in a visual spatial location WM task, particularly when memory capacity was reaching capacity (Curtis & Murtha, 2010).

Other work has shown that pre-cues presented prior to encoding, that predict the semantic category (faces or scenes) of target memory items, improve memory for category specific items for OA, relative to non-cued items (Gazzaley et al., 2005;

Padgaonkar et al., 2017). These cues also suppressed response to distracting non-target stimuli presented during WM maintenance, as evidenced by reduced activation in sensory areas mediating non-target stimuli (Gazzaley et al., 2005; Padgoankar et al., 2017). Similar findings have been shown for retro-cues. Gilchrist and colleagues (2016) found that a feature retro-cue presented during maintenance, that cued the color or location of a memory target, improves location memory to an equal degree for both OA and YA.

The present work extended the previous findings by making several methodological changes to our experimental paradigms. First, our experimental paradigm was designed to more carefully investigate visual spatial location WM. For instance, in our experimental stimuli, we uncoupled location and feature based encoding/retrieval by presenting identical memory targets (i.e., same color and shape). This allows us to more fully attribute any cue effects to their impact on facilitating spatial storage and/or processing in WM. Furthermore, we investigated the effectiveness of spatially informative visual, auditory, and vibrotactile pre-cues presented prior to encoding. This allows us to not only compare the impact of different types of cross-modal cues on visual spatial location WM, but also allows us to see whether any observed cross-modal cue benefit is more consistent or greater than the benefit observed for uni-modal cues. Moreover, unlike previous work (Botta et al., 2011; 2013; Curtis & Murtha, 2010), we also compared the effect of spatially informative cues to centrally presented alerting cues, in order to better understand the nature of the spatially informative cue benefit. If spatially informative cues provide a benefit to WM performance, and alerting cues do not improve performance, then we can more assuredly attribute the cueing effect of spatially informative cues to the spatial attentional orienting component of the cue, as opposed to an alerting component that simply elicits an arousal state and subsequently improves WM performance. Finally, we investigated the impact of this cue benefit under different array sizes (four-item arrays and six-item arrays) and under different types of WM maintenance interference, in order to examine the impact of task demands on any observed cue benefit.

Summary. In general, research has suggested that orienting and alerting attentional networks remain relatively stable with age, whereas executive attention suffers substantial decline. Executive attention is considered analogous with attentional control, and is thought to mediate most of the attention, as well as visual spatial, and visual feature WM deficits experienced with increasing age. Previous accounts of age-related generalized cognitive slowing fail to fully account for these deficits. The cognitive control theory of aging builds on the inhibition theory to explain generalized age-related cognitive decline, and attributes it to inefficient executive processing, thought to be mediated by the frontal lobes.

Research shows that OA can benefit from environmental support such as visual, semantic, or verbal cues presented prior to or during encoding, in order to improve their visual attention of feature WM. However, there are mixed findings regarding whether OA experience increased cue benefit relative to YA, and whether they show similar benefits as observed on spatial location WM tasks.

The next section will discuss the overall research aims of this dissertation, and the questions we sought to answer in studies one and two. Our specific predictions for these questions will also be described.

Research Aims and Hypotheses

The experiments carried out in this dissertation provide insight into the cognitive underpinnings of the cross-modal cueing of visual spatial WM in younger and older individuals. The following section describes our specific research questions and hypothesis.

Research Aim One

Our first research aim was to 1) *examine the impact of cross-modal relative to uni-modal cues on spatial WM for both YA and OA.* We had four main questions we wished to answer, and several predictions. The first research question was:

Q1A) Do spatially predictive auditory and vibrotactile cues improve visual spatial location working memory?

Based on previous research on visual attention, and cross-modal cueing of feature WM showing that cues quickened response time (e.g., Schmidt et al., 2001) and improved recognition accuracy (Botta et al., 2013), respectively, we predicted that, in the present studies, auditory and vibrotactile cues would improve visual spatial location WM performance relative to non-cued trials.

Given that we also compared the impact of these cues with a spatially predictive visual cue, which has been shown to improve visual spatial location WM relative to a non-cued condition (Murray et al., 2011), we also sought to answer the second question:

Q1B) Do cross-modal auditory and vibrotactile cues provide more benefit to visual spatial location WM compared to uni-modal visual cues?

Given that our tasks are visually complex and presumably tax visual resources, we predicted that auditory and vibrotactile cued trials would improve spatial location WM accuracy relative to non-cued trials to a greater degree than visual cues. Such a result would support multiple resource theory (Wickens, 1998). According to this theory, when the demand for visual resources increases, individuals should show a greater benefit of cues in other modalities that utilize cognitive resources in separate modality "stores".

We were also interested in comparing the impact of spatially informative cues to centrally presented alerting cues, thus the third research question was:

Q1C) Do spatially informative cue benefits differ from centrally presented or alerting cue benefits?

While alerting cues have been shown to quicken response time in attention tasks (e.g., Luca & Murtha, 2009), albeit to a lesser degree than spatially informative cues, their impact on WM has not yet been established. It is important to examine whether any observed spatially informative cue benefit is due to its spatial orienting component (orienting spatial attention to a region in space), or simply to a phasic alerting effect that activates the alerting or arousal attention system (Posner & Rothbart, 2007), and subsequently improves WM. We predicted that in a spatial location WM task, alerting cues would provide less benefit (defined as memory performance on cued trials minus non-cued trials) to WM performance than spatially informative cues.

This dissertation also attempts to determine if there are enhanced cueing effects for older adults. Thus, our fourth research question was:

Q1D) Do OA show a greater cue benefit relative to YA?

There is age-related decline in spatial WM, thought to be due to reduced or less efficient executive functioning, mediated by frontal cortices, and OA have shown greater benefit from forms of environmental support in both attention (McLaughlin & Murtha, 2010) and WM (Gazzaley et al., 2005; Padgaonkar et al., 2017) tasks. Therefore, we predicted that relative to YA, OA would benefit to a greater degree from the use of spatially informative pre-cues. If OA are able to utilize these cues, it also suggests that the orienting attention system remains stable with age (Mahoney et al., 2010). Such findings would support the use of this intact orienting system as a main feature of any real world application of environment support paradigms, in order to maximize benefit of cues to higher order cognitive functions such as WM.

Research Aim Two

The second main research aim was 2) *determine the nature of the cross-modal cue benefit.* By using spatial memory arrays of different capacities (four, or six locations occupied per array), altering maintenance/delay intervals between cue and target, and by presenting distracting information during the maintenance interval/delay, we were able to assess several questions. The first we wished to answer was:

Q2A) Can cues improve visual spatial location recognition at higher WM loads relative to lower WM loads? Are there differences between YA and OA?

As it has been suggested that cues exert their effects on feature processing when demands for focused attention are high (Dufour, 1999), we predicted that there would be a greater cue benefit in the larger array size of six-items, relative to four-items. As cues are also thought to act as a spatial rehearsal mechanism during WM maintenance (Awh et al., 2000), we predicted they would be most helpful during a longer maintenance delay of 1800ms, compared to a shorter 900ms duration, as there would be more time for spatial refreshing/rehearsal on cued trials. Given that OA have lower WM capacity for spatial location information compared to YA (e.g., Kessels et al., 2010), we predicted that for OA, the cues would facilitate WM performance to a greater degree across both array sizes, especially when task demands were high (e.g., at array size six and the longer maintenance delay period).

An additional research question we wished to answer was:

Q2B) Do cues prolong decay of visual spatial location WM? Are there differences between YA and OA?

In our first study, we utilized two different maintenance delays (900ms vs. 1800ms). We predicted that in each array size, memory performance between the short and long delay would decline to a lesser degree on cued trials relative to non-cued trials. This would presumably be due to the increased attentional focus and spatial rehearsal during maintenance on cued trials, leading to spatial location representations that are more robust to degradation. It was unclear whether OA and YA would differ in the performance on cued and non-cued trials across the two different maintenance delays.

Q2C) Do cues help protect encoded information from interference? Are there differences between YA and OA?

In our second study, we presented interference during the maintenance delay in a spatial location WM task. This interference was either to be ignored, therefore acted as a distracter, or attended and compared, and therefore acted as an interrupter. We predicted that cues would still improve performance relative to non-cued trials in the ignore interference task, and expected that they would become more important and beneficial to performance when task demands were higher, during attend and compare interference trials. Furthermore, we predicted that the visual resource demand of the attend and compare interference would result in a modality specific cue effect, such that auditory and vibrotactile cues would be more helpful, relative to visual cues. Such a result would support multiple resource theory (Wickens, 2008).

We also expected to observe age-related cueing effects that depended on the type of interference presented. Given that OA are worse than YA at inhibiting irrelevant information during attention and WM tasks (Gazzaley et al., 2005; Padgaonkar et al., 2017), we predicted that relative to YA, OA would show greater cue benefits (performance on cued trials relative to non-cued trials) in the ignore interference task, particularly in more resource demanding situations such as high memory loads (array size of six-items compared to four-items). In the attend and compare interference task, we predicted that both age groups would show improved spatial location WM performance relative to non-cued trials, and given the difficulty of this task due to its high visual memory load and secondary task (comparison) intrusion during WM maintenance, cross-modal cues would be more beneficial than uni-modal cues, supporting multiple resource theory (Wickens, 2008).

Summary

The questions posed in the present dissertation are important ones to answer, as they will help increase our understanding of the impact of and cognitive underpinnings of environmental support (e.g., exogenous uni-modal and cross-modal cues) on WM processes across the lifespan. Our findings will also provide insight for the design of potential real world applications of our cueing paradigms. Such applications could be especially helpful to OA, who are more vulnerable to the effects of cognitive decline in their everyday lives.

Our two empirical studies are formatted as journal article manuscripts. Each manuscript will constitute one dissertation chapter that describes the background, methods, results, and interpretations of the research study. Implications of the findings and areas for future research will also be discussed. Each manuscript will be followed by a short chapter that describes any additional data analysis details (and appendix information) that were not fully described in the manuscript.

Chapter 2: Improving Visual Spatial Working Memory in Younger and Older Adults: Effects of Cross-modal Cues (Study 1)

Summary

Spatially informative auditory and vibrotactile (cross-modal) cues can focus visual attention and quicken response time in target detection and discrimination tasks. However, research is limited on the influence of cues on spatial working memory (WM) across the lifespan. We investigated the effects of cues (spatially informative or alerting pre-cues vs. no cues), cue modality (auditory vs. vibrotactile vs. visual cues), memory array size (4 vs. 6 items), and maintenance delay (900ms vs. 1800ms) on spatial location memory accuracy in younger (aged 18-26) and older (aged 60-78) participants. We observed a significant interaction between spatially informative cue type, array size, and delay ($p < .05$). Both age groups benefitted equally from the presence of a spatially informative cue (regardless of modality), displaying higher accuracy on cued compared to non-cued trials. Greater benefits were seen across long delays in the four-item array, and the greatest cue benefit was observed for the short delay six-item array. Furthermore, individuals with low spatial spans benefitted only from auditory and vibrotactile cues, whereas, individuals with high spatial spans were able to utilize all cue modalities to improve memory performance once task difficulty increased. We found that alerting cues generally impaired performance across both array sizes. The present results are the first to show that spatially informative auditory and vibrotactile cues can improve spatial location WM. Furthermore, we showed that older adults are similar to younger adults at

using these types of cues. Future research should investigate the brain mechanisms mediating these cue effects across the lifespan.

Introduction

Working memory (WM) is defined as the short term maintenance and manipulation of information (Baddeley, 1981; Hitch & Baddeley, 1976; Kiyonaga & Egner, 2012). Within this cognitive system, the visuospatial sketchpad stores visual features and spatial locations. Visual spatial WM refers to memory of the latter. Attention plays a role in WM as well, with some researchers suggesting that attention and WM are, in fact, overlapping cognitive processes (Kiyonaga & Egner, 2012). Selective attention is thought to act as a gatekeeper that prioritizes relevant information to be encoded in WM (Awh, Vogel, & Oh, 2006; Murray, Nobre, & Stokes, 2011), and spatial attention as a rehearsal mechanism that helps to maintain a durable memory store by allocating attention resources to the mental memory representation (Awh, Anllo-Vento, & Hillyard, 2000).

Compared to younger individuals, healthy older adults (OA) show impairments in visual spatial attention and visual spatial WM. For example, their ability to focus on a target and simultaneously inhibit distractor stimuli is impaired due to a deficit in attentional control (e.g., Darowski, Helder, Zacks, Hasher, & Hambrick, 2008; Gazzaley, Cooney, Rissman, & D’Esposito, 2005; Hasher & Zacks, 1979; Madden, 2007)**.** This type of attentional impairment leads to WM deficits in OA (e.g., Craik & Bialystok, 2006; Vaughan & Hartman, 2009). As a result, OA have been shown to have poorer WM for both spatial information such as location (e.g., Kessels, Meulenbroek, Fernández, &

Olde Rikkert, 2010), and feature information such as object identity (e.g., Gilchrist, Duarte, & Verhaeghen, 2016; Vaughan & Hartman, 2009). This decreased WM ability is exacerbated in the presence of distracting, task irrelevant information, due to the increased demand on attentional control (Beigneux, Plaie, & Isingrini, 2007; Craik, 1994; Kessels et al., 2010; McIntosh et al., 1999). Therefore it is important to investigate strategies that are known to help focus attention and enhance control, in order to assess their impact on subsequent cognitive processing, such as WM.

One way in which attention can be facilitated is through the use of cues. There is extensive evidence showing how spatially informative visual cues that engage and focus spatial attention and predict the location of an upcoming visual stimulus can decrease response time in target detection (e.g., Driver & Spence, 1998; Mcdonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Posner, 1980; Spence & Driver, 1997). In addition, spatially informative cues that differ in modality from the target (i.e., cross-modal cues such as auditory or vibrotactile cues) show either similar benefits to visual target detection (e.g., Ho, Tan, & Spence, 2005; Hopkins, Kass, Blalock, & Brill, 2016; McDonald et al., 2003), and localisation discrimination (Schmitt, Postma & De Haan, 2000; 2001), or greater benefits to visual change detection response time (Sklar & Sarter, 1999). Cues that are centrally presented, or “alerting” have also been shown to benefit target localization discrimination, but to a lesser degree than spatially informative cues (Luca & Murtha, 2009). Furthermore, research shows that OA can benefit from different types of environmental support such as cues that help facilitate attentional processes (Pesce, Guidetti, Baldari, Tessitore, & Capranica, 2005). In fact, studies have shown that compared to YA, healthy OA show greater cueing effects, resulting in faster reaction times on visual target detection (Thornton & Raz, 2006), and visual search (McLaughlin & Murtha, 2010) tasks, and greater cue benefit as task complexity increases (McLaughlin & Murtha, 2010). However, contextual cues can hinder WM when task demands or memory load are already high and hinder maintenance of encoded items (Kessels et al., 2010). Therefore although the cues used in the present study are informative, they are primarily exogenous, reflexive cues, which were presented prior to memory encoding, in order to maximize potential benefit to WM. Studying how cues can facilitate top down processing in OA is an important first step in developing potential real world training programs aimed at improving cognitive performance (Pesce et al., 2005). Improving cognitive performance could have a positive impact on everyday functioning (e.g., remembering locations of household items, driving), and could ultimately lead to an increased quality of life by helping OA maintain independent living (Ball et al., 2002).

There is evidence supporting a greater quantifiable benefits (in terms of overall quickening of response time) of using cues in the same modality as the target relative to cross-modal cues (e.g., Driver & Spence, 1998). However, cross-modal cues could arguably prove to be of greater benefit in real world scenarios (Ho et al., 2005), where engaging visual attention is particularly challenging due to the wide variety of visual distracters competing to grab one’s attention (i.e., billboards, traffic lights, and signs). Real world cross-modal cueing paradigms could also be designed with greater flexibility. For example, cue-target spatial separation is less critical for auditory and vibrotactile cues, as their cue benefits extend over a wider region of visual space (Gray, Mohebbi, &

Tan, 2009). In comparison, as cue-target separation increases for visual cues, response time to target detection increases monotonically (Gray et al., 2009).

Despite the proposed interactions between attention and WM, only a handful of studies have examined the effect of attention focusing cues on WM. Most of these studies have incorporated uni-modal paradigms (visual cue/visual targets) that assess feature WM in young adults (YA). For example, it has been shown that visual cues that are spatially informative (attention orienting cues that predict the location of an upcoming target) can improve the accuracy of remembering simple colored shapes (Schmidt, Vogel, Woodman, & Luck, 2002; Souza, 2016), and letters (Belopolsky, Kramer, & Godijn, 2008; Ruff, Kristjánsson, & Driver, 2007) in YA. Similarly, Murray and colleagues (2011) reported that a centrally presented visual cue (arrow pointing left or right) increased the probability that cued targets (arrows with varying orientations) would be encoded into WM of YA and subsequently recalled. Bays and Husain (2008) have shown that when attention is selectively focused, more resources are devoted to the creation of a memory representation, thus more information is stored and recalled. It was posited that spatially informative visual cues might attenuate the visual response of attention grabbing irrelevant salient items, thereby helping to maintain the focus of attention on the relevant items in WM (Pan & Soto, 2010; Soto, Mok, McRobbie, Quest, Waldman, & Rotshtein, 2011). Given that these previous studies were assessing visual WM (e.g, memory for object features such as color or object identity), we were interested in the impact of spatially informative cues on visual spatial location WM facilitation. Previous research showed that these types of cues were more helpful for visual spatial location WM, compared to feature WM (Curtis & Murtha, 2010).

As previously mentioned, the research on cues and WM is mostly limited to uni-modal paradigms and YA. To the best of our knowledge, only two studies beyond the exploratory work completed in our lab (Curtis & Murtha, 2010) have looked at the effects of cross-modal cues on WM. Initially it was discovered that spatially informative auditory cues did not increase the accuracy of feature WM (color of square in a spatial array; Botta, Santangelo, Raffone, Lupianez, & Belardinella, 2011). However, in a follow-up study it was found that these spatially informative auditory cues were only effective when they were associated with visually distinct hemifields (Botta, Lupianez, & Sanabria, 2013). In other words, a clear dissociation between the left and right visual stimulus area was required. In the present study, we did not present any target items in the center or just left/right of center on the computer screen, thereby cueing participants to distinct left and right hemifields. We extend the results of Botta and colleagues (2011, 2013) by comparing auditory cues to vibrotactile and visual cues, and including both YA and OA participants. In our experimental procedure, we also target a more specific type of WM. Although the previously mentioned studies were seminal in showing that auditory cues focus attention and improve visual WM, they did not assess the separate storage components of WM (i.e., visual and spatial). Therefore in order to address whether cross-modal cues can improve visual *spatial location* WM, we presented single colored stimuli (gray rectangles) in our memory arrays and asked participants to remember their location only. Furthermore, we assessed the impact of cues on WM accuracy at two different maintenance delays, in order to help us better understand cue effects on memory decay.

In order to maximize any potential cue benefits, we considered the research on the temporal order of cues and their differing impact on WM. For example, Makovski and Jiang (2007) found that when participants were asked to remember the feature of simple target items (colored disks), central “retro-cues” that pointed towards the target location in WM (presented after encoding, indicating the target item that would later be probed) increased recognition accuracy, compared to a no-cue condition. Given that interference from an irrelevant “mask” array during the delay period/maintenance phase did not impair performance when a cue was present (accuracy was the same for cue before interference and no-cue condition), it was suggested that the visual “retro-cue” protected WM from interference. These retro-cues, however, only effectively increased WM accuracy when one item was cued (Makovski & Jiang, 2007). Additionally, it was found that the retro-cue benefit did not increase with memory load indicating that it does not reduce interference from other items initially encoded (Makovski, Sussman & Jiang, 2008). Instead, it appears that the retro-cue acts to help maintain the durability of the information stored in WM, and increase its resistance to subsequent input (i.e., from probe items). Alternatively, cues presented before encoding or “pre-cues” provided more widespread benefit, as cueing one, two and three locations increased WM accuracy compared to a no-cue condition or an “alerting” condition where all target positions were cued (Makovski & Jiang, 2007). Therefore, it appears that spatial attention can be more extensively oriented prior to WM encoding. Finally, prior research has shown that OA do not benefit from a visual retro-cue (Duarte, Hearons, Jiang, Delvin, Newsome, & Berhaeghen, 2013), relative to younger adults (YA). Therefore to maximize potential benefit to our OA participants, pre-cues were used in the present study. Taken together, previous research suggests that once spatial attention has been deployed through the presentation of pre-cues, subsequently presented irrelevant information becomes less intrusive to WM performance. Pre-cues also provide more widespread benefit for WM encoding and/or maintenance relative to retro-cues.

In sum, we investigated the impact of spatially informative cross-modal (auditory, vibrotactile) and uni-modal (visual cues) on visual spatial location WM recognition performance for YA and OA. We also compared these cues with alerting or centrally presented cues, in order to determine whether the increased cue benefit of spatially informative cues in attention tasks is also observed visual spatial location WM. Additionally, while visual cues have been shown to improve WM, the research on cross-modal cues is limited, and has never addressed the impact on visual spatial WM across either age group. Given that our visual environment is becoming increasingly complex, cross-modal cueing paradigms could be of greater use in real world applications. Cross-modal paradigms might also be easier to implement compared to uni-modal designs, given that they can be designed with greater flexibility (Gray et al., 2009). Overall we predicted that in general cues would improve spatial WM performance compared to no cues, but spatially informative cues would provide greater benefit than alerting cues. In addition, we predicted that cross-modal cues would provide the greatest benefit. We also expected both age groups to benefit from the cues, but OA to show the most benefit. To better understand the nature of any observed cue benefits, we manipulated array size and maintenance delays. By using spatial memory arrays of different sizes (four, or six locations occupied per array) and altering maintenance/delay intervals between presentation of memory arrays and response phases, we were able to better assess whether cues improve recall at higher WM loads and/or prolong decay of spatial location, respectively. We predicted that cues would help maintain memory performance as array size increased, and across longer delay periods.

The results of the present study help us to better understand the cognitive underpinnings of the cross-modal spatial cueing of visual spatial WM in YA and OA. These findings will also help increase our understanding of the influence of the environmental support provided by cues on WM processes in OA with the aim of focusing attention and enhancing spatial WM. Eventually we hope this will inform the design of effective cuing paradigms which could be of use in real world settings such as driving scenarios.

Methods

Participants

A total of 18 YA (aged 18-26, *M* = 20.3, *SD* = 2.4) and 18 OA (aged 60-78, *M* = 66.1, *SD* = 5.0) participated in the present study. The YA group were recruited from York University undergraduate research participant pool, and received course credit for their participation. The OA group were recruited from the York University OA participant pool, and through free advertisements placed on online community websites. They were compensated $10 per hour for their participation. All participants gave informed consent and had normal, or corrected to normal vision and hearing. They also reported no current diagnoses of anxiety, depression, uncontrolled heart conditions, diabetes mellitus, sleep disorders, or any memory impairment disorder such as Mild Cognitive Impairment (MCI) or Alzheimer Disease (AD).

Neuropsychological Testing

An initial telephone screening with the modified Telephone Interview for Cognitive Status survey (TICS-m; Brandt, Spencer, & Folstein, 1988) was administered to all potential OA participants. Scores of 31 and above were considered acceptable, and indicative of no cognitive impairment (e.g., MCI, or dementia), based on previously published criteria for the cut-off for possible memory impairment (Knopman et al., 2010). All other neuropsychological tests were the same for each age group, and were administered during the experimental session in the laboratory. These tests were meant to screen for depression, anxiety and/or cognitive impairments (see Table 1 for test battery). They provided baseline measurements of general intelligence (crystallized and fluid ability), verbal WM visual spatial location WM.

Apparatus and Stimuli

Memory Arrays and Probe Stimuli. The experiment was programmed in Superlab Pro 5.0 and presented on a Dell Latitude E6530 laptop. All stimuli were presented against a light gray background. Memory arrays consisted of dark gray rectangles measuring 6 x 4cm, and were equal in saturation and luminance levels. Arrays consisted of either four or six rectangles. The rectangles occupied locations in an invisible five by five grid within the entire computer screen (measured 34.5 x 19.5cm in area), with an equal number of items always occurring in each hemifield. No items ever appeared in the center column of the grid. The probe stimulus was the same shape (rectangle) and size (same dimensions) as the memory targets, and was black in color.

Cues. Visual cues consisted of a hollow black rectangle (outlining the left/right "grid") presented in either the right or left hemifield of the computer screen. The auditory cue was a 1500Hz tone, presented at 80db, with a duration of 100ms, and was programmed using the Audacity software program (Version 1.2.5). The auditory cue was presented to either a left or right external speaker, lined up against the computer screen, approximately 19cm from fixation. Vibrotactile cues were 250 Hz tones presented via tactors (model C2; Engineering Acoustics Inc.) encased in styrofoam padding and fixated to the dorsal side of the forearm, with the anterior edge of tactor lined up with wrist (Chen, Santos, Graves, Kim, & Tan, 2008) via Velcro straps. Participants were presented with white noise via headphones when performing the vibrotactile cueing task, in order to eliminate any noise contributions of the vibration. Cues were spatially informative, and always correctly predicted the location of the target rectangles (i.e., right visual cue/targets in right hemifield; right speaker/targets in right hemifield, etc.).

Procedure

To control for time of day, which has been shown to affect cognitive performance of YA and OA differently (May, Hasher, & Stoltzfus, 1993), half of the YA (*n* = 9) and OA (*n* = 9) completed the experiment in the morning and the remaining participants in each age group completed the experiment in the afternoon.

Hearing and Vibrotactile Tests. To confirm that participants could properly localize the auditory and vibrotactile cues as coming from the left or right, they were administered two separate tests. In each test, 10 trials were presented where tones or vibrations (depending on the cue condition) were presented randomly to the left, right, both or none of the speakers or tactors, respectively. Participants were required to respond verbally to the experimenter with the location (left, right, both, or none) of the tone or vibration. All participants were able to correctly localize the cues 100 percent of the time.

Spatially Informative Cue Task. As illustrated in Figure 1, each trial began with participants fixating on a central cross-hair for 500ms while simultaneously performing an articulatory suppression task. Articulatory suppression minimizes the potential naming of target memory items (e.g., subvocally rehearsing the verbal location of an item by repeating “top right corner”), a process that could aid WM rehearsal. Thus, we can more purely measure spatial WM when the potential impact of subvocal naming and subvocal rehearsal is minimized (Salame & Baddeley, 1987). Two words “blah blah” (Salame & Baddeley, 1987) appeared directly above the cross-hair for 500ms, and participants were asked to rehearse and repeat these words out loud until the response portion of the trial. The experimenter observed participants to ensure adequate performance of this task. Next, either a cue (100ms) or a blank interval (100ms; non-cued trial) was presented. To eliminate temporal cueing, a blank delay of either 50ms or 100ms was then presented. This ensured varying stimulus onset asynchronies (SOA) of 150ms and 200ms, respectively. Memory arrays were then presented (random presentation of either four or six-item arrays) for 100ms (Schmidt et al., 2002), followed by a blank “maintenance” delay period of either 900ms (short delay) or 1800ms (long delay). Finally, a probe (darkened gray rectangle occupying one of the locations that was or was not previously occupied in the memory array) appeared and participants were required to indicate “yes” (via a designated keyboard response with their dominant hand) if the probed location was previously occupied, or “no” if the probed location was new. Participants were instructed to respond as soon as they knew the answer, but to focus on accuracy over speed. To help maintain motivation in the task, participants also received feedback at the end of every trial, indicating if they answered correctly or made an error. The trials were self-paced, and participants pressed a designated key when they were ready for the next trial. The participant viewing distance was approximately 57cm from the computer screen. To minimize eye movements, participants were instructed to remain fixated on the central crosshair for the duration of each trial.

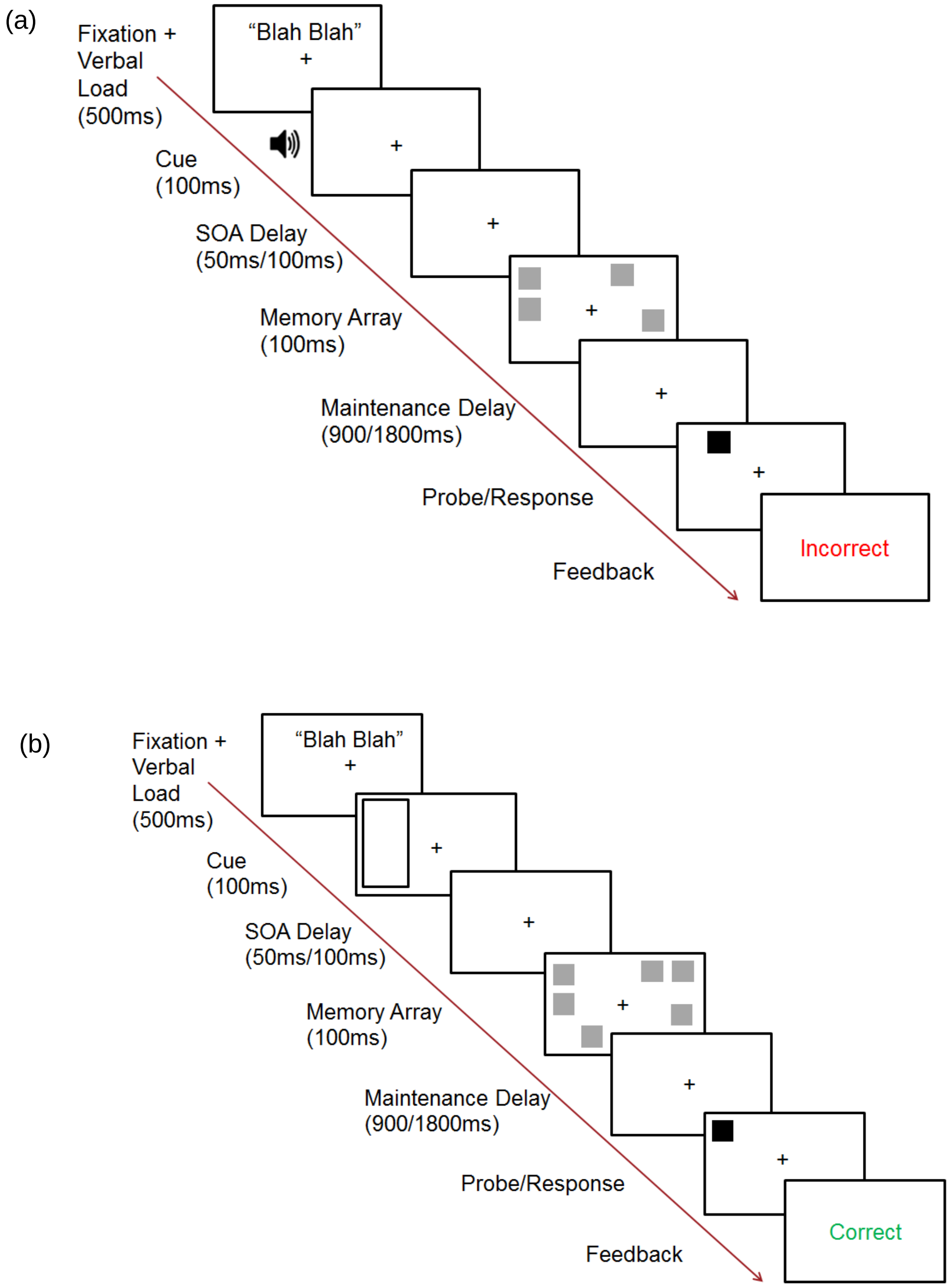

Figure 1. Schematic representation of experimental procedure. A spatially informative auditory cued four-item array trial requiring a “no” response (a) and visually cued six-item array requiring a “yes” response (b) are depicted. Target stimuli/probes are for illustration only and are not drawn to scale.

Cue types were blocked, so that only one type of cue modality occurred within a block of trials. There were a total of 128 trials per cue modality (auditory/vibrotactile/visual), separated into blocks of 32 trials (4 blocks per modality) to reduce fatigue. Each block took approximately 3 minutes to complete. The orders of cue blocks were determined through Latin square partial counterbalancing (possible block orders: auditory, visual, vibrotactile; visual, vibrotactile, auditory; or vibrotactile, auditory, visual). Within each block, there were 16 cued and 16 non-cued trials (50% cued trials), including an equal number of array sizes (four/six) and delays (900/1800ms). Half of the trials within each block were “yes” trials (probe rectangle occupied a previously presented location) and half were “no” trials (probe rectangle occupied a new location). Trial types were randomized within each block. Participants completed eight practice trials before the start of each new set of blocks (within a cue modality), and these trials were excluded from analysis.

Alerting Cue Task. The only difference between the spatially informative cue and alerting cue task procedure was the type of cue used and the distribution of cued trials vs. non-cued trials. All visual stimuli and responses required remained the same, and there were four blocks of trials presented for each modality. For this task, the modality specific alerting cues consisted of two auditory tones, two vibrations, or two visual cues, presented at the same time, to either both speakers (auditory alerting cue), both tactors (vibrotactile alerting cue), or both sides of the computer screen (visual alerting cue).

Participants were informed that in these trials, the cue was meant to keep their attention focused on the task, and to alert them of upcoming stimuli. Cued trials were presented 25%[1] of the time (Luca, & Murtha, 2009; McLaughlin et al., 2014). There were a total of eight alerting cued trials per block, and 24 non-cued trials.

Data Analysis

Our outcome variable of interest was memory recognition performance. This was calculated using d prime (d'), which represents corrected accuracy that controls for response bias (MacMillan & Creelman, 2004), and is defined as the standardized hit rate (proportion of trials with a correct identification or “yes” response to a previously occupied location) minus the standardized false alarm rate (proportion of trials with an incorrect identification “yes” response to a new location; Swets & Green, 1966): d' = z(hit rate) – z(false alarm rate). Higher d' values correspond to better memory performance.

Two separate analyses were conducted for the WM task with spatially informative cues, and the WM task with alerting cues. For each analysis, the d' values were entered into a five-way mixed model ANOVA evaluating the between participant factor age group (YA vs. OA), and within participant factors cue modality (visual vs. auditory vs. vibrotactile), cue type (cued vs. non-cued), array size (four vs. six items), and maintenance delay (short: 900ms vs. long: 1800ms). To account for violations of

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[1] Due to the uninformative nature of the centrally presented alerting cue, participants are likely to ignore it if it is presented in a high proportion of trials (Robertson, Mattingley, Rorden, & Driver, 1998). Therefore, in order for participants to effectively use the cue, a cued percentage of 25% of trials is often used (Luca & Murtha, 2009, McLaughlin & Murtha, 2010)

sphericity, degrees of freedom were adjusted (Huynh & Feldt, 1976). An alpha level of .05 was set as the criterion level for inferential analysis. Significant main effects and interactions were clarified by conducting post-hoc pairwise comparisons with Bonferroni control. Effect sizes (partial eta squared values) are reported where available.

Results

Demographics and Neuropsychological Test Scores

Demographic information and baseline neuropsychological test scores are provided in Table 1. Participants scores were compared against age matched standardized scores, and all participants scored within normal limits.

Table 1

Demographic Variables and Neuropsychological Test Scores for Each Age Group

	YA	OA
Variable	*M* (*SD*)	*M* (*SD*)
Education (years)***	12.8 (.99)	15.2 (2.0)
Sex (M:F)	6:12	11:7
Handedness (R:L)	16:2	17:1
TICS-m	--	37.9 (4.2)
HADS-anxiety**	6.6 (2.4)	3.2 (3.8)
HADS-depression	3.2 (2.6)	2.0 (2.2)
Shipley-2 (Standard Score)	103.8 (11.9)	105.2 (9.5)
Digit Span (forward span)	6.7 (1.2)	7.1 (1.3)
Digit Span – Total (SS)	9.6 (2.0)	10.8 (1.7)
Spatial Span (forward span)	5.3 (.98)	5.4 (.04)
Spatial Span - Total (SS)	9.3 (1.9)	10.5 (2.2)

Note. YA = younger adults; OA = older adults; TICS-m = modified Telephone Interview for Cognitive Status (raw score out of 50; Welsh et al., 1993); HADS – Hospital Anxiety and Depression Scale (raw score out of 21; Zigmund & Snaith, 1983); Shipley-2 (Composite score: verbal + reasoning; Shipley, Gruber, Martin, & Klein, 2009); Digit Span (forward raw span score; Wechsler, 1997); Spatial Span (Corsi Block test; forward raw spatial span score; Wechsler, 1997); SS (age-corrected scaled score);
Significant differences between groups: *$p < .05$. **$p < .01$. ***$p < .001$.

There were no differences on any demographics or neuropsychological measure except education (OA had significantly more years of education than YA, $p < .001$), and the anxiety subscale of the HADS (YA scored significantly higher than OA, $p = .003$)[2]. All OA scored within the normal range on the TICS-m (31 or higher).

Spatial WM Task: Alerting Cue

A five-way ANOVA revealed a main effect of cue type (F (2.0, 64.0) = 35.1, $p < .001$, $\eta_p^2 = .51$) and a main effect of array size (F (2.0, 64.0) = 43.7, $p < .001$, $\eta_p^2 = .51$). As shown in Figure 2, these main effects were further qualified by a significant interaction between cue type and array size (F (2.0, 64.0) = 10.2, $p = .003$, $\eta_p^2 = .23$). The d' values (higher d' means better visual spatial location WM recognition) indicate that the alerting cue significantly worsened visual spatial location WM performance across both array sizes. Scores on alerting cued trials were lower compared to non-cued trials for both four-item (md = .43, *SEM* = .06, $p < .001$), and six-item (md = .18, *SEM* = .07, $p = .013$) arrays.

Surprisingly, we did not observe a main effect of age group (F (2.0, 64.0) = 43.7, $p < .001$, $\eta_p^2 = .51$). However, we did observe a two-way interaction between age group and array size (F (3.1, 16.9) = 6.19, $p = .019$, $\eta_p^2 = .153$). When collapsed across modality, cue type, and delay period, the performance of YA on four-item trials (M = 1.71, *SEM* = .14) did not significantly differ ($p = .60$) from the performance of OA on

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[2] We conducted a Pearson product moment correlation to investigate the relationship between anxiety and education with our dependent variable across all conditions. There was negligible impact. Education did not correlate with any levels of our outcome variable ($p > .05$), and anxiety only significantly correlated ($p < .05$) with 1 level of all experimental conditions. As a result we chose to report the analysis without covarying out the impact of either of these two factors.

four-item trials (*M* = 1.61, *SEM* = .14). However, on six-item array trials, the performance of YA (*M* = 1.51, *SEM* = .11) was significantly higher (*p* = .04) than the performance of OA (*M* = 1.17, *SEM* = .11).

All other main effects and interactions were non-significant (*p* > .05).

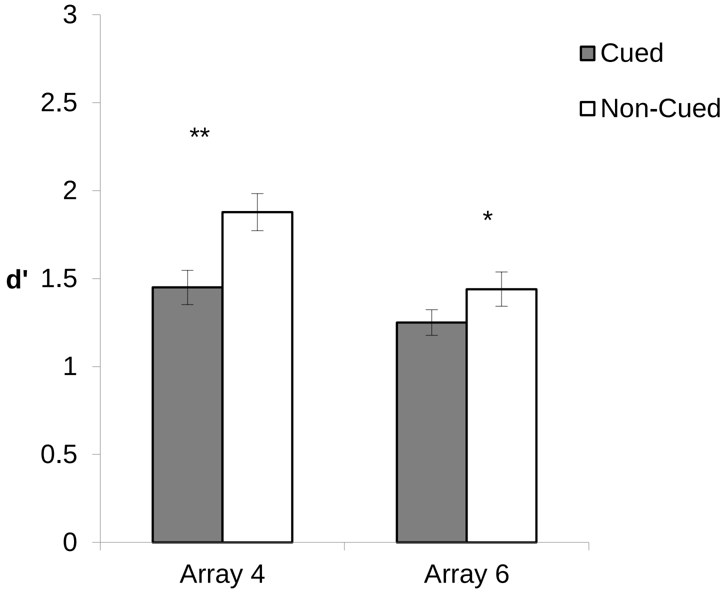

Figure 2. Cue type x Array size interaction. Mean d' values +/- *SEM* (error bars) for younger and older adults on visual spatial location WM task during alerting cued (dark gray bars) and non-cued (white bars) trials. * $p < .05$; **$p < .01$

Spatial WM Task: Spatially Informative Cue

A five-way mixed model ANOVA revealed several interesting findings. Most notably, we observed a significant three-way interaction between cue type, array size, and delay (F (1, 34) = 6.04, $p = .019$, $\eta_p^2 = .15$). As shown in Figure 3, collapsed across age group and modality type, performance on cued trials was significantly higher than performance on non-cued trials.

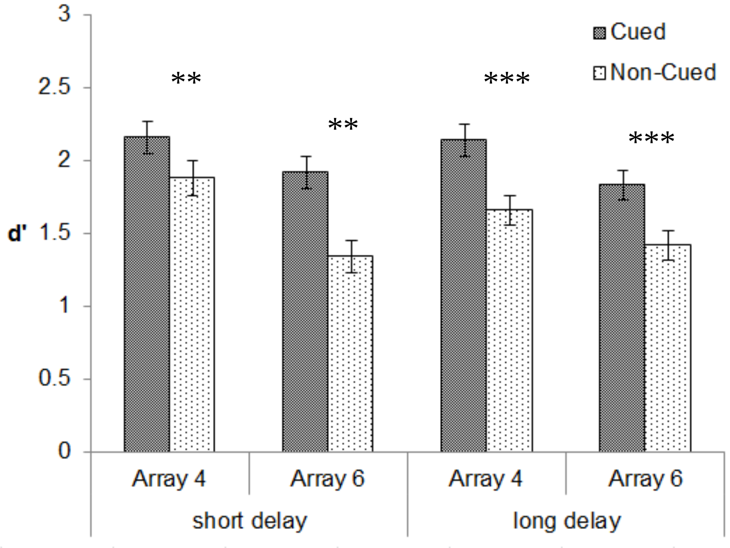

Figure 3.Cue x array size x delay interaction. Mean d' values +/- SEM (error bars) on visual spatial location WM task during spatially informatively cued (dark gray bars) and non-cued (dotted pattern bars) trials, as a function of array size (four or six-items) and delay period (short- 900ms and long – 1800ms). **p* < .05;***p* < .01; ****p* < .001

For the four-item array, the cue significantly improved spatial WM performance over non-cued trials for the short (900ms) delay, mean difference (md) = .27, *SEM* = .09, *p* = .004. Furthermore this cue benefit increased nearly twofold in the longer (1800ms) delay, md = .48, *SEM* = .07, *p* < .001.

The cue improved spatial WM performance to the greatest degree in the six-item array short delay trials, md = .59, *SEM* = .10, *p* < .001, and unlike the pattern observed for the four-item array, this benefit did not increase for the longer delay, md = .41, *SEM* = .09, $p < .001$. Additionally, for the four-item array, there were no differences on cued trials between the short and long delay ($p = .86$). For non-cued trials, WM performance was significantly lower for the long delay (md = .22, *SEM* = .07, $p = .004$). This pattern was not observed for the six-item array, as there was no difference in WM performance between delay periods for the cued trials ($p = .26$) or non-cued trials ($p = .38$). Taken from another perspective, for the short delay, the decline in spatial location WM performance was less across cued trials, md = .23, *SEM* = .08, $p = .005$, relative to non-cued trials, md = .55, *SEM* = .09, $p < .005$, when array size increased from four to six items. This same pattern was not observed for the long delay, where performance decreased to a greater degree across cued trials, md = .32, *SEM* = .08, $p < .001$, relative to non-cued trials, md = .32, *SEM* = .08, $p < .001$.

Surprisingly we did not observe a significant main effect of age group ($p = .51$). We also did not find a significant interaction between age group and cue type ($p = .24$). All three-way, four-way, and five-way interactions with modality, cue type, array size, and delay were also non-significant ($p > .05$). However, we found that when collapsed across cued and non-cued trials, age group performance differences depended on delay period, indicated by the significant two-way interaction between age and delay, F (1, 34) = 6.70, $p = .014$, $\eta_p^2 = .17$. Overall, OA visual spatial location WM performance did not decrease across delay periods ($p = .43$). Conversely, YA performance significantly decreased in the longer delay (md = .17, *SEM* = .06, $p = .007$). We observed a marginally significant interaction between age group and array size (F (1, 34) = 3.45, $p = .07$, η_p^2 =

.09). Regardless of trial type, WM performance decreased to a greater degree for OA (md = .41, *SEM* = .05, $p < .001$) compared to YA (md = .27, *SEM* = .05, $p < .001$) when array size increased from four to six items.

Post-Hoc Exploratory Analysis.

False Alarm Rates. We further examined the impact of age group and cues on false alarm rates because prior research has shown that OA exhibit higher false alarm rates than YA due to their increased difficulties with filtering out irrelevant information from WM (Jost, Bryk, Vogel, & Mayr, 2011). False alarm rates were calculated as the total number of "yes" responses/ total number of "no" trials. Notably, a mixed model ANOVA on false alarm rates revealed a significant two-way interaction between age group and cue type (F (1.94, 65.9) = 6.04, $p = .019$, $\eta_p^2 = .15$). As shown in Figure 4, when collapsed across cue modality, array size and delay, OA showed a significant reduction in false alarm rates between non-cued and cued trials (md = .07, *SEM* = .013, $p < .001$), whereas YA showed no change in false alarm rates ($p = .44$). The cues helped decrease the false alarm rates of OA to the level of YA, evidenced by the lack of significant difference between the cued trials for OA and YA ($p > .05$). Whereas on non-cued trials, false alarm rates for OA were significantly higher than YA (md = .098, *SEM* = .028, $p = .001$).

Of interest in the present analysis of false alarm rates, the combination of age group and cue type did not significantly interact with cue modality, array size, or maintenance delay ($p > .05$). Taken together, these suggest a generalized age effect on false alarm rates, with OA showing a larger reduction in false alarms relative to YA, as a result of the spatially informative cues.

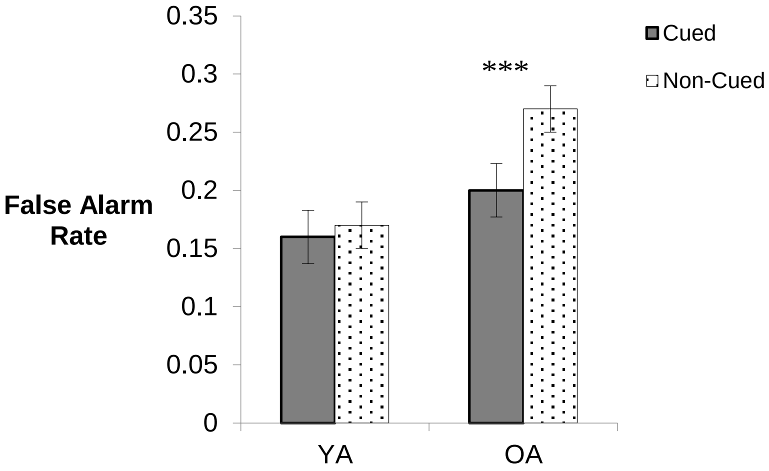

Figure 4. Age group x cue type interaction. Mean false alarm rates +/- *SEM* (error bars) for younger and older adults on visual spatial location WM task during spatially informative cued (dark gray bars) and non-cued (dotted pattern bars) trials. ****p* < .001

Baseline Spatial Span. In order to determine if baseline spatial span impacted the cue effects observed for overall WM performance (d' values), regardless of age group, we conducted an additional analysis including spatial span (performance on the Corsi Block forward task) as a predictor variable. Participants scored raw forward spatial span values of four, five, six, or seven. Participants were coded as low performers if they scored four or five, and high performers if they scored six or seven. This grouping resulted in 17 low span and 19 high span participants. Importantly, when baseline spatial span was considered, modality specific cue effects emerged. We observed a significant five-way interaction between spatial span, modality, cue type, array size, and delay, F (2.0, 64.0) = 4.02, $p = .023$, $\eta_p^2 = .11$. As illustrated in Figure 5, in the low spatial span group (left column of figures a) auditory, b) vibrotactile, and c) visual, the auditory cue was the most consistently helpful to spatial WM performance across array sizes and delays. Performance on cued trials was significantly higher than non-cued trials for four-item short (md = .67, $SEM = .19$, $p = .001$) and long (md = .86, $SEM = .21$, $p < .001$) delays, as well as six-item short delay (md = .44, $SEM = .19$, $p = .026$). In contrast, for this group, the vibrotactile cue only increased performance over non-cued trials in the six-item short delay trials (md = .85, $SEM = .24$, $p = .001$). The visual cue was not helpful for low span individuals, as there was no difference between cued and non-cued trials across all array sizes and delay periods ($p > .05$).

As shown in Figure 5, for the high spatial span group (right column of figures d) auditory, e) vibrotactile, and f) visual), all cue types were helpful, but with some exceptions. We observed no difference between cued and non-cued trials during the easiest difficulty level trials (i.e., the four-item short delay trials) for the auditory ($p = .62$), vibrotactile ($p = .24$), and visual ($p = .84$) cue conditions. For all other trial types, every cue, regardless of modality, helped improve WM performance relative to non-cued trials. Notably, the magnitude of the vibrotactile cue benefit increased with task difficulty. The benefit was highest for the six-item array long delay (md = .85, $SEM = .20$, $p < .001$), followed by the six-item array short delay (md = .69, $SEM = .23$, $p = .005$) and then the four-item array long delay (md = .45, $SEM = .21$, $p = .036$) trials. For auditory cues, the magnitude of WM improvement relative to non-cued trials was comparable for both four-item long delay (md = .49, *SEM* = .20, *p* = .019) and six-item short delay (md = .45, *SEM* = .18, *p* = .015). Similar to the vibrotactile cue, this difference increased in the most difficult task condition: six-item long delay (md = .58, *SEM* = .20, *p* = .006). The magnitude of improvement of the visual cue relative to non-cued trials was largest for four-item long delay (md = .71, *SEM* = .21, *p* = .002), followed by and six-item short delay (md = .66, *SEM* = .22, *p* = .005) trials. This magnitude of improvement was smallest in the six-item long delay (md = .36, *SEM* = .17, *p* = .04).

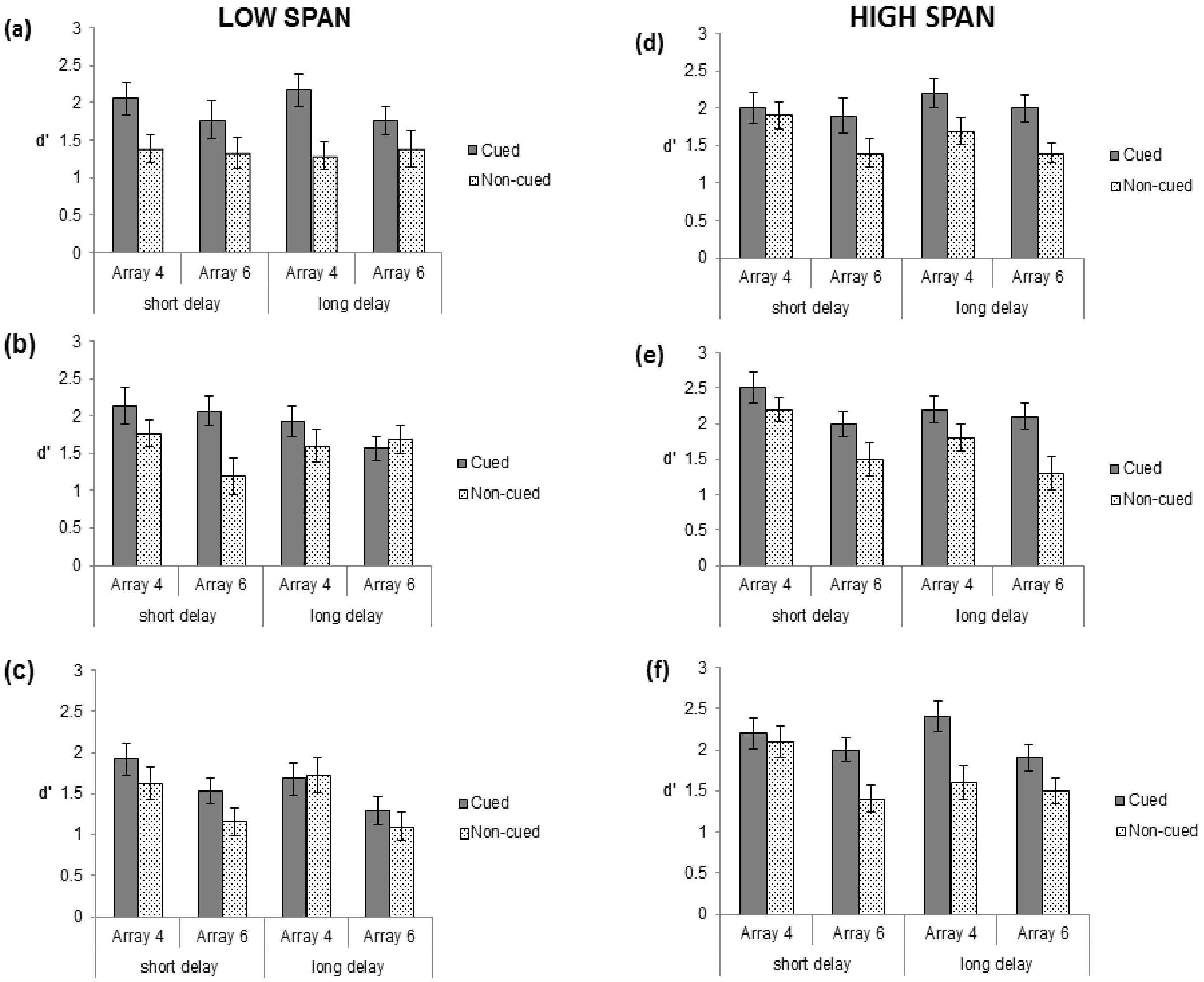

Figure 5. Baseline spatial span x cue type x cue modality x array size x maintenance delay interaction. Mean d' values +/- *SEM* (error bars) on visual spatial location WM task during cued (dark gray bars) and non-cued (dotted pattern bars) trials, as a function of spatial span (high or low) cue modality (auditory or vibrotactile or visual), array size (four or six-items) and delay period (short – 900ms and long – 1800ms), and spatial span. Low spatial span auditory (a), vibrotactile (b) and visual (c) cues. High spatial span auditory (d), vibrotactile (e), and visual (f) cues.

Discussion

Visual, auditory, and vibrotactile cues have been shown to facilitate visual attention in younger and older individuals (e.g. Spence & Driver, 1997; Ho et al., 2010; Hopkins et al., 2016; McLaughlin et al., 2010). Furthermore, cues that are spatially informative are more helpful than cues that prepare or alert someone of an upcoming visual target (Luca & Murtha, 2009). WM performance for feature information can be improved through the use of spatially informative visual cues in YA (e.g., Belpolsky et al., 2008; Schmidt et al., 2002), and verbal cues for both YA and OA (Gilchrist et al., 2016). However, research on the impact of both spatially informative and alerting cross-modal cues on WM (spatial WM in particular), for both YA and OA is limited. Given that OA can utilize cues to help initiate top down attention and improve target detection and visual search (McLaughlin & Murtha, 2010; Pesce et al., 2005) we hypothesized that spatially informative cues would also improve visual spatial WM in OA, and to a greater degree than alerting cues. Prior research has found that spatially informative cues help facilitate the focusing of attention during encoding (e.g., Bays & Hussain, 2008) and WM maintenance (e.g., Awh, Jonides, & Reuter-Lorenz, 1998; Pan & Soto, 2010; Schmidt et al., 2002). The present study investigated the impact of spatially informative visual, auditory, and vibrotactile cues on visual spatial location WM performance of both younger and older adults. We also compared these cues to alerting cues that provided no spatial information. To provide further insight into the nature of the observed cue benefits we assessed these cue effects over varying memory array loads and maintenance delays.

We predicted that cues would improve spatial WM, and the benefit would be greatest for cross-modal cues, and cues that are spatially informative. Consistent with the cue benefits reported in the visual attention literature (Ho et al., 2005; McDonald et al., 2003; Schmitt et al., 2000; 2001; Spence & Driver, 1998), in the present study, auditory, visual, and vibrotactile spatially informative cues facilitated visual spatial WM, compared to non-cued conditions. Botta and colleagues (2011, 2013) found that auditory cues improved visual feature WM. We modified their experimental procedure and extended their findings by including vibrotactile cues, and investigating cue effects on a specific visual WM subtype: spatial location WM. Contrary to our prediction, all modalities were equally effective in terms of improving accuracy on a visual spatial WM task. We also found that alerting cues generally impaired WM performance, across both memory array sizes. This result contrasts the visual attention literature (Luca & Murtha, 2009), suggesting that beyond attention, alerting cues are not helpful for higher order cognitive processing. These results suggest that maintaining an alert or state of high level arousal does not improve spatial WM. Overall, we showed that spatial attention can be guided by spatially informative cues, regardless of their modality. Therefore real world applications of cueing paradigms could effectively utilize a variety of spatially informative sensory cues to improve a cognitive ability such as spatial WM, especially in scenarios where this ability is challenged, such as driving.

We also predicted that OA would receive a greater benefit of cues on visual spatial location WM performance relative to YA. Prior studies have shown greater cue benefits for OA compared to YA in terms of target detection (Thornton & Raz, 2007) and visual search (McLaughlin and Murtha, 2010), suggesting that OA are more reliant on external information or environmental support provided by strategic factors to help engage top down or self-initiated mechanisms that facilitate cognitive processing (Craik, 1994; Madden, 2007). However, we found that OA showed the same cue benefit (for spatially informative cues) to spatial WM performance as YA. This agrees with previous findings on verbal retro-cueing of feature WM, where OA and YA benefitted similarly (Gilchrist et al., 2016). It extends these findings by showing that pre-cueing of spatial locations in WM exhibits a similar pattern of age-related cue benefit to WM recognition. Alerting cues also equally impaired the WM performance of OA compared to YA. Both YA and OA cannot use alerting attention cognitive mechanisms to improve visual spatial location WM performance. Therefore unlike the benefit of altering cues in the facilitation of attention in target detection (e.g., Luca & Murtha, 2009), we failed to observe benefits of these cues to visual spatial location WM.

While overall we observed similar cue benefits of spatially informative cues between age groups, our additional analyses of false alarm rates suggests that mechanisms of cue use may differ between YA and OA. We observed a generalized impact of cues on reducing false alarm rates only in OA, whereas cues did not affect false alarm rates in YA. This is an important finding. Since d' values were improved equally across age groups through the use of cues, the fact that cues decrease false alarms for OA and not YA suggests that these age groups may use cues differently to enhance their visual spatial location WM performance. It has been shown that OA rely to a greater extent on familiarity based or more “shallow” processing in WM recognition tasks relative to YA (e.g., Cabeza, Daselaar, Dolcos, Prince, Budde, & Nyberg, 2004), and this can result in higher false alarm rates due to the lack of encoding at a deeper level, which may be compounded by making decisions at retrieval based on the familiarity of a probe, rather than pure recollection of a memory item (Jost et al., 2011). In sum, our accuracy results showed that cues improve overall hit rates in YA, and reduce false alarm rates in OA. Given that hit rates are associated with degree of recollection and false alarm rates with familiarity based processing (e.g., Yonelinas, 1997), we posit that the cues used in the present study might have assisted YA and OA with recollection and familiarity based processing, respectively.

Despite the absence of age differences in cue benefit to overall WM accuracy (as defined by corrected accuracy, i.e. d'), the finding that OA can use the cues presented in our study is an important one. Given that these types of cues have been shown to automatically orient spatial attention (Spence & Driver, 1997; Ho et al., 2005), they might be of greater use in real world applications targeting WM improvement in OA. Furthermore, our analysis of false alarm rates suggests that mechanisms of cue use might be different between YA and OA. This should be investigated in future studies with neuroimaging measures in order to elucidate possible age differences in brain regions that mediate cue effects. It has been suggested there are differences in the brain regions that mediate true memory and false memory formation (Kim, & Cabeza, 2007), with the former involving earlier visual sensory processing areas (e.g., occipital cortex), medial temporal lobe (e.g., hippocampus) and later visual processing areas (e.g., occipito-temporal cortex), and the latter involving later visual processing areas (e.g., occipitoparietal cortex) . The pre-frontal cortex is also thought to moderate early perceptual processing, important for true memory formation, as well as elaborative processing involved in memory maintenance (Fernández, & Tendolkar, 2001). Our results suggest that for OA, relative to non-cued trials, cued trials might augment prefrontal cortex activity, which in turn could modulate early visual cortex and hippocampal activity and reduce later visual cortex activity, thus contributing to the reduction in false memory formation and false alarm rates. On the other hand, for YA, our results suggest that the shift from late to early visual/hippocampal processing between cued and non-cued trials might not be observed, but rather cue effects might reflect increased activity in regions that mediate true memory formation.

Another goal of the present study was to understand the nature of the cue benefit. Prior research has shown that uni-modal and cross-modal cues focus attention more quickly on cued locations relative to non-cued (Luca & Murtha, 2009) or neutral (Spence & Driver, 1997) locations. Therefore we expected that the spatially informative cues would focus visual spatial attention more quickly and on fewer items in the targeted hemifield. These attended items presumably received priority for entry into spatial WM (Awh et al., 2006; Schmidt et al., 2001), and were encoded more effectively than non-cued items. However, we can gain a deeper understanding of the nature of the cue benefit when we interpret the significant impact of array size and delay periods.

Although the cues improved spatial WM recognition relative to non-cued trials across both array sizes, this improvement was greater for six-item arrays. This suggests that cues become more helpful as the demands on attention increase. It has been suggested that cues interact with visual targets more effectively when focused attention is required (Dufour, 1999). In the six-item array there are greater demands on attention compared to the four-item array since more locations must be attended and ignored. This greater demand on attention could explain why there was a greater overall cue benefit or effect (cued minus non-cued trials) for the larger array size. Furthermore, for the four-item arrays, visual spatial location WM recognition declined when the delay period increased from 900ms to 1800ms in non-cued trials, but was maintained in cued trials. This result suggests that the cues might also help to maintain memory representations and prolong decay of the spatial locations, in agreement with the interpretation that spatially informative cues act as a rehearsal mechanism, by essentially facilitating spatial attention within spatial WM maintenance (Awh et al., 2006; Silk, Bellgrove, Wrafter, Mattingley, & Cunnington, 2010). If cues aid rehearsal by constantly refreshing the cued locations within WM, this could also explain the greater cueing effect observed for the six-item array. In the four-item array, there are two locations to be remembered and two to be ignored. Likewise, in the six-item array, there are three to be remembered and three to be ignored. More rehearsal is required in the latter case. Therefore participants might rely more heavily on the cue in these instances. However, there appear to be limits to the above interpretations. For the six-item array, although visual spatial location WM performance was maintained across delay periods in cued trials, it was also maintained for non-cued trials. This could be due to floor effects of non-cued trials. That is, Simons (1996) suggested a spatial location capacity of five. Therefore, a memory array size of six in the present study could be at the limits of or exceed capacity. The prolonged delay period would have less of an effect if capacity is already overloaded. Although we showed that spatially informative cues consistently improved performance relative to non-cued trials at six-item arrays, the magnitude of this benefit might not be greater at longer maintenance delays relative to shorter maintenance delays due to capacity limitations. In general, however, it appears that the spatially informative cues used in the present study help aid rehearsal during spatial WM maintenance, thereby prolonging decay, and provide the most benefit in situations where the requirement for focused attention is high.

Importantly, our exploratory analyses helped support our initial prediction that cross-modal cues would be more beneficial than uni-modal cues in this visual spatial location WM task. We showed that baseline spatial span values mediated modality specific cue effects. These findings can be understood when we consider multiple resource theory (Wickens, 2008). According to this theory, there are different domains (e.g., sensory modalities, task demands, etc.) that utilize available resources. If two cognitive functions use the same resources, there are less resources available in that “domain” for subsequent task performance or processing. In the visual cue condition, participants were using visual resources (elicited by the visual cue) in addition to visual spatial attention and visual spatial WM resources during the memory array presentation (encoding) and maintenance. Therefore, it is likely that this created interference between the *visual* cue and *visual* WM task. Individuals with low visual spatial spans had limited resources available, and were presumably unable to utilize the visual cue to enhance spatial WM performance, but were still able to benefit from the auditory and vibrotactile cues in certain instances. On the other hand, individuals with high visual spatial spans presumably had more cognitive resources available and were able to use all cues effectively, particularly when the task difficulty increased. They most likely did not show a statistically significant cue effect at the easiest level of the task (four-item short delay trials) because they were able to perform well in those trials without assistance, due to their high visual spatial WM capacity. Interestingly, the high span individuals showed the greatest benefit from the visual cue in the smaller memory array and a greater benefit from cross-modal cues for the larger memory array. According to multiple resource theory, if task demands are low (i.e., in the four-item array), there are more resources available for effective visual cue use. Once task demands are increased, the visual sensory store becomes overloaded, and the cross-modal cues become more effective. In agreement with prior research on high/low WM span, we hypothesize that the high span individuals were better able to utilize the attention directing cue by keeping its predicted location in mind as a task goal (Kane, Bleckley, Conway, & Engle, 2001), effectively orienting attention to a predicted region of space (Posner, 1980; Gazzaley & Nobre, 2012), while ignoring distracters (Conway, Tuholski, Shisler, & Engle, 1999). These processes are more impactful in the cross-modal cue conditions, as there is less demand for visual resources (Wickens, 2008).

There are several limitations in the present study that impact the generalizability of our results. The first is that given the absence of general age related deficits in our visual spatial location WM tasks, our results might not be generalizable to the broader OA population. Our OA sample, who had a higher level of education than our YA participants, might not be representative typical OA. Additionally, our WM task might not have been difficult enough to elicit an age-related cue effect, given that OA were able to generally perform the task equally as well as YA. Future work in our lab will further modify task demands in order to maximize the potential of observe age-related cue effects.

In conclusion, our results are, to the best of our knowledge, the first to show that in addition to visual cues, auditory and vibrotactile pre-cues that are spatially informative are also effective in improving visual spatial location WM recognition performance. Additionally, we show that cues providing no spatial information and simply alerting someone to an upcoming visual spatial target are not helpful for visual spatial location WM. These findings suggest that maintaining a vigilant state of arousal by facilitating the alerting attention system does not help spatial location WM encoding, or maintenance. We also showed that OA are able to use spatially informative cues to aid performance to a similar degree as YA. Our analysis of false alarm rates suggests that the general cognitive mechanisms that mediate cue effects may differ between age groups. Array size and maintenance delays also moderate cue effects. The spatially informative cues used in the present study appear to exert their effect by focusing attention on cued locations thereby facilitating their encoding, particularly when demand for attentional resources are high. For array sizes within spatial WM capacity, the cues also appear to focus spatial attention on cued locations within WM, thereby aiding rehearsal and prolonging decay.

Finally, we found that individuals with low spatial spans benefit most from auditory and vibrotactile cues, while the visual cue is ineffective in improving visual spatial location WM performance. On the other hand, individuals with high spatial span are able to use all cues to improve performance. These results support multiple resource theory, showing that visual task resources can interfere with effective cue use, especially in individuals with limited cognitive resources (i.e., low spatial span). In light of these findings, cross-modal cues could be of greater benefit in the real world, where OA are prone to memory lapses and the environment taxes visual resources. Ongoing work in our lab is investigating the effects of maintenance interference in order to help further elucidate the nature of the observed spatially informative cue benefit. Future research should investigate the underlying neural mechanisms mediating cue use, in order to compliment the present behavioral findings and determine any functional differences between younger and older individuals.

Chapter 2b – Additional Details for Study 1

The following information was not pertinent to the manuscript for Study 1, but is described in detail below and in the specified appendices.

Participant Screening

Participants were asked a series of questions to obtain demographic and physical health information. A sample screening form for YA and OA is given in Appendix A.

Experimental Procedure

Instructions given for the computerized experimental procedure are described in Appendix D. The written debriefing form that was provided at the end of the study is also described in Appendix F.

Sample size determination

An a priori power analysis (see Appendix H) was conducted in G*Power (V3.1.9.2; Faul, Erdfelder, Lang, & Buchner 2007). To detect a mixed model highest order (five-way) interaction in study one with a medium effect size ($\eta_p^2 = .06$, recommended by Cohen, 1988), and achieve 80% power, we would require a total sample of 28, or 14 participants per age group. Given that we included 18 participants per age group, we were appropriately powered for this study. The G*Power output is provided in Appendix G.

Additional Data Analysis Details

Appendix H provides additional descriptive and inferential statistical analyses. These include: correlational analyses of demographic variables and spatial location, d' and false alarm rate scores for each age group and across all factors, complete mixed model ANOVA results (all main effects and interactions) for d' and false alarm rate outcomes, and all relevant pairwise comparisons.

Chapter 3: Improving Visual Spatial Working Memory: Impact of Cue Modality, Age, and Maintenance Interference (Study 2)

Summary

Performance on visual spatial working memory (WM) tasks decline with age. Previous research has shown that older adults (OA) can improve their spatial location WM performance to a similar degree as younger adults (YA) from the use of spatially informative uni-modal (visual) or cross-modal (auditory and vibrotactile) cues presented prior to encoding of target stimuli. The present study investigated whether age and modality specific cue effects would emerge when there was interference presented during spatial WM maintenance. We employed a five-factor design, exploring the effects of age group (YA vs. OA) cue type (cued trials vs. non-cued trials), cue modality (visual vs. auditory vs. vibrotactile), memory array size (four-item vs. six-item), and maintenance interference (ignore interference vs. attend and compare interference) on recognition accuracy in a visual spatial location WM task. We found that a five-way interaction between all factors moderated the cue benefit (improvement on cued trials vs. non-cued trials) in spatial location WM. While OA benefited from all cue types when interference was to be ignored in the smaller four-item array, YA only showed benefit from vibrotactile cues in the larger six-item array. In contrast, when interference was to be attended and compared, OA only benefitted from cross-modal auditory cues in the four-item array and the vibrotactile cues in the six-item array, while YA utilized all cues in all modalities to improve spatial WM performance. These results support age-related increases in benefit of environmental support to spatial location WM, and show that

cross-modal cues are more beneficial to performance under conditions of higher attentional demand.

Introduction

Visual spatial working memory (WM) is the short term active maintenance of spatial information such as locations or spatial orientations (Baddeley, 1996). It overlaps with spatial attention, which is the allocation of attentional resources to regions in external space or internal representations (Posner & Dehaaene, 1994). It is well established that older adults (OA) show declines in WM for static locations (e.g., Gilchrist, Duarte, & Verhaeghen, 2016; Kessels, Meulenbroek, Fernández, & Olde Rikkert, 2010), sequential order of locations (Schmiedek, & Lindenberger, 2009), or spatial orientations (e.g, Murray, Nobre, & Stokes, 2011). This is thought to be due to deficits in self-initiated cognitive control or executive attention (Paxton, Barch, Racine, & Braver 2008; Townsend, Adamo, & Haist, 2006), which interferes with the successful maintenance of items in WM (Geerligs, Saliasi, Maurits, Renken, & Lorist, 2014).

Research also indicates that cues can quicken response time in target detection (e.g., Spence & Driver, 1997; Posner, 1980), localization discrimination (e.g., Schmidt, Postma, & De Haan, 2001), visual search (e.g., McLaughlin & Murtha, 2010; McLaughlin, Anderson, Rich, Chertkow, & Murtha, 2013), and visual change detection (Sklar & Sarter, 1999). Cues can also be used to improve WM processing by facilitating executive attention resources during encoding and maintenance (Baddeley, 1981; Kiyonago & Egner, 2012), and by augmenting spatial attention mechanisms during WM maintenance (Awh & Jonides, 2001). Facilitating WM performance through the use of spatially informative visual pre-cues presented prior to WM encoding (Schmidt, Vogel, Woodman, & Luck, 2002; Souza, 2016), as well as feature retro-cues that cue memory items during WM maintenance (Gilchrist et al., 2016), have been shown to improve performance in visual feature based WM tasks. However the impact of these types of cues on spatial location WM has been mainly limited to uni-modal (i.e., cues in the same modality as memory stimuli) domains (e.g., Murray et al., 2011).

Only a handful of studies have investigated the effect of cross-modal (i.e., cues in a different modality as memory stimuli) cues on WM. A previous study (Botta, Lupianez, & Sanabria, 2013) found that spatially informative auditory cues can improve feature WM. In addition, our previous work (Curtis, Park, Turner, & Murtha, 2016), showed that cross-modal auditory and vibrotactile cues that are spatially informative can also facilitate spatial location WM accuracy relative to no cues, and do so to a greater degree than uni-modal visual cues when spatial processing resources are limited. Furthermore, these spatially informative cues are also more beneficial to spatial location WM than centrally presented alerting cues, which we found to impair spatial location WM performance (Curtis, Park, Turner, & Murtha, submitted).

Investigations of cueing effects in WM of OA are also limited. In a WM recognition task, Gilchrist and colleagues (2016) found similar cue benefits (relative to no cues) of feature retro-cues (presented during WM maintenance) for both YA and OA. Similarly, in our previous work (Curtis et al., 2016), we found cue benefits of spatially informative visual, auditory, and vibrotactile pre-cues (presented prior to WM encoding).

We found that all cue types improved spatial location WM recognition in OA to a similar degree as YA. These findings of no increased cue benefit for OA relative to YA contrasts with the visual attention literature that has found that OA benefit from environmental support from pre-cues to a greater degree than YA in various attention tasks, such as visual search (Mclaughlin & Murtha, 2010), and target detection (Thornton & Raz, 2006). However, in our recent study (Curtis et al., 2016), we observed that baseline spatial WM capacity (measured by the Corsi block spatial span task) determined the amount of observed cue benefit. Individuals with lower spatial spans, and thus fewer visual spatial WM resources, showed greater benefit from cross-modal auditory and vibrotactile cues, compared to uni-modal visual cues. In contrast, we found that individuals with high spans, and presumably a greater amount of visual spatial WM resources, were able to benefit from all cue types to improve visual spatial location memory performance, relative to non-cued trials (Curtis et al., 2016).

Our previous results provide evidence for multiple resource theory (Wickens, 2008), suggesting that once visual resources are taxed, utilizing resources in other sensory modalities is more beneficial to cognitive performance. Accordingly, as a spatial attention rehearsal mechanism is thought to mediate WM maintenance (Awh et al., 2001), we attributed our previous findings of spatially informative cue benefits (Curtis et al., 2016) to cues acting as spatial attention rehearsal mechanisms (Awh et al., 2001), as individuals with lower baseline spatial WM capacity presumably have fewer spatial attention resources available for cue benefit. However, it is not yet known if uni-modal and cross-modal cue benefits are moderated by other factors that alter task demands, such as WM maintenance interference. For example, when visual interference is presented during WM delays/maintenance, it presumably disrupts the attentional control and spatial processing that helps maintain items within WM (e.g., Clapp & Gazzaley, 2012). Therefore, in conditions of distracting visual interference, cross-modal cues might become more beneficial to spatial location WM performance, compared to uni-modal cues. In the present study we investigated whether presenting different types of interference during the visual spatial location WM maintenance period further moderates the cross-modal cue increased benefit, relative to uni-modal cues. More specifically, we investigated two different types of interference that varied in attentional demand. We asked participants to either ignore, or pay attention and make a decision regarding the stimuli presented, so that the interference was either a distracter or interrupter (Clapp & Gazzaley, 2012), respectively. We also examined whether cue benefits differ between YA and OA, under the two types of interference. Given that OA experience more difficulty in inhibiting task irrelevant information, relative to YA (e.g., Gazzaley, Cooney, Rissman, & D’Esposito, 2005; Padgaonkar et al., 2017; Hasher & Zack, 1979), we predicted that spatially informative cues would provide differential cue benefits, depending on age group. For instance, when the stimuli presented during WM maintenance was to be ignored, we predicted that the cue benefit (improvement in location memory accuracy on cued trials relative to non-cued trials) experienced by OA would be greater than in YA, as they require more attentional focusing due to their inhibition deficit. We also predicted that similar to our previous study (Curtis et al., 2016), cross-modal cues would provide the most benefit due to the visual cognitive demands on the task (visual targets, visual interference). When the interference item was to be attended and compared, we predicted that both age groups would show a cue benefit, and this benefit would be largest for cross-modal cues. If interference moderates cue effects, this supports the notion that spatially informative pre-cues exert their effect during WM maintenance, acting as spatial rehearsal mechanisms that refresh the contents of encoding memory items (Awh et al., 2001; Curtis et al., 2016; Schmidt et al., 2002).

In sum, our study investigated the impact of spatially informative auditory, vibrotactile, and visual cues presented prior to encoding, on recognition accuracy of both younger and older individuals in a visual spatial location WM task. We extended previous findings (Curtis et al., 2016), and investigated this cue benefit for memory array sizes of four-items and six items, under two different maintenance interference conditions that were either distracting (orientation of two rectangles was to be *ignored*) or interrupting (the orientation of the two rectangles was to be *attended and compared*) to WM storage. We predicted that the cue benefit for YA and OA would differ, depending on the type of interference. More specifically, we predicted that given the deficits in inhibitory control experienced by OA (e.g., Gazzaley et al., 2005; Hasher & Zacks, 1979), OA should show a greater cue benefit relative to the benefit experienced by YA when interference is to be ignored or “passive” in the distracting condition. Presumably they would use the cue to help keep attention focused on relevant items in spatial location WM, and improve the inhibition of the irrelevant interference. Due to the visual load of the memory task, we also predicted that cue benefits would be greatest for both age groups for cross-modal (auditory and vibrotactile cues) relative to the uni-modal (visual) cues. We also expected that the cross-modal cues would be more consistently helpful relative to visual cues in the active or interrupting maintenance interference condition (compared to cue benefits observed in the ignore interference condition), due to the increased visual load of the WM task. Consistent with our previous findings (Curtis et al., 2016), such results would support multiple resource theory (Wickens, 2008), which suggests that when visual cognitive resources are shared amongst cognitive tasks, the visual resource store can become taxed, and it is more beneficial to utilize resources in other sensory modalities.

The present study provides critical information regarding the nature of cross-modal cue benefit to visual spatial location WM, as well as insight into cognitive models of aging. This information could be used in the development of cueing paradigms aimed at improving everyday cognitive functions, a skill that would be particularly useful for OA, who are vulnerable to age-related spatial WM decline.

Methods

Participants

A total of 18 YA (aged 18-30, *M* = 20.9, *SD* = 3.1) and 18 OA (aged 60-77, *M* = 68.7, *SD* = 5.1) participated in the present study[1]. The YA group were recruited from York University undergraduate research participant pool, and received course credit for their participation. The OA group were recruited from the York University OA

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[1] Two additional YA participants initially participated but were removed from all analyses due to high anxiety (one) and a failure to perform the orientation discrimination task properly (one), as evidenced by no key response provided during the task. Four additional OA participants initially participated but were removed from all analyses due to the following reasons: withdrew consent (one), language barrier and inability to follow instructions (one), and poor performance on the orientation discrimination task (two), as evidenced by an accuracy rate of 34%. The final 18 participants achieved adequate performance (> 70%) in the orientation discrimination task and met all other inclusion criteria.

participant pool, and through community websites. They were compensated $10 per hour for their participation. All participants gave informed consent and had normal, or corrected to normal vision and hearing. They also did not report any current diagnoses of anxiety disorders, depression, uncontrolled heart conditions, diabetes mellitus, sleep disorders, or memory disorders such as Mild Cognitive Impairment (MCI) or Alzheimer Disease (AD).

Neuropsychological Testing

The Telephone Interview for Cognitive Status survey (TICS-m) was first administered to all potential OA participants. Scores of 31 and above were considered acceptable, based on previously published criteria for the cut-off for possible memory impairment (Knopman et al., 2010). All other neuropsychological tests were administered to both OA and YA, during the experimental procedure. These tests were meant to screen for depression, anxiety and/or cognitive impairments (see Table 1 for test battery). They provided baseline measurements of general intelligence (crystallized and fluid ability), verbal WM visual spatial location WM.

Apparatus and Stimuli

Memory Arrays and Probe Stimuli. The experiment was programmed in Superlab Pro 5.0 and presented on a Dell Latitude E6530 laptop. All stimuli were presented against a light gray background. Memory arrays consisted of dark gray rectangles measuring 6 x 4cm, and were equal in saturation in luminance levels. Arrays consisted of either four or six rectangles. The rectangles occupied locations in an invisible five by five grid within the entire computer screen (measured 34.5 x 19.5cm in area), with an equal number of items always occurring in each hemifield. No items ever appeared in the center column of the grid. The probe stimulus was the same shape (rectangle) and size (same dimensions) as the memory targets, and was black in color.

Maintenance Inteference Stimuli. The stimuli presented during interferences consisted of one white rectangle measuring 5.3 x 1.3cm appearing 2.6 cm above the center of the computer screen, and another identical rectangle appearing 2.6 cm below the center of the screen. These rectangles were either oriented vertically or horizontally (90 degrees from vertical position), depending on the trial type.

Cues. Visual cues consisted of a hollow black rectangle (outlining the left/right “grid”) presented in either the right or left hemifield of the computer screen. The auditory cue was a 1500Hz tone, presented at 80db, with a duration of 100ms, and was programmed using the Audacity software program (Version 1.2.5). The auditory cue was presented to either a left or right external speaker, lined up against the computer screen, approximately 19cm from fixation. Vibrotactile cues were 250 Hz tones presented via tactors (model C2; Engineering Acoustics Inc.) encased in styrofoam padding and fixated to the dorsal side of the forearm, with the anterior edge of tactor lined up with wrist (Chen, Santos, Graves, Kim, & Tan, 2008) via Velcro straps. Participants were presented with white noise (created in Audacity V.1.2.5) via headphones when performing the vibrotactile cueing task, in order to eliminate any noise contributions of the vibration. Cues were spatially informative, and always correctly predicted the location of the target rectangles (i.e., right visual cue/targets in right hemifield; right speaker/targets in right hemifield, etc.).

Procedure

To confirm that participants could properly localize the auditory and vibrotactile cues as coming from the left or right, they were administered two separate tests. In each test, 10 trials were presented in which tones or vibrations (depending on the cue modality condition) were presented randomly to the left, right, both or none of the speakers or tactors, respectively. Participants were required to respond verbally to the experimenter with the location (left or right) of the tone or vibration. All participants were able to correctly localize the cues 100 percent of the time.

The participant viewing distance was approximately 57cm from the computer screen. To minimize eye movements, participants were instructed to remain fixated on the central crosshair for the duration of each trial. Prior to each block of trials, participants were instructed to "Ignore" (*Ignore* task) or "Compare" (*Attend and Compare* task) the white rectangles presented during the maintenance delay. As illustrated in Figure 6, each trial began with participants fixating on a central cross-hair for 500ms while simultaneously performing an articulatory suppression task. Two words "blah blah" (Salame & Baddeley, 1987) appeared directly above the cross-hair for 500ms, and participants were asked to rehearse and repeat these words out loud until the response portion of the trial. The experimenter observed participants to ensure adequate performance of this task. Next, either a cue (100ms) or a blank interval (100ms; non-cued trial) was presented. To eliminate temporal cueing, a blank delay of either 50ms or 100ms was then presented. This delay ensured varying stimulus onset asynchronies (SOA) of 150ms and 200ms, respectively. Memory arrays were then presented (random presentation of either four or six-item array) for 100ms (Schmidt et al., 2002), followed by a blank “maintenance” delay period of 500ms. This was followed by the maintenance interference stimuli, which appeared on the screen for 800ms. In “Ignore” trials, interference was to be inhibited or ignored, thus was considered “distracting” (Clapp & Gazzaley, 2012). In these trials participants were to follow previous instructions and not pay attention to the stimuli and simply ignore these rectangles. In “Attend and Compare” trials, interference was to be attended, and was thus considered “interrupting” (Clapp & Gazzaley, 2012). In these trials, participants were to also follow the previously given instructions and quickly decide whether the rectangles were in the same orientation (i.e., both vertical or both horizontal), or in different orientations (i.e., one vertical and one horizontal). They indicated this decision with a designated key press for “same” or “different”, using their dominant hand. Following the presentation of the interference stimuli, a 500 ms blank screen then appeared. Finally, a probe (darkened gray rectangle occupying one of the locations that was or was not previously occupied in the memory array) appeared and participants were required to indicate “yes” (via a designated keyboard response with their dominant hand) if the probed location was previously occupied, or “no” if the probed location was new. Designated keys were the same for the “compare and attend” trials and all memory probe trials, for ease of responding. Participants always pressed the same key for “same orientation” and “yes, location was previously occupied”. Similarly, they pressed the same key for “different orientations” and “no, location not previously occupied”. When the memory probe was presented, participants were instructed to respond as soon as they knew the answer, but to focus on accuracy over speed. To help maintain motivation in the task, participants also received feedback at the end of every trial, indicating if they answered correctly or made an error. The trials were self-paced, and participants pressed a designated key when they were ready for the next trial.

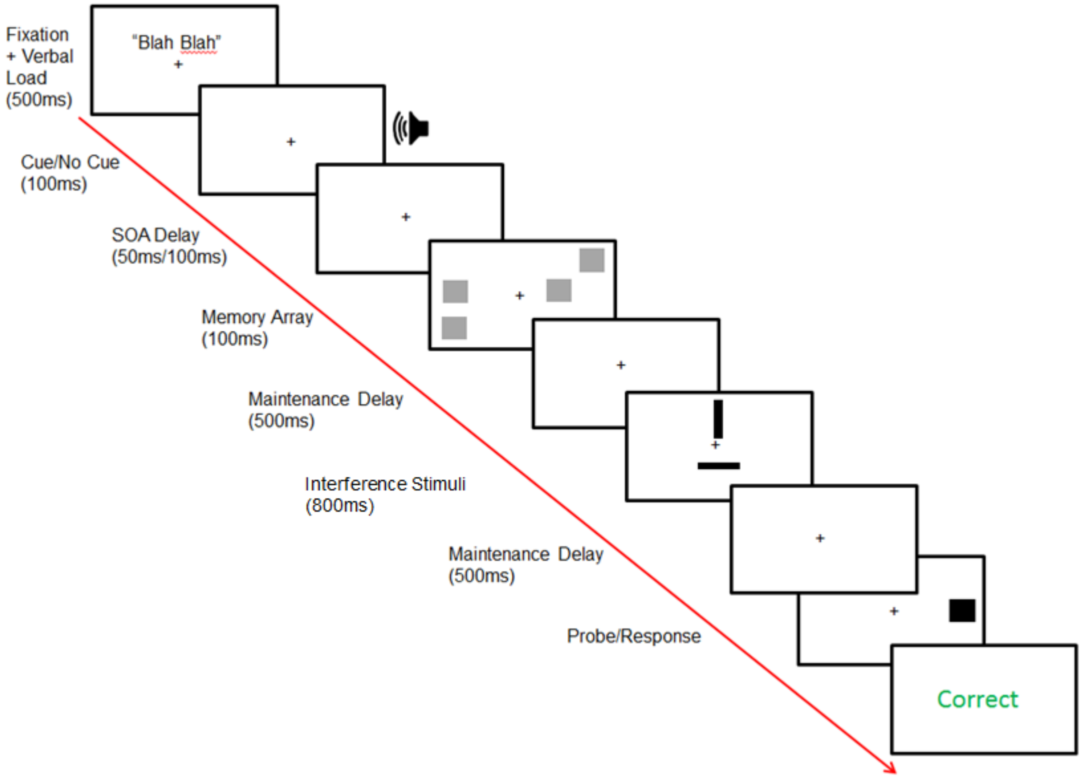

Figure 6. Schematic representation of the experimental procedure. During “attend and compare” trials, participants were required to indicate a “different” response regarding the rectangle orientations at maintenance interference. In “ignore” trials, they were required to ignore these rectangles and withhold a response. This example trial would also require a “no” response to the visual spatial location WM probe.

Cue types were blocked, so that one type of interference task (Ignore or Attend and Compare) occurred within a block of trials. There were a total of 64 trials per interference task, separated into two blocks of 32 trials. Participants were pseudorandomly assigned to either complete the *attend and compare* blocks first, followed by the *ignore* blocks, or vice versa. Each block took approximately three minutes to complete. All blocks were repeated for each cue modality condition (four blocks per auditory, vibrotactile, and visual cue), which were also blocked by modality type. The order of cue modality presentation was determined through Latin square partial counterbalancing (possible block orders: auditory, visual, vibrotactile; visual, vibrotactile, auditory, or vibrotactile, auditory, visual). Within each block, there were 16 cued and 16 non-cued trials, including an equal number of array sizes (four/six). Half of the trials within a block contained maintenance interference stimuli that were either both vertical or both horizontal (would require a “same” comparison response in the attend and compare block), and half contained interference stimuli in different orientations (e.g., one vertical and one horizontal, would require a “different” response in the attend and compare interference task). Half of the trials within each block were also “yes” trials (probe rectangle occupied a previously presented location) and half were “no” trials (probe rectangle occupied a new location). Trial types were randomized within each block.

Participants completed eight practice trials before the start of each new *attend and compare* or *ignore* block for each cue modality block of trials. These practice trials were excluded from analysis. To control for time of day, which has been shown to affect cognitive performance of YA and OA differently (May et al., 1993), half of the YA (*n* =

9) and OA (*n* = 9) completed the experiment in the morning and the remaining participants in each age group completed the experiment in the afternoon.

Data Analysis

Our outcome variable of interest was memory recognition performance. This was calculated using d prime (d'), a measure of corrected accuracy that controls for response bias (MacMillan & Creelman, 2004), and is the standardized hit rate (number of trials where participants gave a "yes" response/total number of trials where the correct response was "yes") minus the standardized false alarm rate (number of trials where participants gave a "yes" response/total number of trials where the correct response was "no"); Swets & Green, 1966): = z(hit rate) – z(false alarm rate). Higher d' values correspond to better memory performance. Given our previous findings of age related differences in false alarm rates on a spatial location WM task without maintenance interference (Curtis et al., submitted), we also examine false alarm rates, calculated as previously described: total number of "yes" responses/ total number of "no" trials.

The d' values and false alarm rates were entered into separate 5-way mixed model ANOVAs evaluating the between participant factor age group (YA vs. OA), and within participant factors cue modality (visual vs. auditory vs. vibrotactile), cue type (cued vs. non-cued), array size (four vs. six items), and interference (compare vs. ignore). To account for violations of sphericity, degrees of freedom were adjusted (Huynh & Feldt, 1976). An alpha level of .05 was set as the criterion level for inferential analysis. Significant main effects and interactions were clarified by conducting post-hoc pairwise comparisons with Bonferroni control. Effect sizes (partial eta squared values) are reported where available.

Results

Demographics and Neuropsychological Test Scores

Additional demographic information and baseline neuropsychological test scores can be seen in Table 2. Participants scores were compared against age matched standardized scores, and all participants scored within normal limits. All OA scored within the normal range on the TICS-m (31 or higher). There were no differences on any demographics or neuropsychological measure except education (OA had significantly more years of education than YA, $p = .02$), anxiety subscale of the HADS (YA score significantly higher than OA, $p = .002$), and digit span (Surprisingly, OA scored significantly higher than YA, $p = .001$).[2]

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[2] To assess the potential impact of variables that significantly differed between age groups, we conducted Pearson product moment correlations between these variables and performance on our visual spatial location WM task. Digit span did not significantly correlate with d' scores across any experimental condition ($p > .05$). Anxiety and education each only significantly correlated ($p < .05$) with one out of a total of 24 possible conditions. As a result we chose to report the analysis without covarying out the impact of any of these three variables.

Table 2

Demographic Variables and Neuropsychological Test Scores for Each Age Group

	YA	OA
Variable	*M* (*SD*)	*M* (*SD*)
Education (years)*	13.3 (2.1)	15.1 (2.3)
Sex (M:F)	2:16	6:12
Handedness (R:L)	17:1	17:1
TICS-m	--	37.3 (3.4)
HADS-anxiety**	7.2 (2.7)	3.6 (3.5)
HADS-depression	3.0 (2.3)	2.3 (2.1)
Shipley-2 (Standard Score)	103.8 (11.9)	105.2 (9.5)
Digit Span (forward span)	7.1 (1.3)	7.5 (1.4)
Digit Span - Total (SS)**	8.3 (2.1)	10.8 (1.9)
Spatial Span (forward span)	5.4 (.98)	5.2 (1.1)
Spatial Span – Total (SS)	9.2 (2.4)	10.5 (2.8)

Note. YA = younger adults; OA = older adults; TICS-m = modified Telephone Interview for Cognitive Status (raw score out of 50; Welsh et al., 1993); HADS – Hospital Anxiety and Depression Scale (raw score out of 21; Zigmund & Snaith, 1983); Shipley-2 (Composite score: verbal + reasoning; Shipley, Gruber, Martin, & Klein, 2009); Digit Span (forward raw digit span score;Wechsler, 1997); Digit Span-Total (Total Score; Wechsler, 1997); Spatial Span – (Corsi Block test; forward raw spatial span score;Wechsler, 1997); Spatial Span – Total (Total Score; Corsi Block test; Wechsler, 1997); SS (age-corrected scaled score)
Significant differences between groups: **p* < .05. ***p* < .01.

Attend and Compare Task Accuracy

The attend and compare task was designed to allow for quick decision making that required a relatively easy response. To verify that this task was equally difficult and did not require more attentional resources for the OA group than the YA, the accuracy of responses in the task were compared between age groups. Overall accuracy rates were quite high (89-92%), and OA and YA performed similarly in the task across all cue modality conditions ($p > .05$).

Spatial WM Task - d' Scores

The five-way mixed model ANOVA revealed a significant five-way interaction of all factors (age group x cue modality x cue type x interference type x array size), F (1.84, 62.5) = 3.5, $p = .04$, $\eta_p^{2\,=}$ .09. As illustrated in Figure 3, the degree of cue benefit varied for YA and OA, and depended on all other experimental factors.

OA. Interestingly, for OA (Figure 7, left panel), when maintenance delay interference was to be ignored, cues of all modalities improved spatial location WM performance (higher d' scores on cued trials relative to non-cued trials), but only in the smaller array size of four-items. Visual cues showed the greatest benefit, as observed by the significant mean difference (md = .74, *SEM* = .18, $p < .001$) between memory accuracy of cued trials relative to non-cued trials for four-item arrays. The benefit of vibrotactile cues was smaller in magnitude than the visual cue benefit for four-item arrays (md = .46, *SEM* = .17, $p = .012$). Finally, auditory cues showed a marginally significant cue benefit over non-cued trials (md = .37, *SEM* = .19, $p = .053$). Visual, auditory, and vibrotactile cues did not improve memory performance relative to non-cued trials for six-item arrays in the interference task (*p* > .05).

When the maintenance interference was to be compared (interrupter condition), OA showed only cross-modal cue benefits, but these depended on array size. We observed significant improvement in memory accuracy performance on auditory cued four-item array trials, relative to non-cued trials (md = .70, *SEM* = .18, *p* < .001), whereas there was no difference between performance on auditory cued and non-cued six-item array trials (*p* = .327). Vibrotactile cues, on the other hand, were only helpful for OA in six-item memory arrays, as observed in the marginally significant difference between vibrotactile cued and non-cued trials (md = .50, *SEM* = .23, *p* = .058). Vibrotactile cues did not improve performance over non-cued trials for four-item arrays (*p* > .05). Visual cues were not helpful in the interrupter task, as performance on cued and non-cued trials were similar for four-item arrays (*p* > .05) and six-item arrays (*p* > .05).

YA. As shown in Figure 7 (right panel), YA showed a different pattern regarding cue benefits across interference tasks. Unlike the OA group, when maintenance delay interference was to be ignored, YA showed no improvement in their memory performance on cued trials relative to non-cued trials (*p* > .05), in auditory and visually cued blocks, regardless of memory array size. However, they did show a vibrotactile cue benefit on six-item array trials, as observed by the significantly higher performance on vibrotactile cued trials relative to non-cued trials (md = .59, *SEM* = .22, *p* = .012). No vibrotactile cue benefit was observed for four-item arrays (*p* = .071).

Also illustrated in Figure 7 (right panel), was that when the rectangles presented during maintenance were to be attended and compared, and therefore acted as an interrupter, performance of YA on cued trials was better than non-cued trials, but this varied by modality and array size. Auditory cues showed the most widespread benefit across array sizes. During auditory cued blocks, performance on cued trials was significantly higher than non-cued trials (md = .48, *SEM* = .18, *p* = .01) for four-item arrays. Auditory cue benefit increased by a factor of approximately 1.5 for six-item array trials, as observed by the significant improvement on auditory cued trials relative to non-cued trials (md =.75, *SEM* = .23, *p* = .002). Vibrotactile cues were also helpful for YA, but only in four-item array trials, as observed between the significantly higher WM performance on cued trials relative to non-cued trials (md = .73, *SEM* = .20, *p* = .001). For the six-item array, there was no significant difference between vibrotactile cued and non-cued trials (*p* = .41) in the compare interference task. Finally, visual cues were helpful to YA across both array sizes in the compare interference condition. In the four-item array, performance on visually cued trials was significantly higher than performance on non-cued trials (md = .62, *SEM* = .21, *p* = .007). Unlike the pattern observed for auditory cues, this visual cue benefit did not increase for six-item arrays, but still improved performance on cued trials relative to non-cued trials (md = .49, *SEM* = .21, *p* = .02).

YA vs. OA. As Figure 7 illustrates, OA generally performed worse (*p* < .05) than YA across all experimental conditions, with several exceptions. There were no age group differences in the vibrotactile block for non-cued four-item array trials in the ignore interference condition (*p* = .64), and non-cued six-item trials in the compare interference condition (*p* = .13). Additionally, we observed no age group differences in the visual block for non-cued four-item trials (*p* = .20) and six-item trials (*p* = .81) in the ignore interference condition, and only a marginally significant higher performance of YA relative to OA on cued trials in the compare interference condition (md = .52, *SEM* = .29, *p* = .078).

Summary. Taken together, the pattern of results show that OA generally have worse visual spatial location WM performance and when the maintenance interference was to be ignored, only OA showed any substantial cue benefit, and this benefit was greatest for visual cues, and was only seen at lower memory loads (four-item arrays). On the other hand, YA only benefitted from the vibrotactile cue in the larger six-item array trials. When the maintenance information was to be compared, we observed a different pattern of results. In these trials, YA utilized all cue modalities to improve spatial WM performance, and the auditory cue was the most helpful, compared to vibrotactile and visual cues, in the more difficult six-item array. OA, on the other hand, only benefitted from the cross-modal cues in the compare trials.

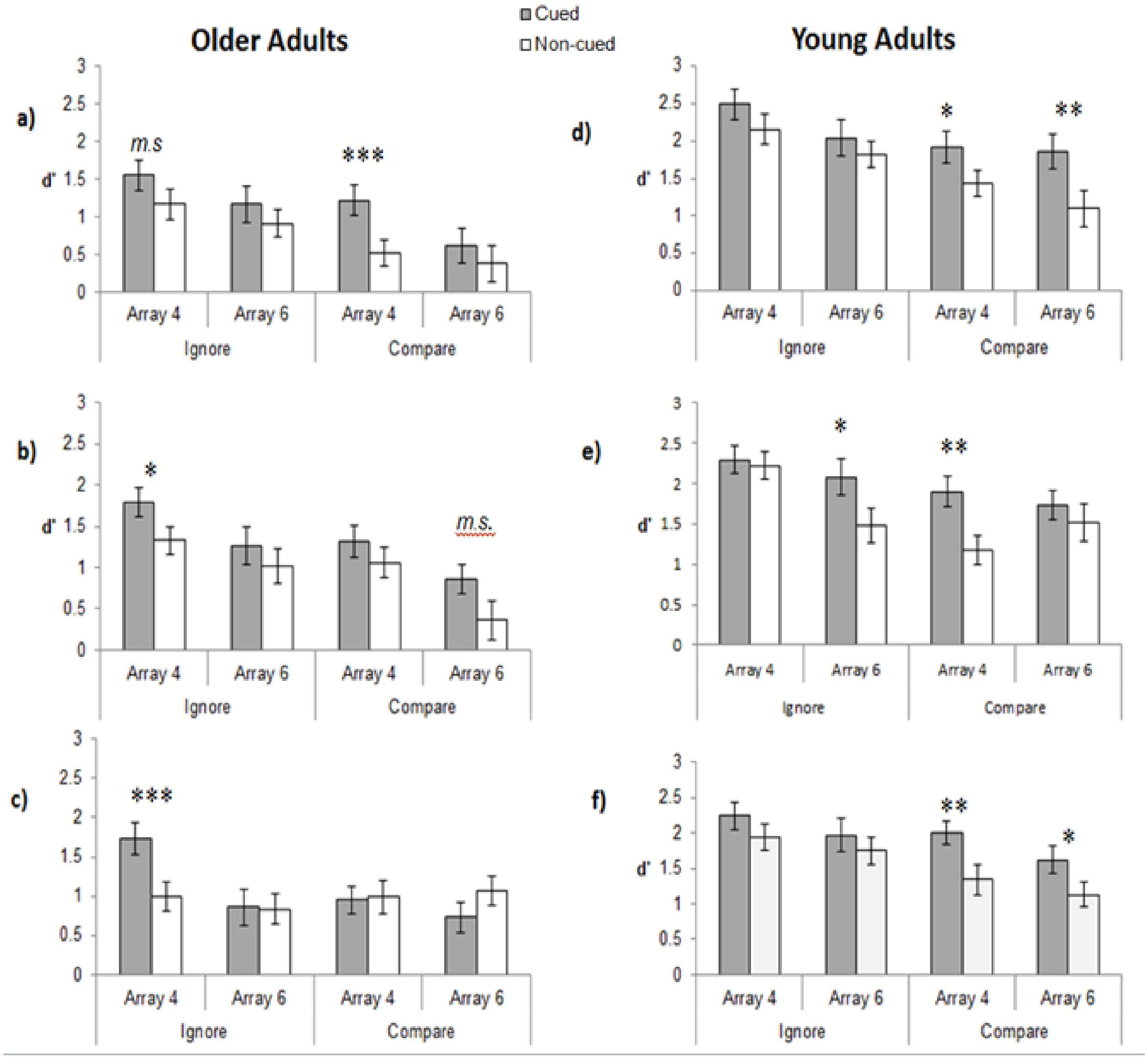

Figure 7. Age group x cue modality x cue type x array size x interference interaction for d' scores. Mean performance (d') on visual spatial location WM task during attend and compare interference vs. ignore interference trials. Gray bars +/- *SEM* represent performance on cued trials; white bars +/- *SEM* represent performance on non-cued trials. OA performance for auditory cue blocks (a), vibrotactile cue blocks (b), and visual cue blocks (c); YA performance on auditory (d), vibrotactile (e), and visual cue (f) blocks. Significant differences between cued and non-cued trials are denoted as: **p* < .05, ***p* < .01, ****p* < .001, *m.s.* = marginally significant

Spatial WM Task – False Alarm Rates

The mixed model ANOVA on false alarm rates revealed a significant five-way interaction between age group, cue modality, cue type, interference type, and array size, *F* (1.89, 64.1) = 4.5, *p* = .017, $\eta_p{}^{2\,=}$ .12. As shown in Figure 8, overall, there was limited reduction in false alarm rates on cued trials relative to non-cued trials across all experimental conditions. However, relative to YA, OA showed a benefit of cues (relative to no cues) on false alarm rates most consistently. In the auditory cue condition and when interference was to be attended and compared, OA showed lower false alarm rates on cued trials relative to non-cued trials (md = .13, *SEM* = .05, *p* = .01) on four-item arrays. In the visual cue condition, OA had significantly higher false alarm rates on cued trials relative to non-cued trials in six-item arrays for the attend and compare condition (md = .09, *SEM* = .04, *p* = .01), significantly lower false alarm rates on cued trials relative to non-cued trials on four-item arrays when interference was to be ignored (md = .10, *SEM* = .04, *p* = .02). For OA, all other false alarm rate differences between cued and non-cued trials were non-significant (*p* > .05).

YA only showed significantly lower false alarm rates on cued trials relative to non-cued trials (md = .12, *SEM* = .04, *p* = .01) on four-item array trials in the vibrotactile cue condition when interference was to be attended and compared. For YA, all other false alarm rate differences between cued and non-cued trials were non-significant (*p* > .05).

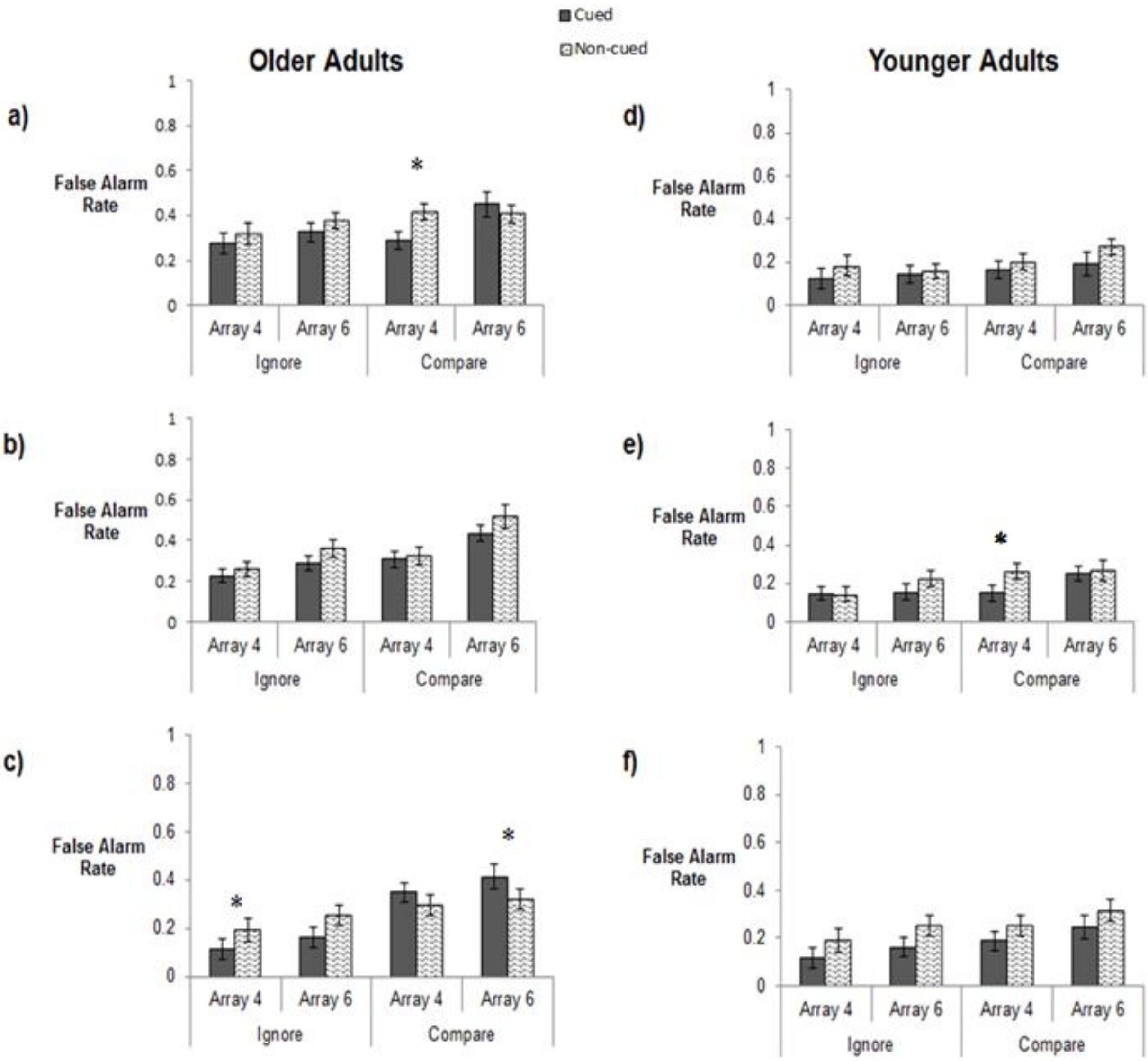

Figure 8. Age group x cue modality x cue type x array size x interference interaction for false alarm rates. Mean performance (false alarm rate) on visual spatial location WM task on attend and compare interference vs. ignore interference trials. Dark gray bars +/- *SEM* represent performance on cued trials; patterned bars +/- *SEM* represent performance on non-cued trials. OA performance for auditory cue blocks (a), vibrotactile cue blocks (b), and visual cue blocks (c); YA performance on auditory (d), vibrotactile (e), and visual cue (f) blocks. Significant differences between cued and non-cued trials are denoted as: **p* < .05, ***p* < .01, ****p* < .001, *m.s.* = marginally significant

Discussion

Spatial location WM has been shown to decline with age (e.g., Light & Zelinski, 1983; Naveh-Benjamin, 1988). The benefits of visual, auditory, and vibrotactile cues on spatial attention tasks such as visual target detection have been well established (e.g., Spence & Driver, 1997; Gray, Mohebbi, & Tan, 2009), with OA often showing increased benefit of uni-modal cue environmental support (e.g., McLaughlin & Murtha, 2010; Thornton & Raz, 2007). Visual cues have been shown to improve feature (Schmidt et al., 2002) and spatial (Murray et al., 2007) WM, however, evidence regarding the impact of auditory and vibrotactile cues on spatial WM is limited. Furthermore, it is not yet established whether the finding of increased cue benefit for OA relative to YA, observed in visual attention tasks, is also found in WM tasks. Previous work suggests that the age-related increased cue benefit might not apply to WM. For instance, verbal retro-cues have been shown to provide similar benefit to feature WM for OA and YA (Gilchrist et al., 2016). Similarly, we previously found that spatially informative pre-cues, regardless of modality, improved spatial WM performance to a similar degree for OA and YA (Curtis et al., submitted).

The present study sought to investigate the impact of uni-modal and cross-modal cues under the presence of WM maintenance interference in young and older adults. We extended our previous work by examining the impact of spatially informative visual, vibrotactile and auditory cues on visual spatial location WM performance, in a task where maintenance interference was to be ignored, therefore acting as a distracter, or attended and compared, therefore acting as an interrupter. We compared performance at two different memory array sizes (four items and six items), and between younger and older individuals. Our results shed light on age specific cue effects, and the nature of cross-modal cue benefit.

We predicted that interference type would moderate modality specific, and age-related cue effects. When interference was to be ignored we hypothesized that OA would experience greater cue benefit compared to YA. Our results found this to be the case, but also found that WM load played an important role. Our observation of worse spatial location WM performance for OA, compared to YA is consistent with previous reports (e.g., Naveh-Benjamin, 1988), and further suggests that our previous null findings of age deficits in spatial location WM (Curtis et al., submitted) were due to task demands. In terms of cue effects, it appears that OA are able to benefit from cues in all modalities when interference is to be ignored during WM maintenance, however only when demand on visual spatial location WM is low (i.e., four-item arrays). In higher array sizes (i.e., six-items), it is likely that the visual spatial resources of OA are taxed, and therefore there are no available resources for cue use.

YA, on the other hand, showed a different cue benefit pattern. When interference was to be ignored, YA only showed a benefit of vibrotactile cues in the higher WM load condition (i.e., six-item array). Therefore, it appears that YA are able to effectively ignore irrelevant interference during WM maintenance, and do not receive any additional benefit from cues under low task demands. When visual task demands are increased (in the higher memory array size), YA start to show a benefit from cross-modal cues. Taken together, these results support inhibition theory (Hasher & Zacks, 1979; Gazzaley et al.,

2012) and extend its implications to environmental support theories (Craik, 1994). We found that relative to YA, OA can more extensively benefit from environmental support of spatially informative cues to help improve spatial location memory of encoded visual items when irrelevant interference (stimuli that is to be ignored or inhibited) is presented during WM maintenance. At least, this is the case for lower WM loads (four items). This is not surprising, given that YA have better attentional control (Braver & Barch, 2002), and can presumably effectively filter or inhibit irrelevant information, to a certain extent, therefore do not receive additional benefit from cues for improving memory performance at lower WM loads. However, the vibrotactile cue benefit observed in for YA in the six-item array suggests that increasing WM load interferes with the ability of YA to inhibit distracters. Under this condition of higher visual demand, a cross-modal cue that helps focus attentional resources on encoded items, can improve WM performance in YA. Our findings for YA also support multiple resource theory (Wickens, 2008), suggesting that once visual resources are taxed, as in the six-item array, cross-modal cues that utilize separate sensory processing stores become more helpful.

Of further interest, we found that in ignore interference trials, the OA cue benefit in the smaller memory array trials (four-item arrays) was largest for visual cues, followed by vibrotactile, and then auditory cues. This suggests that in this visual spatial location WM task with visual interference, OA are relying mainly on visual processing, which helps explains the finding that once this capacity is exceeded (e.g., in six-item array trials), we observe no cue effect.

In the attend and compare interference conditions we also predicted cross-modal cues would be more consistently helpful relative to visual cues, due to the increased visual load of the WM task. Our results generally support this hypothesis, but suggest that visual spatial location WM load and age moderate cue effects. For instance, OA only benefitted from cross-modal cues (higher performance relative to no cues), but this depended on array size. Auditory cues provided the largest benefit to WM performance, but only for four-item arrays, whereas vibrotactile cues provided a marginally significant benefit in six-item arrays. On the other hand, YA were able to utilize all cue types to improve visual spatial location WM performance in the attend and compare interference task. Of note, while YA showed a benefit to visual spatial location WM performance (relative to no cues) across all cue modalities, we observed a larger benefit of auditory cues when array size increased from four to six-items, and a larger benefit of vibrotactile cues (in the four-item array) compared to visual cues. These results suggest that, similar to the results observed in the ignore interference task, YA benefit most from cross-modal cues compared to uni-modal cues when task demands are high. Generally, these results further support multiple resource theory (Wickens, 2008). When interfering items were to be compared and attended, additional visual spatial attention resources were presumably utilized during spatial location WM maintenance. When this occurred, cross-modal cues were generally more helpful to performance compared to visual cues, but as a caveat, only under lower WM loads for OA. Taken together, these results suggest that regardless of age group, in more difficult visual spatial location WM tasks, such as those that involved an interrupting interference task (attend and compare) presented during maintenance, spatially informative cross-modal pre-cues are more helpful than uni-modal cues.

The results of the present study provide insight into the nature of the cross-modal cue benefit. While it has been posited that spatially informative pre-cues exert their effects during WM maintenance (Awh et al., 2001), our results suggest there are caveats to this account. If spatially informative pre-cues acted as a spatial rehearsal mechanism tapping into spatial attention and executive attention resources, we would expect that overall cue benefits would be smaller in the attend and compare condition relative to the ignore interference condition. Mainly because comparing the rectangles and making a decision as to whether they were the same or different also utilized available spatial attention and executive attention resources. However, we found that the cue benefits actually increased in the more difficult maintenance condition. We suggest that while cues might work to facilitate spatial attention during WM, there is an increased benefit to this facilitation when the demand for executive attention is high, particularly for cross-modal cues. It is possible that this increased cross-modal cue benefit is mediated by a supramodal attention system (Driver & Spence, 1998) that comes “online” when the need for attentional control is increased. While the supramodal system is thought to be mediated by the superior colliculus and inferior parietal cortices (Alvarado et al., 2007; Macaluso, 2010), which activate sensory processing in a top-down manner, our results suggest that the executive attention network in the frontal lobes might also mediate this system, under certain task demands. Therefore, future research should investigate the brain mechanisms mediating our observed cue effects.

Our investigations of false alarm effects also provide additional information regarding age differences in the nature of cue benefits. Similar to previous findings (Curtis et al., submitted), we found that OA received the most consistent benefit (compared to YA) in terms of lowering false alarm rates on cued trials relative to non-cued trials, whereas false alarm rates for YA generally did not change between cued and non-cued trials. Given that false alarm rates are thought to be associated with familiarity based processing (e.g., Yonelinas, 1997), our results suggest that the mechanisms of cue use might differ between age group. More specifically, OA might show a reduction in familiarity processing on cued trials relative to non-cued trials and cues help promote deeper encoding and retrieval that is recollection based in OA, whereas, YA already encode information more deeply (e.g., Cabeza, Daselaar, Dolcos, Prince, Budde, & Nyberg, 2004), therefore the reductions to familiarity based processing (and false alarm rates) are not as apparent. The cue effects experienced by YA may reflect improvements to deep encoding and/or recollection at retrieval.

There are several limitations in the present study that impact generalizability of our results. For example, there are some inconsistent results for modality specific cue benefits across array sizes and interference type. Although we observed general patterns of increased cross-modal cue benefit with increased task demands, these inconsistencies in cue benefits somewhat limit the generalizability of our results to cognitive underpinnings of spatial location WM processes. Furthermore, given that OA did not show cue benefits in the most difficult task condition (six-item arrays in the compare task), in order to examine whether cue benefits increase as a function of memory load, it would be useful to test OA on smaller memory array sizes (e.g., two items). This would allow for further generalization of the finding for increased cue benefit of cross-modal cues relative to uni-modal cues when task demands are increased.

In conclusion, our results support previous research showing that spatially informative visual, auditory, and vibrotactile pre-cues improve memory for visual spatial location WM relative to no cues (Curtis et al., submitted). Importantly, we also extend these findings by showing that age, modality, WM load, and maintenance interference moderate these cue effects. While YA generally do not benefit from cues when maintenance interference is to be ignored, and only show a benefit of a vibrotactile cue in a high WM load condition, OA use all cues, regardless of modality, to improve location memory in lower WM load conditions. Thus, OA show greater benefit from cues, relative to YA, in a WM task that requires additional inhibition, an ability that declines with age (Gazzaley et al., 2005; Padgaonkar et al., 2017). Furthermore, when the interference in WM is to be attended and compared, OA show selective benefit from cross-modal cues, while YA benefit from all cue modalities. Thus, WM task demands and age play a role in cross-modal cue benefit.

Our results provide several avenues for future consideration. Future research should investigate the neural mechanisms that mediate observed age and modality differences in cue effects. This would allow for a more complete understanding of the nature of cross-modal cue benefits. Our results also provide insight into the design of real world applications, and suggest that cross-modal cueing paradigms would provide the most benefit (relative to uni-modal paradigms) to everyday cognitive function. These cross-modal cueing paradigms would likely be most helpful in complex visual environments, such as those experienced during driving. Given the declines that OA experience in driving performance relative to YA (Cassavaugh, & Kramer, 2009), cueing applications in automobiles might prove to be most beneficial to OA. For example, assisting OA in the focusing of attention during driving scenarios where they must remember the location of an upcoming destination (e.g., cueing the location of a destination shown on a GPS system), under distracting conditions (e.g., other cars on the road, traffic signs, etc.), could likely improve their visual spatial WM performance. Therefore, future work should also examine our observed cue benefits in more realistic experimental paradigms, such as driving simulators.

Chapter 3b – Additional Details for Study 2

Participant Screening

The same screening procedures employed in study one were carried out in study two. Sample screening forms are provided in Appendix A.

Experimental Procedure

Instructions given for the computerized experimental procedure are described in Appendix D. The written debriefing form that was provided at the end of the study is also described in Appendix F.

Sample size determination

An a priori power analysis (see Appendix H) was conducted in G*Power (V3.1.9.2; Faul, Erdfelder, Lang, & Buchner 2007). To detect a mixed model highest order (five-way) interaction in study two with a medium effect size ($\eta_p^2 = .06$, recommended by Cohen, 1988), and achieve 80% power, we would require a total sample of 28, or 14 participants per age group. Given that we included 18 participants per age group, we were appropriately powered for this study.

Data Analysis

For illustrative purposes, cue benefits (d' performance on cued trials minus non-cued trials) across age groups, interference type, array sizes, and cue types are presented in Appendix I.

Despite the finding that baseline visual spatial span moderated modality specific cue benefits in study one, we did not examine the impact of visual spatial span in study two. Given that we observed a five-way interaction between all of our manipulated (cue modality, cue type, array size, and interference type) and participant (age group) factors, an analysis of spatial span would have had to be conducted on separate age groups (instead of collapsed across age groups as shown in study one where no age effects were observed). If half of the participants in each age group had high spatial spans, and half of them had low spatial spans, this would have resulted in a sample size of nine per group, which would not allow for appropriate power to detect a significant highest order interaction with baseline spatial span.

Results

All participant scores for d' scores and false alarm rates, as well as mixed model ANOVA results and relevant pairwise comparisons conducted are provided in Appendix I.

Chapter 4: General Discussion

Attention and WM are considered overlapping cognitive mechanisms. Both of these cognitive abilities decline as individuals age. OA show deficits in both feature (e.g., Gilchrist et al., 2016) and spatial (e.g., Naveh-Benjamin, 1988) WM. Using cues as a form of environmental support can help facilitate attention in both YA (e.g., Luca & Murtha, 2009; Spence & Driver, 1997), and OA (e.g., McLaughlin & Murtha, 2010; Schmidt et al., 2002). While research on uni-modal and cross-modal cueing of attention is well established, research investigating cross-modal cues on WM across the lifespan is limited. This dissertation sought to determine the effects of two cross-modal cues: auditory, and vibrotactile pre-cues (presented prior to encoding) on visual spatial WM, and compare these with visual cues in younger and older adults.

In study one, we also investigated if there was a difference in the benefit of cues that are spatially informative and those that are centrally presented (alerting cues) and provide no spatial information, and simply signal individuals to be alert to the upcoming WM task. We also varied the difficulty of the spatial WM task by presenting memory arrays of varying sizes (four-items vs. six-items) and maintenance delays (900ms vs. 1800ms), in order to further elucidate the nature of any cue benefits.

In study two, we varied the difficulty of the visual spatial WM task by either presenting visual stimuli during WM maintenance that was to be ignored and thus distracting, or required active attention and was to be compared, and thus interrupting. Investigating the effects of different types of interference allowed us to understand the nature of the observed cue benefit from a cognitive perspective, and how this benefit differs with age.

The next sections of this final chapter summarize the important findings and interpretations of study one and two. These are followed by discussions of the potential applications of the observed findings, limitations of our work, and proposed areas for future research. This chapter ends with a general summary conclusion in which the overall importance of our findings is presented.

Summary of Major Findings

Study 1. Study one was seminal in adding to the cueing literature by showing that in addition to facilitating performance in attention tasks (by quickening response time to target detection), auditory and vibrotactile cues can also improve visual spatial location WM. Overall, we found auditory and vibrotactile cues do not provide additional benefits compared to visual cues, nor is there any increased benefit for OA, at least on a task where there is no maintenance interference. The finding of cue benefits on spatial location WM was important, and the fact that there were no modality specific cue benefits suggests that in general, all types of spatially informative cues can improve visual spatial location WM. These findings support the existence of a supramodal attention system (Driver & Spence, 1998) that mediates non-modality specific spatial attention, and subsequently facilitates spatial attention in the visual modality. This appears to be the case at least, in the absence of interference during the maintenance phase of WM.

We also explored whether baseline visual spatial span moderated modality specific cue effects. This analysis revealed that in low span individuals, who presumably have a smaller pool of spatial resources available, cross-modal cues were most helpful to their visual spatial location WM performance. In contrast, high span individuals were able to utilize all cue modality types to improve performance. This supports the idea that cue use requires spatial attention processing resources, which can also be utilized during visual spatial location WM performance. Therefore, when there are fewer resources available for cue use, as in cases of low baseline span capacity or during high task demands (higher array size, longer maintenance delay), cross-modal cues are more beneficial, relative to visual cues. These results support the multiple resource theory (Wickens, 2008).

The findings of study one shed light on the nature of the cross-modal cue benefit and provide important insight for the future design of real world application of cueing paradigms, which will be discussed in detail in a later section of this chapter.

Study 2. Study two sought to determine whether age or modality specific cue effects would emerge under conditions where WM interference during the maintenance phase was presented. It is well known that OA have difficulties with attentional control (e.g., Darowski et al., 2008; Madden, 2007). Therefore in study two, we investigated whether the cues used in study one would be more beneficial to OA when the WM procedure also included a secondary task that involved ignoring or paying attention and comparing the visually presented items. We found that cues were more beneficial to OA relative to YA when the WM maintenance interference task also involved ignoring the presented items. Not being distracted by the irrelevant items requires inhibition, an ability that declines with age (Hasher & Zacks, 1979). However, this cue benefit disappeared when the WM load was increased from four-item to six item-arrays. In contrast, YA did not show any cue benefit in this WM task until the WM load was increased (from four to six items). When the items presented during WM delay were to be attended and compared (thus interfering with or interrupting maintenance), both age groups benefitted from cue use to improve their visual spatial location WM accuracy. OA showed selective cross-modal cue benefit under low WM loads, and YA were able to benefit from cues in all modalities, generally under both low and high WM loads, with a greater cross-modal auditory cue benefit relative to visual cue benefit in higher WM loads. These results generally support multiple resource theory (Wickens, 2008), and suggest that in situations where demand for attentional control is high, age-related cue modality effects emerge.

The findings of study two agree with previous attention literature showing increased benefit from environmental support for OA (McLaughlin & Murtha, 2010; Thornton & Raz, 2007), and extend these results to visual spatial location WM, and cross-modal cues. As cue benefits were greater for OA under situations of high attentional control, these findings also shed light on mechanisms contributing to cognitive aging, supporting a reduced amount of cognitive resources and/or reduced attentional control in OA (Braver & Barch, 2002; Craik, 1994). Study two results provide important theoretical insights regarding how WM performance can be enhanced in OA by utilizing spatial orienting attention mechanisms (elicited by the cues) to facilitate attentional control processes in WM, and could help inform the design of future cueing paradigms. Our results suggest that these applications should utilize cross-modal cues, in order to maximize any potential benefit to everyday WM function in OA.

Real World Applications: Cueing Paradigms

The results of this dissertation have shown that both uni-modal and cross-modal cues can improve spatial WM. However, the cross-modal auditory and vibrotactile cues provided the most widespread and consistent benefit across the various conditions. Furthermore, only cues that are spatially informative appear to provide any benefit to spatial WM. While this was a controlled, laboratory based study, our findings shed light on possible cueing paradigms that could be created and of use in the real world. In simple tasks where individuals must remember the location of an item, without any interference, spatially informative cues of any modality improve performance. However, in the real world this is rarely the case.

A direct application of our visual spatial WM findings pertains to driving scenarios. Given that increasing age is a risk factor for prevalence of driving accidents, especially under distracting conditions (e.g, Guo et al., 2016; Pope, Bell, & Stavrinos, 2017), and driving cessation of OA is associated with many cognitive and physical deficits (e.g, Chihuri et al., 2015), driving scenarios are an important avenue for application of our findings. Spatially informative auditory and vibrotactile cues have been shown to decrease response time to potentially dangerous driving events (Ho & Spence, 2005; Ho, Tan, & Spence, 2005). Our findings suggest that these types of cues could also be helpful in more demanding situations where visual spatial WM is involved.

For example, dashboard GPS systems are commonly used during driving, as they provide real time visual directions to driving destinations. In order for a GPS to not be completely distracting, individuals must glance at the digital road map as well as keep their attention on the road and their surroundings, and remember these directions or locations, thus utilizing WM. In a more complex driving situations, such as that experienced on a crowded highway, it becomes even more crucial to utilize selective attention and spatial WM to remember the information provided by the GPS. Driving requires the extensive use of visual processing resources, therefore according to our findings, cross-modal cues would be of greater benefit to visual spatial WM tasks carried out during driving scenarios. Developing spatially informative cueing systems, such as wearable tactors (e.g., attached to the wrist in a similar fashion as a watch) or auditory tones (e.g., sounds that emanate from distinct spatial locations in the interior of an automobile) that direct you to the location of relevant GPS directions could potentially be helpful to individuals of all ages, especially the OA population. Presumably, these types of cueing systems could do two things: help reduce the reliance on visual resources, and improve visual spatial memory for the driving route and destination location.

Another potential application of our experimental results could be implemented in the homes of OA. For example, OA often complain of misplacing common household items (e.g., Woolverton, Scogin, Shackelford, Black, & Duke, 2001). It would be interesting to create a spatially informative cueing system that could be activated when older individuals are placing an object like their keys or wallet in a certain location (e.g., an auditory cue that makes a beeping sound at the location where you place a household item). Based on our findings, this would presumably assist in the encoding and maintenance of these items in WM, and would also hopefully translate into a longer term memory benefit.

Limitations of Current Research

Our research has several limitations. In study one, we did not observe a generalized age-related visual spatial WM deficit, which contrasts with the myriad of studies showing such a decline (e.g., Kessels et al., 2010; Light & Zelinksi, 1983; Naveh-Benjamin, 1988). Given that our OA group had a high level of education, they might not be representative of the general OA population, and thus this limits the generalizability of our results. Even though education did not correlate with any levels of our dependent variable, thus did not appear to impact performance, the fact that they performed as well as YA suggests they might be functioning at a higher level than the general OA population. Another possibility is that the task used in study one was not difficult enough to elicit an age effect. Given previous findings of increased age-related WM deficits in recall tasks compared to recognition tasks (e.g., Craik & McDowd, 1987), it is possible that age deficits would be observed if the spatial location WM task involved recall of the locations. However, we did observe a strong general age effect in the recognition task in study two, which was more difficult due to the presence of maintenance interference. Therefore, it is likely that task demands, and not types of retrieval, mediate the age effects. In any case, it would be interesting to investigate the cueing paradigms of the present dissertation in retrieval based visual spatial WM tasks, in order to generalize our observed effects to both types of visual spatial location WM (recall and recognition).

Another possibility for the lack of age effects in study one could be due to the average age of the OA studies. In study one, the OA participants were slightly younger (*M* = 66.1 years of age) than the OA in study two (*M* = 68.7). Thus, the OA in study two might be more representative of the OA population, who suffer age-related spatial location WM decline. Additionally, the WM task employed in study two is more in line with cognitive functioning in the real world, where interference is constantly presented in the visual environment. Therefore, it is likely a combination of age of OA and task demands that contributed to the null age effects in study one.

There were also several limitations of study two. We observed some inconsistent results in terms of the increased cross-modal relative to uni-modal cue benefit across array sizes and interference task during the maintenance phase. Although generally it appears as though cross-modal cue benefits increase with task demands, our inconsistent results do not allow us to generalize across the types of task demands measured (memory load and interference task). Task difficulty might have played a role in the results observed for OA, given that they did not show any cue benefits in the most difficult task conditions (six-item arrays in the interference task). Thus, in order to provide further generalization to the observation that cue benefits increase as a function of memory load, it might be useful to test the performance of OA at smaller memory array sizes (e.g., two-items) in the more difficult interrupting or “attend and compare” interference condition.

Future Research

The findings of the current work provide insight and several questions for future research. As suggested in study one, while OA and YA show similar cue benefit to visual spatial location WM, they might be utilizing different cognitive and neural mechanisms to achieve this benefit (Townsend et al., 2006). Therefore future research should explore the neural networks mediating these strategic cue effects. This could be achieved by modifying the current experimental paradigms (e.g., increase delay periods, increase the time between trials) and examining focal or network activation in an event related functional magnetic resonance (fMRI) study. The attentional networks of orienting, alerting, and executive systems are well established. The orienting system is thought to be mediated by frontal-parietal areas such as the frontal eye fields, superior parietal lobe, temporal parietal junction, as well as the superior colliculus (Corbetta, Kincade, Ollinger, McAvoy & Shulman, 2000; Jackson, Marrocco, & Posner, 1994; Posner & Peterson, 1990; Shipp, 2004). The alerting attention system is mediated by the locus coeruleus, which supplies norepinephrine to cortical structures in the right hemisphere (Jackson et al., 1994; Posner & Peterson, 1990), as well as portions of the frontal-parietal network that help quicken the speed of orienting attention when making a response following a warning or alerting signal (Petersen & Posner, 2012). The executive attention system has been shown to be mediated by areas in the frontal lobes, namely the anterior cingulate and medial frontal cortex (Posner & Peterson 1990; Peterson & Posner, 2012). In particular, it would be interesting to investigate the extent to which the visual, auditory, and vibrotactile cues used in the present study activate neural attentional networks. This information could be useful in understanding how the cues exert their effect on attentional processing (both prior to WM encoding and perhaps within WM processing), and could better inform their use in real world applications aimed at ultimately improving WM performance.

Additionally, to more fully understand how the cues in the present study exert their effect on component WM processes, it would be important to investigate which phases of WM are facilitated by the uni-modal and cross-modal cues. This could be examined in an Electroencephalograph (EEG) or modified fMRI paradigm (modified to account for the temporal properties of the blood oxygenation level response), where brain activation is observed between cued and non-cued trials, across phases of WM: encoding, maintenance, and retrieval. For example, there might be differences between cued and non-cued trials in the neural areas that are thought to mediate the three WM phases. Neural regions of interest for encoding would be cortical attentional systems, namely left parietal regions and bilateral frontal cortices (Macpherson et al., 2014), as well as the inferior frontal junction (IFJ; Todd, Han, Harrison, & Marois, 2011). WM maintenance is thought to be mediated by a distributed network comprised of the executive attention network (Ranganath, DeGutis, & D'Esposito, 2004), dorsolateral prefrontal cortex (DLPFC; e.g., Curtis & D’Esposito, 2003), the left inferior frontal gyrus (e.g., Bergmann, Daselaar, Fernández, & Kessels, 2016; D'Esposito, Postle, Ballard, & Lease, 1999; Gazzaley, Rissman, & D’Esposito, 2004), the IFJ (Todd et al., 2011), and inferior temporal cortices (for a review see D’Esposito, 2007). Retrieval in WM has been shown to be mediated by the posterior parietal cortex (Berryhill & Olson, 2008; Öztekin et al., 2009), the left inferior frontal gyrus (Öztekin et al., 2009), and the hippocampus (Öztekin et al., 2009). Interestingly, these “retrieval” areas have also been shown to be involved in long term memory retrieval (Cabeza, Dolcos, Graham, & Nyberg, 2002; Ranganath, Johnson, D'Esposito, 2003), suggesting overlapping neural mechanisms for retrieval over brief and long durations. The extent to which cues facilitate processing in the neural regions thought to mediate component processes of WM could deepen our understanding of how uni-modal and cross-modal cues exert their effects on WM.

A related question for future investigation is whether or not the cues themselves are encoded into WM. According to Baddeley and colleagues (2011), multimodal information is thought to be bound together and stored in coherent memory representations within the episodic buffer. While we attributed the cueing benefits in the present studies to the facilitation of attentional resources prior to encoding and spatial attention and executive attention during maintenance (by facilitating processing within the central executive), it remains to be determined whether the cues themselves are encoded along with the memory target stimuli. Although the role of the episodic buffer in WM is still not fully understood (Baddely et al., 2011), the right hippocampus is thought to contribute to its function of feature binding (Piekema, Kessels, Mars, Petersson, & Fernández, 2006). Thus, future research could explore whether cross-modal cues elicit activity in this region, relative to uni-modal cues. If this is the case, then this would provide support for the episodic buffer playing a possible role in cognitive and neural mechanisms of cross-modal cue benefits in WM.

Future research should also explore the neural bases of the age-related cueing effects observed in study two. It is well established that relative to YA, OA show compensatory activity in the form of increased bilateral activity in the frontal lobes in order to achieve the same behavioural performance of YA in memory tasks (Cabeza et al., 2002). Therefore, it is likely that the cues used in the present study are a form of environmental support that augment compensatory activity for OA and increase visual spatial location WM performance to a level that is closer to the performance of YA. Therefore, a follow-up study could investigate whether the cue benefits observed for OA (in more resource demanding conditions, especially for cross-modal cues) are associated with increased compensatory activity bilaterally in the frontal lobes, relative to non-cued conditions. Similar to the seminal study by Cabeza and colleagues (2002), this proposed follow-up study could employ fMRI or positron emission tomography (PET) methods.

It is also possible that the cue benefit is elicited at different time points in WM for OA and YA. For example, the temporal activation of selective spatial attention, attentional control, and visual spatial WM might differ between cued and non-cued trials, and this activation might differ by age group. Presumably, any difference in temporal activation (e.g., attenuation of neural response) between cued and non-cued trials might represent the neural areas involved in the cue benefit. Investigating age differences in these temporal responses will help us to better understand whether or not cues are used in similar ways for each age group.

While the present studies only investigated the impact of spatially informative cues on short term memory (i.e., WM), it would be interesting to determine whether similar cue benefits are observed in long term memory. If cues are shown to be beneficial to memory performance over a longer period of time, this could have more direct applications to real world applications involving long term memory, such as the previously mentioned cueing of location of household items that are later recalled.

Of note, we only investigated the effects of cues on visual spatial location WM. While this is a strength of our work, allowing us to speak directly about how our results relate to the spatial memory of target stimuli, dissociated from any feature encoding, it also raises new questions. In our studies, participants were instructed to remember only the location of the identical stimuli. It would be interesting to investigate whether the use of non-identical stimuli results in any incidental improvements to feature memory as a result of the spatially informative cue. For example, this could be examined by presenting memory items such as novel shapes and asking participants to remember their location only, but then later asking them questions regarding the object features. If feature memory is better on cued trials relative to non-cued trials, this would suggest that a spatially informative cue also automatically assists encoding and maintenance of object visual features.

It would also be informative to conduct similar experimental procedures in middle aged individuals. This would allow for a more complete understanding of cueing effects across the entirety of the lifespan. Finally, these types of experimental cueing paradigms should also be assessed in other vulnerable populations, such as individuals with Parkinson’s Disease (PD). In these patients, spatial location short and long term memory show substantial deficits, as a result of decline in attentional resource processing (Pillon, Deweer, Vidailhet, Bonnet, Hahn-Barma, & Dubois, 1998). Depletion of striatal dopamine receptors, which interferes with projection to the frontal cortices that mediate executive control, is thought to cause this decline (Pillon, Deweer, Vidailhet, Bonnet, Hahn-Barma, & Dubois, 1998). Therefore, PD patients could likely show a large degree of benefit from the use of spatially informative cues that facilitate top down attentional control in spatial WM.

General Conclusions

To the best of our knowledge, the present studies are the first to show that spatially informative cross-modal cues can improve visual spatial location WM. We also showed that alerting cues provide no benefit to visual spatial location WM, and in fact act as distracters, impairing performance for both younger and older individuals.

Overall, auditory and vibrotactile cues are more helpful to visual spatial location WM, relative to a visual cue under certain conditions. There is a larger cross-modal benefit when spatial processing resources are limited, either by baseline levels of cognition, or by increased levels of task demands caused by larger array sizes, longer maintenance delays, or presentation of interrupting interferences during maintenance. We found that age affects the pattern of cue benefits in the presence of distracting or interrupting interference during visual spatial location maintenance. Overall, relative to YA, OA receive more widespread and larger benefit from cross-modal auditory and vibrotactile cues relative to uni-modal visual cues.

We recommend the use of cross-modal paradigms in any future real world cueing applications, especially in applications aimed at an OA population. Facilitating attentional control and visual spatial WM could have important benefits to the day to day cognitive function of older adults, and ultimately help them maintain an independent lifestyle for a longer period of time.

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Appendix A

Sample Screening Interviews

Interview – Young Adults

General Information

Date of Birth (y/m/d): ___/___/___ Sex: M or F Handedness: L or R

Level of Education: ______________ Year of Study: _____ Major: _____________

Birthplace: _____________________ First Language: ____________________

Spoken Languages: _________________________

(If not English, at what age did you learn English): _____

Medications

Medical History

			Details
Heart attack / surgery	Y	N	
Head injury (loss of consciousness?)	Y	N	
Neurological (PD, AD, MS – family hx)	Y	N	
Head / brain surgery	Y	N	
Thyroid (meds?)	Y	N	
Diabetes (meds?)	Y	N	
Treated for emotional difficulties?	Y	N	
How’s your mood today?			
Cancer / brain tumour?	Y	N	
Learning disability?	Y	N	
ADHD?	Y	N	
Other problems focusing attention?	Y	N	
Problems with memory?	Y	N	
Problems hearing? (L or R)	Y	N	

Problems with vision (cataracts, glaucoma)	Y	N
Problems sleeping (# hours:___/night)	Y	N

Interview – Older Adults

General Information

Date of Birth (y/m/d): ___/___/___ Sex: M or F Handedness: L or R

Education: ____________________ Retired: _______ Birthplace: ____________________

First Language: ____________________ Spoken Languages: ________________________

(If not English, at what age did you learn English): _____

Medications

Medical History

			Details
Stroke / Aneurysm / TIA	Y	N	
Heart attack / surgery	Y	N	
Head injury (loss of consciousness?)	Y	N	
Neurological (PD, AD, MS – family hx)	Y	N	
Head / brain surgery	Y	N	
Thyroid (meds?)	Y	N	
Diabetes (meds?)	Y	N	
High blood pressure (meds?)	Y	N	
Treated for emotional difficulties?	Y	N	
How’s your mood today?			
High cholesterol (meds?)	Y	N	
Cancer / brain tumour?	Y	N	
Learning disability?	Y	N	

Problems hearing? (L or R)	Y	N
Problems with vision (cataracts, glaucoma)	Y	N
Problems sleeping (# hours:___/night)	Y	N

Memory Questions

Do you have any concerns about your memory? Provide examples:

Have you noticed any changes in your memory?	
If yes, when did you first notice these changes?	
If yes, was the onset GRADUAL / SUDDEN	
If yes, is the course PROGRESSIVE / STABLE / VARIABLE	
How does your memory compare to other people your age – SAME / BETTER / WORSE?	
Do you have any problems remembering: Names Numbers Your Meds	 Words in conversation Appointments
Do you have problems concentrating?	
Are you getting lost?	

Activities of Daily Living - Independence

Are you responsible for cleaning (including laundry)?
Cooking?
Driving or organizing public transportation?
Medications?
Shopping?
Finances?
Do you live in a house, apartment/condo, or a supportive senior’s building?
Do you live alone?
Leisure Activities? Aids?

Appendix B

Sample of Informed Consent

Informed Consent Form

Study Name: Cueing Visuospatial Working Memory: Effects of Cue Modality and Age

Researchers: Ashley Curtis & Dr. Susan Murtha

Sponsors: York University

Purpose of the Research: To examine the effects of different types of cues on short-term memory performance in both younger and older adults.

What You Will Be Asked to Do in the Research: You will be asked to fill out a questionnaire pertaining to your age, gender, years of education, general health and any medications you may be taking. You will then be asked to participate in a series of tests (both written and oral) that assess various mental abilities such as general intelligence, attention span, visual spatial abilities and memory. You will also be asked to perform tasks on the computer, requiring you to answer questions regarding locations of objects on the screen. It should be noted that you might find some of these tests tedious or even difficult. Please do not be discouraged by feelings of frustration - you are not expected to get every question correct. The length of time for the study is estimated to be 150 minutes. Younger adults recruited from the Department of Psychology undergraduate research participant pool will receive course credit towards their introductory psychology course grade for their participation (2.5 credits for 2.5 hrs of participation). Older adults will receive $10/hour for their parti cipation ($25 for 2.5 hrs of participation) in order to defray the cost of travel and/or their time.

Risks and Discomforts: There are no known risks for participating in the research. However, you might experience fatigue from the various interview questions and from completing the cognitive tasks for the experiment.

Benefits of the Research and Benefits to You: Although there may be no direct benefits for participating in this study, your involvement will help us enhance our understanding of cueing attention and memory across the lifespan.

Voluntary Participation: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision to refrain from volunteering will not influence the nature of your ongoing relationship with the researcher or study staff, nor will it affect the nature of your relationship with York University either now, or in the future.

Withdrawal from the Study: You can stop participating in the study at any time, for any reason, if you so decide. If you decide to stop participating, you will still be eligible to receive the promised pay or course credit for agreeing to be in the project. Your decision to stop participating, or to refuse to answer particular questions, will not affect your relationship with the researchers, York University, or any other group associated with this project. In the event you withdraw from the study, all associated data collected will be immediately destroyed.

Confidentiality: Your identity will remain anonymous during all interviews, written and computerized tests. All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. Informed consent will be stored separately from all experimental data. This will ensure confidentially of results. All documents and data will be securely stored in password protected computer (for electronic data) or a locked cabinet in ou r laboratory. Confidentiality will be provided to the fullest extent possible by law. Paper based data will be dumped in confidential bins and electronic data will be deleted once a manuscript based on the data has been accepted for publication, or after a duration of 10 years, which ever comes first.

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact (Place appropriate contact information here).

This research has been reviewed and approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact (place appropriate contact information here).

Legal Rights and Signatures:

I______, consent to participate in this study conducted by ______.
I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature: ________________________________ Date: __________________________________
Participant

Signature: ________________________________ Date: __________________________________
Principle Investigator

Appendix C

Neuropsychological Tests

1.Telephone Interview of Cognitive Status (TICS)–Revised

(Spencer & Folstein, 1988)

2. Hospital Anxiety and Depression Scale (HADS)

(Zigmond & Snaith, 1983)

3. Spatial Span - Forward and Backward

(Wechsler, 1997)

4. Digit Span - Forward and Backward

(Wechsler, 1997)

5. Shipley-2

(Shipley, Gruber, Martin & Klein, 2009)

Appendix D

Study 1 Instructions

The following instructions appeared on the screen prior to beginning the spatial WM task:

This experiment will test your memory for locations.

Throughout this experiment you will need to respond using certain keys.

Please place your middle finger on the "i" (pink) key, and your index finger on the "m" (green) key now.

(Press the spacebar to continue)

Targets (gray boxes) will appear at different locations on the computer screen. There will be 4 or 6 boxes shown at a time.

After the boxes are presented, there will be a delay. You will then be shown a "probe" black box in one of the screen locations.

You will need to decide whether or not it is in the same location as one of the boxes you previously saw.

If your answer is "yes" (in the same location as a box), you will press the "i" key or top key (pink).

If your answer is "no" (not in the same location as a box), you will press the "m" key or bottom key (green).

(Please press the space bar to continue.)

Sometimes, before the gray boxes are shown, you will be given a sound cue/vibration cue/visual cue (coming from the left or right speaker/left of right wrist/left or right side of the screen). This cue is meant to help focus your attention.

If the cue comes from the right speaker/wrist/side of the screen, it is telling you to pay attention to that side of the computer screen (the location of the gray boxes appearing in that side of the screen will most likely need to be remembered). Likewise, if the cue comes from the left speaker/wrist/side of the screen you need to pay attention to the boxes in the left hand side of the screen.

The cues are meant to help you and will be correct 100% of the time.

(Please press the spacebar to continue.)

After a delay, you will then answer the memory question: whether the probe box is in the **same or different** location as one of the previously presented grey boxes.

Remember, for all your responses: **top key = "yes"** (same location)

Bottom key = "no" (different location)

(Press the spacebar for an example of this task.)

We will now try a few practice trials to familiarize yourself with the task.

(Press the spacebar to continue with the practice trials)

Appendix E

Study 2 Instructions

The following instructions appeared on the screen prior to beginning the spatial WM task:

This experiment will test your memory for locations.

Throughout this experiment you will need to respond using certain keys.

Please place your middle finger on the "i" (pink) key, and your index finger on the "m" (green) key now.

(Press the spacebar to continue)

Targets (gray boxes) will appear at different locations on the computer screen. There will be 4 or 6 boxes shown at a time.

After the boxes are presented, there will be a delay. You will then be shown a "probe" black box in one of the screen locations.

You will need to decide whether or not it is in the same location as one of the boxes you previously saw.

If your answer is "yes" (in the same location as a box), you will press the "i" key or top key (pink).

If your answer is "no" (not in the same location as a box), you will press the "m" key or bottom key (green).

(Please press the space bar to continue.)

Sometimes, before the gray boxes are shown, you will be given a sound cue/vibration cue/visual cue (coming from the left or right speaker/left of right wrist/left or right side of the screen). This cue is meant to help focus your attention.

If the cue comes from the right speaker/wrist/side of the screen, it is telling you to pay attention to that side of the computer screen (the location of the gray boxes appearing in that side of the screen will most likely need to be remembered). Likewise, if the cue comes from the left speaker/wrist/side of the screen you need to pay attention to the boxes in the left hand side of the screen.

The cues are meant to help you and will be correct 100% of the time.

(Please press the spacebar to continue.)

Remembering the location of the gray boxes is your main priority.

However, after the boxes disappear and you are trying to keep their locations in your memory, you will also be presented new information.

These will be white rectangles near the center of the screen.

Press the spacebar to see an example of what these white rectangles will look like.

Half of the time you will be asked to ignore these white rectangles. Therefore try your best to ignore them and just keep your attention focused on remembering the locations of the gray boxes. When you need to ignore the lines, you will see the words "IGNORE" before a block of trials.

(Press the spacebar to continue.)

The other half of the time, you will have to make a decision about these white rectangles. You will see the word "COMPARE" before a block of trials.

You will quickly decide if they are in the SAME orientation (both vertical or horizontal) or DIFFERENT orientations (one vertical/one horizontal).

If they are in the SAME orientation, you will press the "yes" key - the top key pink key ("i").

If they are in DIFFERENT orientations, you will press the "no" key - the bottom "green" key ("m")

(Press the spacebar to continue)

Then after a short delay, you will then answer the memory question: whether the probe box is in the **same or different** <u>location</u> as one of the previously presented grey boxes.

Remember, for all your responses: **top key = "yes"** (same location)

Bottom key = "no" (different location)

(Press the spacebar for an example of this task.)

We will now try a few practice trials to familiarize yourself with the task.

(Press the spacebar to continue with the practice trials)

Before a block of IGNORE trials, participants saw the following instructions appear on the screen:

IGNORE

- ignore the lines presented during the delay. Focus on remembering the gray box locations.

Before a block of COMPARE trials, participants saw the following instructions appear on the screen:

COMPARE

Same orientation = "yes", top key

Different orientation = "no", bottom key

Appendix F

Debriefing Form

The following written information was provided as a handout to each participant upon completion of the study:

Thank you for participating in the experimental session today. Your assistance is very much appreciated and will help us with our understanding of cognitive psychology.

The purpose of the questionnaires and paper/pen type tasks you completed were to provide baseline measures of intelligence, memory, attention, and mood. Aggregated group data might appear in future publications, but your individual results will be kept entirely anonymous.

The overall goal of the experimental research conducted for this study is to investigate how different types of cues (visual, sound, and vibration) affect our ability to remember spatial locations. Research has shown that cues that differ in modality from the objects you are asked to remember (e.g., a sound cue and a visual object) help you more than those that are similar to the items to be remembered (e.g., a visual cue and a visual object). Different characteristics about the cue were also manipulated, in order to see how these changes affect cue benefit. For example, you might have noticed that sometimes a cue indicated the location of a target item you were asked to remember. Other times, it simply alerted you that items were going to be presented. Prior research has shown that when cues tell you *where* something is going to appear, our attention is focused to a greater degree than simply telling us *when* something is going to appear.

Another goal of the research is to see how our age affects our ability to use cues to focus our attention and remember item locations. Research has shown that older adults are worse at remembering where things are located, compared to younger adults. However, they have also shown to be helped more by cues than younger adults. We would like to know which type of cue is most helpful for their memory.

I hoped you learned something today about the psychological method. Your participation today will help the growth of the scientific literature, as the results obtained from this study might appear in future publications. All information collected will be kept entirely anonymous.

Appendix G

Power Calculations for Required Sample Size

Power Analysis - Output

80% Power

```
F tests - ANOVA: Repeated measures, within-between interaction
Analysis:     A priori: Compute required sample size
Input:        Effect size f                   =  0.2526456
              α err prob                      =  0.05
              Power (1-β err prob)            =  0.80
              Number of groups                =  2
              Number of measurements          =  4
              Corr among rep measures         =  0.50
              Nonsphericity correction ε      =  1
Output:       Noncentrality parameter λ       =  12.2553214
              Critical F                      =  2.7437108
              Numerator df                    =  3.0000000
              Denominator df                  =  66.0000000
              Total sample size               =  24
                                    Actual power      =          0.8245854
```

90% Power

```
F tests - ANOVA: Repeated measures, within-between interaction
Analysis:     A priori: Compute required sample size
Input:        Effect size f                   =  0.2526456
              α err prob                      =  0.05
              Power (1-β err prob)            =  0.90
              Number of groups                =  2
              Number of measurements          =  4
              Corr among rep measures         =  0.50
              Nonsphericity correction ε      =  1
Output:       Noncentrality parameter λ       =  15.3191518
              Critical F                      =  2.7132271
              Numerator df                    =  3.0000000
              Denominator df                  =  84.0000000
              Total sample size               =  30
              Actual power                    =  0.9095522
```

Appendix H

Study One Additional Data and Analyses

Table H.1

Between Age group (YA vs. OA) comparisons for demographic variables

Variable	*SS*	*df*	*MS*	*F*	*p*
Age***	18860.4	1	18860.4	1248.1	.000
Education*	51.4	1	51.4	20.9	.000
HADS- anxiety*	103.4	1	103.4	10.0	.003
HADS- depression	13.4	1	13.4	2.3	.14
Shipley – composite (Standard Score)	16	1	16	0.14	.71
Digit Span - forward span	1.4	1	1.4	0.90	.35
Digit Span – Total (SS)	12.3	1	12.3	3.49	.07
Spatial Span – forward span	0.03	1	0.03	0.033	.86
Spatial Span – Total (SS)	13.4	1	13.4	3.13	.09

Note. Significant differences between groups: **p* < .05. ***p* < .01. ****p* < .001.

Table H.2

Correlations of predictor variables that differ by age group with dependent variables

Measure	Education	HADS-A
Spatially Informative Cue		
Auditory Cued 4 short delay	.083	.037
Auditory Non-Cued 4 short delay	.154	-.081
Auditory Cued 4 long delay	.172	.114
Auditory Non-Cued 4 long delay	-.016	-.229
Auditory Cued 6 short delay	-.009	.019
Auditory Non-Cued 6 short delay	-.070	.007
Auditory Cued 6 long delay	.170	-.197
Auditory Non-Cued 6 long delay	-.043	-.063
Tactile Cued 4 short delay	.102	-.062
Tactile Non-Cued 4 short delay	-.079	.016
Tactile Cued 4 long delay	.231	-.088
Tactile Non-Cued 4 long delay	.141	.063
Tactile Cued 6 short delay	.019	.012
Tactile Non-Cued 6 short delay	.120	.120
Tactile Cued 6 long delay	.087	.047
Tactile Non-Cued 6 long delay	-.008	-.013
Visual Cued 4 short delay	-.063	.051
Visual Non-Cued 4 short delay	.171	.119
Visual Cued 4 long delay	.029	-.070
Visual Non-Cued 4 long delay	.167	-.056
Visual Cued 6 short delay	-.165	-.013
Visual Non-Cued 6 short delay	-.225	.374*
Visual Cued 6 long delay	.352*	.010
Visual Non-Cued 6 long delay	.025	.051

Alerting Cue		
Auditory Cued 4 short delay	.057	-.033
Auditory Non-Cued 4 short delay	.222	-.137
Auditory Cued 4 long delay	.115	.018
Auditory Non-Cued 4 long delay	.080	.159
Auditory Cued 6 short delay	-.404*	.325
Auditory Non-Cued 6 short delay	-.058	.047
Auditory Cued 6 long delay	.006	.095
Auditory Non-Cued 6 long delay	-.097	.339*
Tactile Cued 4 short delay	.068	.036
Tactile Non-Cued 4 short delay	.085	-.156
Tactile Cued 4 long delay	.268	.032
Tactile Non-Cued 4 long delay	.237	-.055
Tactile Cued 6 short delay	.208	.203
Tactile Non-Cued 6 short delay	.084	.119
Tactile Cued 6 long delay	-.039	.193
Tactile Non-Cued 6 long delay	.025	.280
Visual Cued 4 short delay	.117	.044
Visual Non-Cued 4 short delay	.174	-.153
Visual Cued 4 long delay	.137	-.098
Visual Non-Cued 4 long delay	-.016	.068
Visual Cued 6 short delay	-.258	-.072
Visual Non-Cued 6 short delay	.156	.103
Visual Cued 6 long delay	.298	-.050
Visual Non-Cued 6 long delay	.023	.031

Note. Values represent Pearson's *r*.
*significant at .05

Table H.3

Accuracy values (d') in Spatial Location WM task for Spatially Informative Cue across all trial levels and both age groups

	OA				YA			
	Cued		Non-Cued		Cued		Non-Cued	
Trial Type	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Auditory Cue Blocks								
Short Delay								
Array Size 4	2.10	0.21	1.73	0.20	2.05	0.21	1.70	0.20
Array Size 6	1.79	0.24	1.20	0.19	1.90	0.24	1.55	0.19
Long Delay								
Array Size 4	2.25	0.21	1.51	0.21	2.19	0.21	1.62	0.21
Array Size 6	2.08	0.19	1.29	0.23	1.76	0.19	1.49	0.23
Vibrotactile Cue Blocks								
Short Delay								
Array Size 4	2.20	0.22	1.90	0.18	2.46	0.22	2.11	0.18
Array Size 6	2.12	0.19	1.19	0.24	2.10	0.19	1.50	0.24
Long Delay								
Array Size 4	2.11	0.19	1.69	0.19	2.18	0.19	1.73	0.19
Array Size 6	1.72	0.17	1.50	0.18	2.12	0.17	1.51	0.18
Visual Cue Blocks								
Short Delay								
Array Size 4	2.02	0.19	1.84	0.21	2.11	0.19	2.05	0.21
Array Size 6	1.59	0.16	0.79	0.16	2.02	0.16	1.74	0.16
Long Delay								
Array Size 4	2.06	0.20	1.80	0.20	2.06	0.20	1.60	0.20
Array Size 6	1.71	0.18	1.34	0.18	1.61	0.18	1.40	0.18

Note. OA = older adults; YA = younger adults

Table H.4

Mixed Model Analysis of Variance of d' values on Spatial Location WM Task (Spatially Informative Cue)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
	Between Subjects					
Intercept	2777.26	1	2777.26	360.98	.000	.914
Age Group	3.40	1	3.40	0.44	.511	.013
Error	261.59	34	7.69			
	Within Subjects					
modality	3.43	1.91	1.80	3.34	.044	.089
modality * Age Group	0.86	1.91	0.45	0.84	.432	.024
Error (modality)	34.91	64.84	0.54			
array size	24.54	1.00	24.54	78.20	.000	.697
Array size * Age Group	1.08	1.00	1.08	3.45	.072	.092
Error (array size)	10.67	34.00	0.31			
Delay	0.82	1.00	0.82	2.10	.156	.058
Delay * Age Group	2.62	1.00	2.62	6.70	.014	.165
Error (Delay)	13.30	34.00	0.39			
Cue Type	41.18	1.00	41.18	69.08	.000	.670
Cue Type * Age Group	0.86	1.00	0.86	1.44	.238	.041
Error (Cue Type)	20.27	34.00	0.60			
Modality * Array	0.83	1.86	0.44	0.95	.386	.027
Modality * Array Size * Age Group	0.76	1.86	0.41	0.87	.416	.025
Error(Modality* Array Size)	29.53	63.14	0.47			

Modality * Delay	0.90	1.88	0.48	1.34	.269	.038
Modality * Delay * Age Group	1.84	1.88	0.98	2.73	.076	.074
Error(Modality*Delay)	22.86	63.76	0.36			
Array size * Delay	0.64	1.00	0.64	2.42	.129	.066
Array Size * Delay * Age Group	0.71	1.00	0.71	2.65	.113	.072
Error (Array Size * Delay)	9.04	34.00	0.27			
Modality * Array * Delay	0.35	1.93	0.18	0.62	.537	.018
Modality * Array Size * Delay * Age Group	1.37	1.93	0.71	2.42	.099	.066
Error(Modality*Array Size*Delay)	19.29	65.58	0.29			
Modality * Cue Type	1.43	1.88	0.76	1.44	.245	.041
Modality * Cue Type * Group	0.82	1.88	0.44	0.83	.436	.024
Error(Modality*Cue Type)	33.90	63.81	0.53			
Array Size * Cue Type	0.82	1.00	0.82	2.12	.155	.059
Array Size * Cue Type * Age Group	0.77	1.00	0.77	1.98	.169	.055
Error(Array Size* Cue Type)	13.19	34.00	0.39			
Modality * Array Size * Cue Type	0.54	1.82	0.30	0.62	.528	.018
Modality * Array Size * Cue Type * Age Group	0.35	1.82	0.19	0.40	.652	.012
Error(Modality*Array Size*Cue Type)	29.61	61.78	0.48			
Delay * Cue Type	0.01	1.00	0.01	0.03	.861	.001
Delay * Cue Type * Age Group	0.32	1.00	0.32	0.85	.362	.024
Error(Delay*Cue Type)	12.88	34.00	0.38			
Modality * Delay * Cue Type	0.95	1.97	0.48	1.48	.236	.042
Modality * Delay * Cue Type * Age Group	0.80	1.97	0.41	1.25	.294	.035
Error(Modality*Delay*Cue Type)	21.85	66.95	0.33			

Array Size * Delay * Cue Type	1.98	1.00	1.98	6.04	.019	.151
Array Size * Delay * Cue Type * Age Group	0.19	1.00	0.19	0.59	.448	.017
Error(Array Size*Delay*Cue Type)	11.15	34.00	0.33			
Modality * Array Size * Delay * Cue Type	0.20	1.99	0.10	0.30	.741	.009
Modality * Array Size * Delay * Cue Type * Age Group	0.42	1.99	0.21	0.63	.533	.018
Error(Modality*Array Size*Delay*Cue Type)	22.27	67.67	0.33			

Note. Degrees of freedom (df) were adjusted for violations of the sphericity assumption (Huynh & Feldt, 1976)

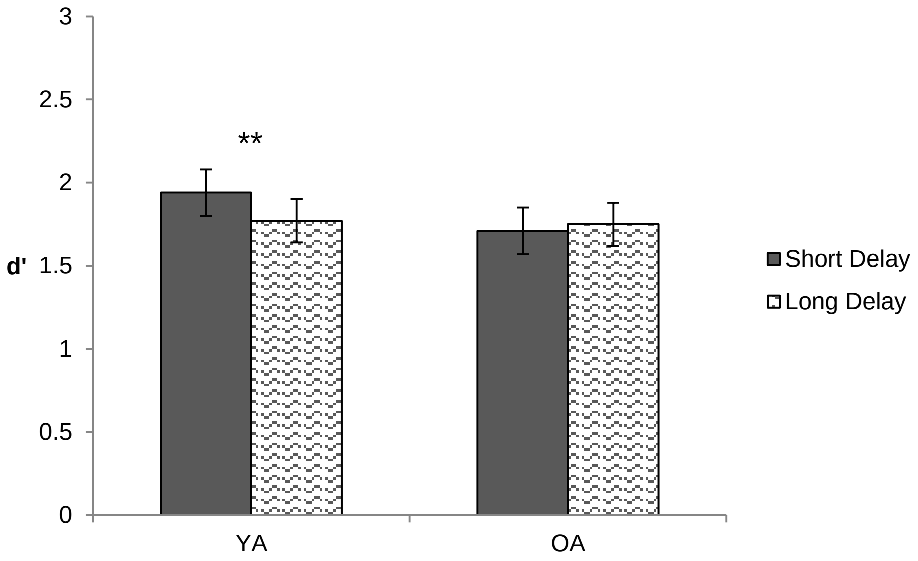

Figure H.2. Age group x delay significant interaction. Mean d' values +/- *SEM* (error bars) between YA and OA across short (900ms) and long (1800ms) delay periods, collapsed across cue modality, cue type (spatially informative cue vs. no cue), and array size.

***p* < .001

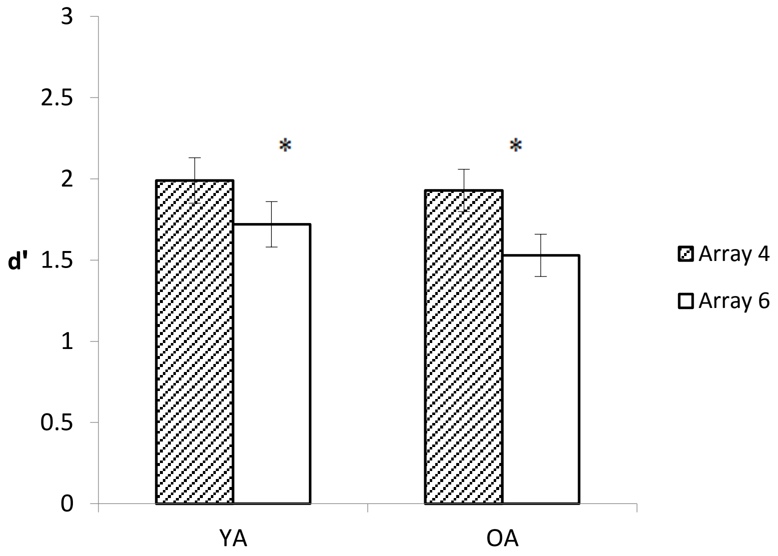

Figure H.2. Age group x array size marginally significant (*p* = .07) interaction. Mean d' values +/- *SEM* (error bars) between YA and OA, collapsed across cue modality, cue type (spatially informative cue vs. no cue), and delay period.
*denotes significant differences between array sizes.

Table H.5

False Alarm rates for Spatial WM task – Spatially Informative Cue

	OA				YA			
	Cued		Non-Cued		Cued		Non-Cued	
Trial Type	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Auditory Cue Blocks								
Short Delay								
Array Size 4	0.184	0.03	0.267	0.048	0.149	0.03	0.174	0.048
Array Size 6	0.257	0.039	0.361	0.037	0.201	0.039	0.149	0.037
Long Delay								
Array Size 4	0.167	0.037	0.243	0.039	0.142	0.037	0.167	0.039
Array Size 6	0.181	0.028	0.302	0.033	0.163	0.028	0.212	0.033
Vibrotactile Cue Blocks								
Short Delay								
Array Size 4	0.264	0.037	0.188	0.037	0.208	0.037	0.164	0.037
Array Size 6	0.438	0.039	0.296	0.033	0.188	0.039	0.188	0.033
Long Delay								
Array Size 4	0.174	0.035	0.229	0.033	0.229	0.035	0.135	0.033
Array Size 6	0.264	0.03	0.275	0.03	0.181	0.03	0.196	0.03
Visual Cue Blocks								
Short Delay								
Array Size 4	0.139	0.024	0.188	0.025	0.083	0.024	0.129	0.025
Array Size 6	0.17	0.029	0.333	0.045	0.146	0.029	0.236	0.045
Long Delay								
Array Size 4	0.167	0.04	0.17	0.024	0.174	0.04	0.129	0.024
Array Size 6	0.205	0.033	0.229	0.036	0.181	0.033	0.198	0.036

Note. OA = older adults; YA = younger adults

Table H.6

Mixed Model Analysis of Variance of False Alarm Rates in Spatial WM Task - Spatially Informative Cue

Source	SS	df	MS	F	p	η_p^2
		Between Subjects				
Intercept	34.16	1.00	34.16	189.02	.000	.848
Group	1.08	1.00	1.08	5.88	.020	.150
Error	6.15	34.00	.181			
		Within Subjects				
Modality	0.158	1.97	0.080	3.09	.053	.083
Modality * Age Group	0.113	1.97	0.057	2.22	.118	.061
Error(Modality)	1.737	67.08	0.026			
Array Size	0.911	1.00	0.911	84.88	.000	.714
Array Size * Age Group	0.090	1.00	0.090	8.39	.007	.198
Error(Array Size)	0.365	34.00	0.011			
Delay	0.071	1.00	0.071	5.11	.030	.131
Delay * Age Group	0.298	1.00	0.298	21.54	.000	.388
Error(Delay)	0.471	34.00	0.014			
Cue	0.306	1.00	0.306	16.94	.000	.333
Cue * Age Group	0.163	1.00	0.163	9.00	.005	.209
Error(Cue)	0.615	34.00	0.018			
Modality * Array Size	0.078	1.86	0.042	2.21	.122	.061
Modality * Array Size * Age Group	0.047	1.86	0.025	1.34	.268	.038
Error(Modality*Array Size)	1.196	63.30	0.019			
Modality * Delay	0.059	1.88	0.032	2.44	.098	.067
Modality * Delay * Age Group	0.117	1.88	0.062	4.79	.013	.123
Error(Modality*Delay)	0.827	63.81	0.013			

Array Size * Delay	0.047	1.00	0.047	3.67	.064	.098
Array Size * Delay * Age Group	0.049	1.00	0.049	3.84	.058	.101
Error(Array Size*Delay)	0.434	34.00	0.013			
Modality * Array Size * Delay	0.008	1.57	0.005	0.33	.669	.010
Modality * Array Size * Delay * Age Group	0.038	1.57	0.024	1.56	.221	.044
Error(Modality*Array Size*Delay)	0.817	53.27	0.015			
Modality * Cue	0.056	1.80	0.031	2.00	.148	.056
Modality * Cue * Age Group	0.026	1.80	0.015	0.94	.387	.027
Error(Modality*Cue)	0.947	61.32	0.015			
Array Size * Cue	0.050	1.00	0.050	2.76	.106	.075
Array Size * Cue * Age Group	0.024	1.00	0.024	1.33	.256	.038
Error(Array Size*Cue)	0.614	34.00	0.018			
Modality * Array Size * Cue	0.030	1.91	0.016	1.52	.227	.043
Modality * Array Size * Cue * Age Group	0.005	1.91	0.003	0.28	.747	.008
Error(Modality*Array Size*Cue)	0.669	65.01	0.010			
Delay * Cue	0.129	1.00	0.129	7.64	.009	.183
Delay * Cue * Age Group	0.043	1.00	0.043	2.51	.122	.069
Error(Delay*Cue)	0.575	34.00	0.017			
Modality * Delay * Cue	0.159	1.91	0.083	5.47	.007	.139
Modality * Delay * Cue * Age Group	0.024	1.91	0.013	0.84	.430	.024
Error(Modality*Delay*Cue)	0.986	64.87	0.015			
Array Size * Delay * Cue	0.000	1.00	0.000	0.00	.976	.000
Array Size * Delay * Cue * Age Group	0.019	1.00	0.019	1.27	.268	.036
Error(Array Size*Delay*Cue)	0.501	34.00	0.015			
Modality * Array Size * Delay * Cue	0.027	1.94	0.014	0.94	.393	.027
Modality * Array Size * Delay * Cue * Age Group	0.003	1.94	0.002	0.11	.889	.003
Error(Modality*Array Size*Delay*Cue)	0.994	65.86	0.015			

Note. Degrees of freedom (df) were adjusted for violations of the sphericity assumption (Huynh & Feldt, 1976)

Table H.7

Pairwise comparisons of differences in d' scores between cue type, and across array size, delay periods, and cue modality between high spatial span and low spatial span participants

Spatial Span Group	Modality	Array size	Delay	(I) cue	(J) no-cue	Mean Difference (I-J)	SE	p^a	95% Confidence Interval for Difference	
									Lower Bound	Upper Bound
Low	Auditory	4	short	1	2	.699*	0.201	.001	0.289	1.108
				2	1	-.699*	0.201	.001	-1.108	-0.289
			long	1	2	.982*	0.213	.000	0.547	1.416
				2	1	-.982*	0.213	.000	-1.416	-0.547
		6	short	1	2	.496*	0.196	.017	0.096	0.896
				2	1	-.496*	0.196	.017	-0.896	-0.096
			long	1	2	0.382	0.222	.095	-0.071	0.836
				2	1	-0.382	0.222	.095	-0.836	0.071
	Vibrotactile	4	short	1	2	0.248	0.285	.391	-0.333	0.829
				2	1	-0.248	0.285	.391	-0.829	0.333
			long	1	2	0.335	0.23	.154	-0.132	0.803
				2	1	-0.335	0.23	.154	-0.803	0.132
		6	short	1	2	1.047*	0.249	.000	0.54	1.555
				2	1	-1.047*	0.249	.000	-1.555	-0.54
			long	1	2	-0.138	0.231	.554	-0.608	0.332
				2	1	0.138	0.231	.554	-0.332	0.608
	Visual	4	short	1	2	0.271	0.23	.247	-0.197	0.74
				2	1	-0.271	0.23	.247	-0.74	0.197
			long	1	2	0.09	0.246	.715	-0.41	0.591
				2	1	-0.09	0.246	.715	-0.591	0.41
		6	short	1	2	0.35	0.245	.163	-0.15	0.849
				2	1	-0.35	0.245	.163	-0.849	0.15
			long	1	2	0.165	0.19	.392	-0.222	0.552
				2	1	-0.165	0.19	.392	-0.552	0.222
High	Auditory	4	short	1	2	0.1	0.178	.578	-0.262	0.462
				2	1	-0.1	0.178	.578	-0.462	0.262
			long	1	2	.455*	0.189	.022	0.071	0.839
				2	1	-.455*	0.189	.022	-0.839	-0.071
		6	short	1	2	.422*	0.173	.021	0.068	0.775
				2	1	-.422*	0.173	.021	-0.775	-0.068
			long	1	2	.551*	0.197	.008	0.151	0.952
				2	1	-.551*	0.197	.008	-0.952	-0.151

Vibrotactile	4	short	1	2	0.373	0.252	.149	-0.141	0.887
			2	1	-0.373	0.252	.149	-0.887	0.141
		long	1	2	.419*	0.203	.047	0.006	0.833
			2	1	-.419*	0.203	.047	-0.833	-0.006
	6	short	1	2	.587*	0.22	.012	0.139	1.036
			2	1	-.587*	0.22	.012	-1.036	-0.139
		long	1	2	.811*	0.204	.000	0.396	1.226
			2	1	-.811*	0.204	.000	-1.226	-0.396
Visual	4	short	1	2	0.081	0.203	.694	-0.333	0.495
			2	1	-0.081	0.203	.694	-0.495	0.333
		long	1	2	.620*	0.217	.007	0.178	1.062
			2	1	-.620*	0.217	.007	-1.062	-0.178
	6	short	1	2	.660*	0.217	.005	0.218	1.101
			2	1	-.660*	0.217	.005	-1.101	-0.218
		long	1	2	.358*	0.168	.041	0.016	0.7
			2	1	-.358*	0.168	.041	-0.7	-0.016

[*] mean difference is significant at .05 level

[a] Adjusted for multiple comparisons: Bonferroni

Table H.8

Accuracy values (d′) in Spatial Location WM task for Alerting Cue across all trial levels and both age groups

	OA				YA			
	Cued		Non-Cued		Cued		Non-Cued	
Trial Type	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Auditory Cue Blocks								
Short Delay								
Array Size 4	1.25	0.20	2.02	0.22	1.36	0.20	1.91	0.22
Array Size 6	0.79	0.19	1.33	0.19	1.47	0.19	1.77	0.19
Long Delay								
Array Size 4	1.54	0.19	1.53	0.19	1.42	0.19	2.10	0.19
Array Size 6	1.10	0.17	1.22	0.21	1.51	0.17	1.69	0.21
Vibrotactile Cue Blocks								
Short Delay								
Array Size 4	1.49	0.18	1.87	0.20	1.30	0.18	1.93	0.20
Array Size 6	1.27	0.21	1.10	0.20	1.39	0.21	1.46	0.20
Long Delay								
Array Size 4	1.45	0.21	1.81	0.20	1.49	0.21	1.89	0.20
Array Size 6	0.94	0.19	1.31	0.20	1.40	0.19	1.66	0.20
Visual Cue Blocks								
Short Delay								
Array Size 4	1.32	0.19	1.91	0.20	1.56	0.19	1.89	0.20
Array Size 6	1.01	0.15	1.45	0.20	1.67	0.15	1.44	0.20
Long Delay								
Array Size 4	1.42	0.18	1.72	0.18	1.75	0.18	1.97	0.18
Array Size 6	1.22	0.19	1.34	0.21	1.26	0.19	1.46	0.21

Note. OA = older adult; YA = younger adult

Table H.9

Mixed Model Analysis of Variance of d' values on Spatial Location WM Task (Alerting Cue)

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Between Age groups						
Intercept	1953.33	1.00	1953.33	314.78	.000	.903
Age group	10.67	1.00	10.67	1.72	.198	.048
Error (Age group)	210.98	34.00	6.205			
Within Age groups						
modality	0.22	1.95	0.11	0.15	.859	.004
modality * Age group	0.80	1.95	0.41	0.54	.583	.016
Error(modality)	50.95	66.35	0.77			
array	21.77	1.00	21.77	43.70	.000	.562
array * Age group	3.05	1.00	3.05	6.12	.019	.153
Error(array)	16.94	34.00	0.50			
delay	0.03	1.00	0.03	0.06	.802	.002
delay * Age group	0.16	1.00	0.16	0.32	.574	.009
Error(delay)	16.77	34.00	0.49			
cue	20.44	1.00	20.44	35.12	.000	.508
cue * Age group	0.02	1.00	0.02	0.03	.863	.001
Error(cue)	19.79	34.00	0.58			
modality * array	0.17	1.97	0.09	0.21	.807	.006
modality * array * Age group	1.59	1.97	0.81	1.96	.149	.055
Error(modality*array)	27.59	66.82	0.41			

modality * delay	0.05	1.68	0.03	0.07	.907	.002
modality * delay * Age group	0.27	1.68	0.16	0.36	.665	.010
Error(modality*delay)	25.55	57.16	0.45			
array * delay	0.05	1.00	0.05	0.08	.774	.002
array * delay * Age group	0.77	1.00	0.77	1.34	.255	.038
Error(array*delay)	19.57	34.00	0.58			
modality * array * delay	0.23	1.90	0.12	0.33	.707	.010
modality * array * delay * Age group	0.53	1.90	0.28	0.77	.462	.022
Error(modality*array*delay)	23.25	64.51	0.36			
modality * cue	0.81	1.93	0.42	0.96	.387	.027
modality * cue * Age group	1.26	1.93	0.65	1.48	.236	.042
Error(modality*cue)	28.91	65.53	0.44			
array * cue	3.36	1.00	3.36	10.15	.003	.230
array * cue * Age group	0.41	1.00	0.41	1.24	.272	.035
Error(array*cue)	11.24	34.00	0.33			
modality * array * cue	0.10	1.87	0.06	0.12	.872	.004
modality * array * cue * Age group	0.15	1.87	0.08	0.19	.818	.005
Error(modality*array*cue)	28.23	63.71	0.44			
delay * cue	0.37	1.00	0.37	0.85	.363	.024
delay * cue * Age group	0.91	1.00	0.91	2.09	.158	.058
Error(delay*cue)	14.82	34.00	0.44			
modality * delay * cue	1.56	1.98	0.79	2.15	.125	.060
modality * delay * cue * Age group	2.00	1.98	1.01	2.76	.071	.075
Error(modality*delay*cue)	24.68	67.43	0.37			
array * delay * cue	0.93	1.00	0.93	2.98	.093	.081
array * delay * cue * Age group	0.01	1.00	0.01	0.03	.855	.001

Error(array*delay*cue)	10.63	34.00	0.31			
modality * array * delay * cue	0.44	1.87	0.24	0.76	.466	.022
modality * array * delay * cue * Age group	0.79	1.87	0.42	1.35	.265	.038
Error(modality*array*delay*cue)	19.80	63.67	0.31			

Note. Degrees of freedom (df) were adjusted for violations of the sphericity assumption (Huynh & Feldt, 1976)

Appendix I

Study Two Additional Data and Analyses

Table I.1

Between Age group (YA vs. OA) comparisons for demographic variables

Variable	*SS*	*df*	*MS*	*F*	p^a
Age***	20592.25	1	20592.25	1137.71	.000
Education*	28.44	1	28.44	6.10	.019
HADS- anxiety*	113.78	1	113.78	11.35	.002
HADS- depression	4.00	1	4.00	0.82	.372
Shipley – composite (Standard Score)	225.0	1	225.0	1.87	.18
Digit Span (forward span)	1.78	1	1.78	.92	.34
Digit Span – Total (SS)	58.78	1	58.78	14.68	.001
Spatial Span (forward span)	.44	1	.44	.43	.52
Spatial Span - Total (SS)	16.00	1	16.00	2.31	.137

Note. Significant differences between groups: *$p < .05$. **$p < .01$. ***$p < .001$.

Table I.2

Correlations of predictor variables that differ by age group with dependent variables (d' scores)

Measure	Education	HADS- A	Digit Span (SS)
<u>*Compare Task*</u>			
Auditory Cued 4 array	.091	.120	-.089
Auditory Non-Cued 4 array	-.141	.256	-.131
Auditory Cued 6 array	-.234	.054	-.092
Auditory Non-Cued 6 array	-.118	.158	.020
Vibrotactile Cued 4 array	-.179	.106	.071
Vibrotactile Non-Cued 4 array	-.409*	-.157	.000
Vibrotactile Cued 6 array	-.175	.002	-.262
Vibrotactile Non-Cued 6 array	-.289	.064	-.053
Visual Cued 4 array	-.229	.182	-.188
Visual Non-Cued 4 array	.056	.173	.125
Visual Cued 6 array	-.212	.109	.125
Visual Non-Cued 6 array	-.043	-.032	.005
<u>*Ignore Task*</u>			
Auditory Cued 4 array	-.032	.067	-.002
Auditory Non-Cued 4 array	-.221	.178	-.042
Auditory Cued 6 array	-.160	.101	-.098
Auditory Non-Cued 6 array	-.285	.099	-.005
Vibrotactile Cued 4 array	-.177	-.010	.115
Vibrotactile Non-Cued 4 array	-.071	.039	-.083
Vibrotactile Cued 6 array	-.034	.152	-.010
Vibrotactile Non-Cued 6 array	.050	.166	.071
Visual Cued 4 array	-.007	.162	.148
Visual Non-Cued 4 array	-.115	.378*	-.171
Visual Cued 6 array	-.100	.177	.177
Visual Non-Cued 6 array	.014	.322	-.137

Note. Values represent Pearson's *r*.
*significant at *p* <.05

Table I.3

Orientation comparison accuracy scores by age group

Condition	Age Group	*M* % Correct (*SD*)
Auditory Cue	YA	88.7 (7.6)
	OA	90.8 (8.2)
	Total	90.0 (7.9)
Vibrotactile Cue	YA	85.9 (11.7)
	OA	91.1 (9.2)
	Total	88.5 (10.7)
Visual Cue	YA	90.8 (6.0)
	OA	91.6 (7.0)
	Total	91.2 (6.5)

Note. OA = younger adult; YA = older adult

Table I.4

Between age group (YA vs. OA) comparisons of accuracy scores on orientation comparison

Measure	*df*	*MS*	*F*	*p*
% Correct Compare (Auditory Cue)	1	40.11	0.64	.430
% Correct Compare (Vibrotactile Cue)	1	245.44	2.21	.146
% Correct Compare (Visual Cue)	1	6.25	0.15	.704

Table I.5

Memory Accuracy d' scores on spatial location WM task across trial levels and age groups

	OA				YA			
	Cued		Non-cued		Cued		Non-cued	
Trial Type	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Auditory Cue Blocks								
Compare Interference								
Array 4	1.22	0.21	0.52	0.18	1.92	0.21	1.43	0.18
Array 6	0.61	0.23	0.38	0.24	1.86	0.23	1.1	0.24
Ignore Interference								
Array 4	1.55	0.21	1.17	0.2	2.49	0.21	2.16	0.2
Array 6	1.17	0.24	0.91	0.18	2.04	0.24	1.82	0.18
Vibrotactile Cue Blocks								
Compare Interference								
Array 4	1.32	0.19	1.06	0.18	1.9	0.19	1.17	0.18
Array 6	0.86	0.18	0.36	0.23	1.73	0.18	1.51	0.23
Ignore Interference								
Array 4	1.79	0.17	1.33	0.17	2.29	0.17	2.22	0.17
Array 6	1.27	0.23	1.02	0.21	2.08	0.23	1.48	0.21
Visual Cue Blocks								
Compare Interference								
Array 4	0.95	0.17	0.99	0.21	2	0.17	1.34	0.21
Array 6	0.73	0.19	1.07	0.18	1.62	0.19	1.13	0.18
Ignore Interference								
Array 4	1.73	0.2	0.99	0.18	2.24	0.2	1.94	0.18
Array 6	0.86	0.23	0.83	0.195	1.97	0.23	1.75	0.2

Note. OA = older adult; YA = younger adult

Table I.6

Mixed Model Analysis of Variance on d' values on Experiment Two: Spatial Location WM Task with Interference

Source	SS	df	MS	F	*p*	η_p^2
Between Subjects						
Intercept	1731.08	1	1731.08	232.14	.000	.872
Age Group	129.02	1	129.02	17.3	.000	0.34
Error (Age Group)	253.54	34	7.46			
Within Subjects						
Modality	0.97	1.82	0.54	0.62	.527	0.02
Modality * Age Group	2.23	1.82	1.23	1.42	.250	0.04
Error(Modality)	53.42	61.74	0.87			
Interference	39.53	1.00	39.53	57.65	.000	0.63
Interference * Age Group	0.52	1.00	0.52	0.76	.391	0.02
Error(Interference)	23.31	34.00	0.69			
Array Size	21.58	1.00	21.58	53.19	.000	0.61
Array Size * Age Group	0.81	1.00	0.81	2.00	.167	0.06
Error(Array Size)	13.80	34.00	0.41			
Cue Type	26.60	1.00	26.60	46.54	.000	0.58
Cue Type * Age Group	0.93	1.00	0.93	1.63	.210	0.05
Error(Cue Type)	19.44	34.00	0.57			
Modality * Interference	2.00	1.93	1.04	2.26	.114	0.06
Modality * Interference * Age Group	0.88	1.93	0.46	1.00	.371	0.03
Error(Modality*Interference)	30.01	65.63	0.46			
Modality * Array Size	0.15	1.79	0.08	0.20	.796	0.01
Modality * Array Size * Age Group	0.87	1.79	0.49	1.15	.320	0.03

Error(Modality*Array Size)	25.72	60.73	0.42			
Interference * Array Size	1.20	1.00	1.20	3.58	.067	0.10
Interference * Array Size * Age Group	0.31	1.00	0.31	0.94	.340	0.03
Error(Interference*Array Size)	11.38	34.00	0.34			
Modality * Interference * Array Size	0.17	1.98	0.09	0.23	.790	0.01
Modality * Interference * Array Size * Age Group	3.56	1.98	1.80	4.93	.010	0.13
Error(Modality*Interference*Array Size)	24.55	67.35	0.36			
Modality * Cue Type	1.10	1.90	0.58	1.48	.236	0.04
Modality * Cue Type * Age Group	0.85	1.90	0.45	1.13	.326	0.03
Error(Modality*Cue Type)	25.39	64.49	0.39			
Interference * Cue Type	0.23	1.00	0.23	0.57	.455	0.02
Interference * Cue Type * Age Group	2.10	1.00	2.10	5.29	.028	0.14
Error(Interference*Cue Type)	13.48	34.00	0.40			
Modality * Interference * Cue Type	1.35	1.98	0.68	1.74	.184	0.05
Modality * Interference * Cue Type * Age Group	1.58	1.98	0.80	2.04	.139	0.06
Error(Modality*Interference*Cue Type)	26.28	67.14	0.39			
Array Size * Cue Type	1.00	1.00	1.00	3.64	.065	0.10
Array Size * Cue Type * Age Group	0.86	1.00	0.86	3.15	.085	0.09
Error(Array Size*Cue Type)	9.33	34.00	0.27			
Modality * Array Size * Cue Type	0.92	1.78	0.52	1.26	.287	0.04
Modality * Array Size * Cue Type * Age Group	0.46	1.78	0.26	0.63	.519	0.02
Error(Modality*Array Size*Cue Type)	24.75	60.57	0.41			
Interference * Array Size * Cue Type	0.02	1.00	0.02	0.04	.845	0.00
Interference * Array Size * Cue Type * Age Group	0.51	1.00	0.51	1.24	.274	0.04
Error(Interference*Array Size*Cue Type)	14.05	34.00	0.41			
Modality * Interference * Array Size * Cue Type	0.57	1.84	0.31	0.71	.483	0.02
Modality * Interference * Array Size * Cue Type * Age Group	2.77	1.84	1.51	3.50	.040	0.09
Error(Modality*Interference*Array Size*Cue Type)	26.90	62.53	0.43			

Note. Degrees of freedom (df) were adjusted for violations of the sphericity assumption (Huynh & Feldt, 1976)

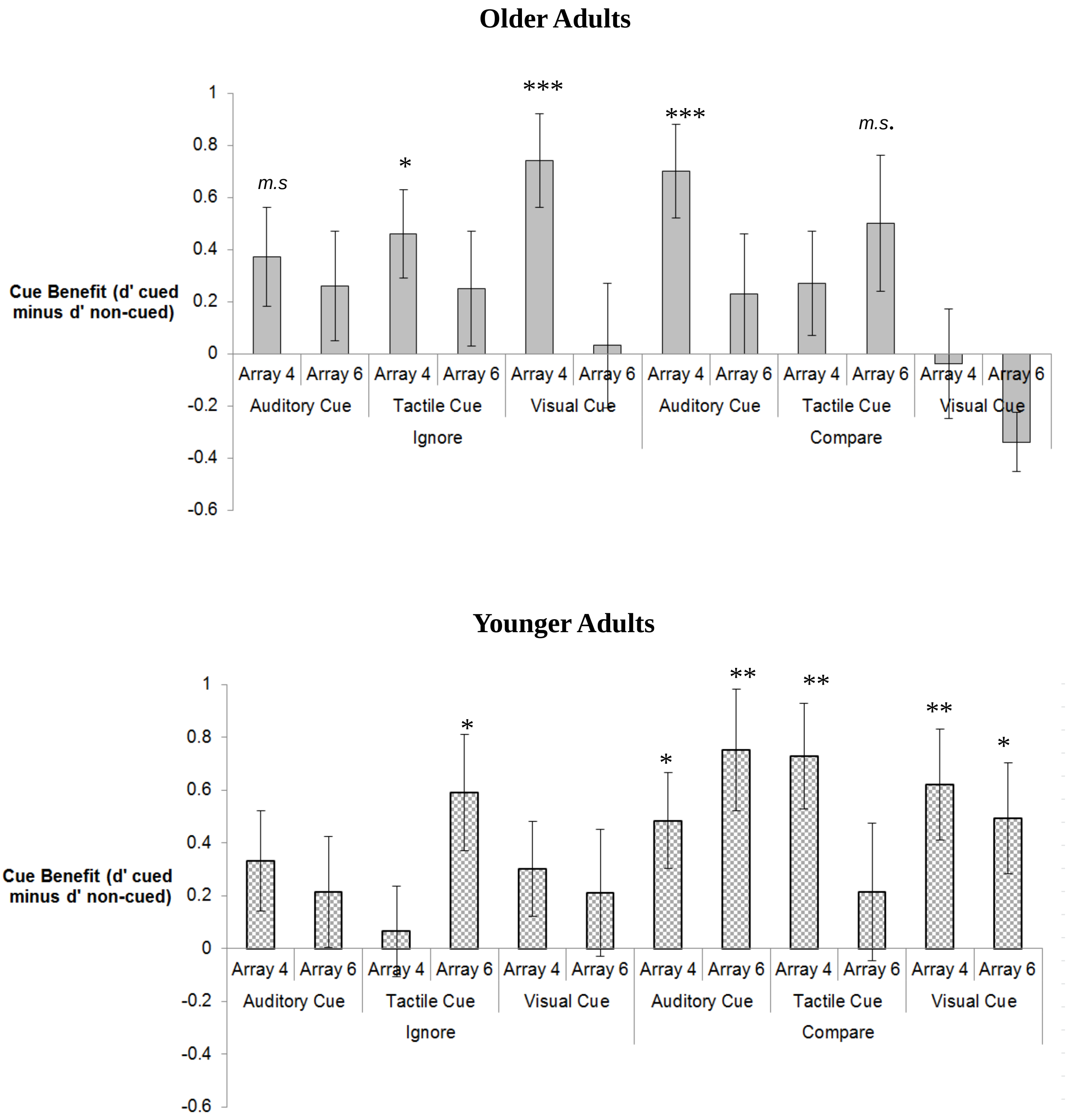

Figure I.1. Cue benefit (mean of d' on cued trials minus mean of d' on non-cued trials) +/- *SEM* of mean difference across all cue array sizes (four and six), cue modalities (auditory, Vibrotactile, and visual), and interference task (ignore, compare). Top panel shows results for OA, bottom panel for YA. Significant differences between cued and non-cued trials are denoted as: *$p < .05$, **$p < .01$, ***$p < .001$, *m.s.* = marginally significant

Table I.7

Pairwise comparisons of spatial location WM performance between age groups, across cue modality, interference type, array size, and cue type cue modality

Cue modality	Interference type	Array size	cue	(I) Age Group	(J) Age Group	Mean Difference (I-J)	*SEM*	*p*
Auditory	Compare	4 array	cued	OA	YA	-.699*	0.293	0.023
				YA	OA	.699*	0.293	0.023
			non-cued	OA	YA	-.915*	0.258	0.001
				YA	OA	.915*	0.258	0.001
		6 array	cued	OA	YA	-1.250*	0.322	0
				YA	OA	1.250*	0.322	0
			non-cued	OA	YA	-.723*	0.342	0.042
				YA	OA	.723*	0.342	0.042
	Ignore	4 array	cued	OA	YA	-.945*	0.298	0.003
				YA	OA	.945*	0.298	0.003
			non-cued	OA	YA	-.984*	0.285	0.002
				YA	OA	.984*	0.285	0.002
		6 array	cued	OA	YA	-.868*	0.338	0.015
				YA	OA	.868*	0.338	0.015
			non-cued	OA	YA	-.910*	0.258	0.001
				YA	OA	.910*	0.258	0.001
Vibrotactile	Compare	4 array	cued	OA	YA	-.576*	0.27	0.04
				YA	OA	.576*	0.27	0.04
			non-cued	OA	YA	-0.119	0.256	0.646
				YA	OA	0.119	0.256	0.646
		6 array	cued	OA	YA	-.866*	0.258	0.002
				YA	OA	.866*	0.258	0.002
			non-cued	OA	YA	-1.152*	0.318	0.001
				YA	OA	1.152*	0.318	0.001
	Ignore	4 array	cued	OA	YA	-.500*	0.243	0.047
				YA	OA	.500*	0.243	0.047
			non-cued	OA	YA	-.891*	0.238	0.001
				YA	OA	.891*	0.238	0.001
		6 array	cued	OA	YA	-.803*	0.318	0.016
				YA	OA	.803*	0.318	0.016
			non-cued	OA	YA	-0.466	0.296	0.125

				YA	OA	0.466	0.296	0.125
Visual	Compare	4 array	cued	OA	YA	-1.048*	0.24	0
				YA	OA	1.048*	0.24	0
			non-cued	OA	YA	-0.391	0.295	0.195
				YA	OA	0.391	0.295	0.195
		6 array	cued	OA	YA	-.890*	0.268	0.002
				YA	OA	.890*	0.268	0.002
			non-cued	OA	YA	-0.058	0.249	0.818
				YA	OA	0.058	0.249	0.818
	Ignore	4 array	cued	OA	YA	-0.517	0.285	0.078
				YA	OA	0.517	0.285	0.078
			non-cued	OA	YA	-.955*	0.257	0.001
				YA	OA	.955*	0.257	0.001
		6 array	cued	OA	YA	-1.101*	0.33	0.002
				YA	OA	1.101*	0.33	0.002
			non-cued	OA	YA	-.922*	0.276	0.002
				YA	OA	.922*	0.276	0.002

Based on estimated marginal means

* The mean difference is significant at the .05 level.
b Adjustment for multiple comparisons: Bonferroni.
OA = Older Adults
YA = Younger Adults

Table I.8

Mixed Model Analysis of Variance on False Alarm rates on Experiment Two: Spatial Location WM Task with Interference

Source	*SS*	df	*MS*	*F*	*p*	η_p^2
	Between Groups					
Intercept	*64.49*	1	*64.50*	*286.72*	*0*	0.89
AgeGroup	*4.86*	1	*4.86*	*21.61*	*0*	0.39
Error	*7.65*	34	*0.23*			
	Within Groups					
Modality	0.027	1.87	0.015	0.26	0.76	0.007
Modality * AgeGroup	0.096	1.87	0.051	0.893	0.41	0.03
Error(Modality)	3.64	63.52	0.057			
Interference	0.81	1	0.809	13.84	0.001	0.29
Interference * AgeGroup	0.002	1	0.002	0.034	0.86	0.001
Error(Interference)	1.99	34	0.058			
Array	0.85	1	0.848	38.37	0	0.53
Array * AgeGroup	0.075	1	0.075	3.41	0.074	0.09
Error(Array)	0.75	34	0.022			
Cue	0.44	1	0.443	27.57	0	0.45
Cue * AgeGroup	0.031	1	0.031	1.94	0.17	0.05
Error(Cue)	0.55	34	0.016			
Modality * Interference	0.12	1.93	0.061	1.62	0.21	0.05
Modality * Interference * AgeGroup	0.14	1.93	0.074	1.96	0.15	0.06
Error(Modality*Interference)	2.48	65.55	0.038			
Modality * Array	0.064	1.983	0.032	1.93	0.15	0.05
Modality * Array * AgeGroup	0.044	1.98	0.022	1.32	0.28	0.04

Error(Modality*Array)	1.13	67.42	0.017			
Interference * Array	0.028	1	0.028	1.37	0.25	0.04
Interference * Array * AgeGroup	0.00	1	0	0.011	0.92	0
Error(Interference*Array)	0.70	34	0.021			
Modality * Interference * Array	0.032	1.93	0.016	0.73	0.48	0.02
Modality * Interference * Array * AgeGroup	0.031	1.93	0.016	0.70	0.49	0.02
Error(Modality*Interference*Array)	1.47	65.49	0.023			
Modality * Cue	0.005	1.80	0.003	0.11	0.88	0.003
Modality * Cue * AgeGroup	0.063	1.80	0.035	1.48	0.24	0.04
Error(Modality*Cue)	1.45	61.10	0.024			
Interference * Cue	0.022	1	0.022	1.31	0.26	0.04
Interference * Cue * AgeGroup	0.058	1	0.058	3.51	0.07	0.09
Error(Interference*Cue)	0.56	34	0.016			
Modality * Interference * Cue	0.11	1.91	0.058	3.38	0.04	0.09
Modality * Interference * Cue * AgeGroup	0.035	1.91	0.018	1.06	0.35	0.03
Error(Modality*Interference*Cue)	1.12	65.03	0.017			
Array * Cue	0.008	1.00	0.008	0.45	0.51	0.01
Array * Cue * AgeGroup	0.006	1.00	0.006	0.30	0.59	0.009
Error(Array*Cue)	0.64	34	0.019			
Modality * Array * Cue	0.035	1.87	0.019	1.10	0.34	0.03
Modality * Array * Cue * AgeGroup	0.055	1.87	0.029	1.71	0.19	0.05
Error(Modality*Array*Cue)	1.09	63.52	0.017			
Interference * Array * Cue	0.024	1.00	0.024	1.44	0.24	0.041
Interference * Array * Cue * AgeGroup	0.001	1.00	0.001	0.078	0.78	0.002
Error(Interference*Array*Cue)	0.57	34	0.017			
Modality * Interference * Array * Cue	0.009	1.89	0.005	0.32	0.72	0.009

Modality * Interference * Array * Cue * AgeGroup	0.13	1.89	0.067	4.49	0.017	0.12
Error(Modality*Interference*Array*Cue)	0.96	64.10	0.015			

a Computed using alpha = .05

Table I.9

Pairwise comparison of False Alarm Rates on Cued vs. Non-Cued Trials in a Spatial Location WM Task, across cue modalities, array size, and maintenance interference

Age Group	Cue Modality	Interference Type	Array Size	(I) cue	(J) cue	Mean Difference (I-J)	*SEM*	*p*
OA	Auditory	Compare	4-items	Cued	Non-cued	-.128*	0.047	0.01
				Non-cued	Cued	.128*	0.047	0.01
			6-items	Cued	Non-cued	0.045	0.045	0.32
				Non-cued	Cued	-0.045	0.045	0.32
		Ignore	4-items	Cued	Non-cued	-0.042	0.048	0.39
				Non-cued	Cued	0.042	0.048	0.39
			6-items	Cued	Non-cued	-0.049	0.045	0.29
				Non-cued	Cued	0.049	0.045	0.29
	Vibrotactile	Compare	4-items	Cued	Non-cued	-0.017	0.043	0.69
				Non-cued	Cued	0.017	0.043	0.69
			6-items	Cued	Non-cued	-0.087	0.051	0.10
				Non-cued	Cued	0.087	0.051	0.10
		Ignore	4-items	Cued	Non-cued	-0.035	0.033	0.30
				Non-cued	Cued	0.035	0.033	0.30
			6-items	Cued	Non-cued	-0.073	0.04	0.078
				Non-cued	Cued	0.073	0.04	0.078
	Visual	Compare	4-items	Cued	Non-cued	0.052	0.039	0.19
				Non-cued	Cued	-0.052	0.039	0.19
			6-items	Cued	Non-cued	.094*	0.036	0.013
				Non-cued	Cued	-.094*	0.036	0.013
		Ignore	4-items	Cued	Non-cued	-.097*	0.04	0.02
				Non-cued	Cued	.097*	0.04	0.02
			6-items	Cued	Non-cued	-0.063	0.049	0.21
				Non-cued	Cued	0.063	0.049	0.21
YA	Auditory	Compare	4-items	Cued	Non-cued	-0.038	0.047	0.42
				Non-cued	Cued	0.038	0.047	0.42
			6-items	Cued	Non-cued	-0.08	0.045	0.085
				Non-cued	Cued	0.08	0.045	0.085
		Ignore	4-items	Cued	Non-cued	-0.059	0.048	0.23
				Non-cued	Cued	0.059	0.048	0.23
			6-items	Cued	Non-cued	-0.014	0.045	0.76
				Non-cued	Cued	0.014	0.045	0.76
	Vibrotactile	Compare	4-items	Cued	Non-cued	-.115*	0.043	0.012
				Non-cued	Cued	.115*	0.043	0.012
			6-items	Cued	Non-cued	-0.014	0.051	0.79

			Non-cued	Cued	0.014	0.051	0.79
	Ignore	4-items	Cued	Non-cued	0.003	0.033	0.92
			Non-cued	Cued	-0.003	0.033	0.92
		6-items	Cued	Non-cued	-0.069	0.04	0.093
			Non-cued	Cued	0.069	0.04	0.093
Visual	Compare	4-items	Cued	Non-cued	-0.066	0.039	0.10
			Non-cued	Cued	0.066	0.039	0.10
		6-items	Cued	Non-cued	-0.069	0.036	0.059
			Non-cued	Cued	0.069	0.036	0.059
	Ignore	4-items	Cued	Non-cued	-0.076	0.04	0.063
			Non-cued	Cued	0.076	0.04	0.063
		6-items	Cued	Non-cued	-0.09	0.049	0.076
			Non-cued	Cued	0.09	0.049	0.076

Note. OA = Older Adults. YA = Younger Adults

Table I.10

Pairwise comparison of False Alarm Rates of Older Adults vs. Younger Adults in a Spatial Location WM Task, across cue modalities, cue type, array size, and maintenance interference

modality	interference	array	cue	(I) AgeGroup	(J) AgeGroup	Mean Difference (I-J)	Std. Error	Sig.b
Auditory	Compare	4-item	Cued	O	Y	.125*	0.054	0.027
				Y	O	-.125*	0.054	0.027
			Non-cued	O	Y	.215*	0.052	0
				Y	O	-.215*	0.052	0
		6-item	Cued	O	Y	.260*	0.079	0.002
				Y	O	-.260*	0.079	0.002
			Non-cued	O	Y	.135*	0.054	0.017
				Y	O	-.135*	0.054	0.017
	Ignore	4-item	Cued	O	Y	.156*	0.064	0.02
				Y	O	-.156*	0.064	0.02
			Non-cued	O	Y	.139*	0.066	0.042
				Y	O	-.139*	0.066	0.042
		6-item	Cued	O	Y	.184*	0.058	0.003
				Y	O	-.184*	0.058	0.003
			Non-cued	O	Y	.219*	0.05	0
				Y	O	-.219*	0.05	0
Vibrotactile	Compare	4-item	Cued	O	Y	.160*	0.056	0.007
				Y	O	-.160*	0.056	0.007
			Non-cued	O	Y	0.063	0.06	0.307
				Y	O	-0.063	0.06	0.307
		6-item	Cued	O	Y	.181*	0.056	0.003
				Y	O	-.181*	0.056	0.003
			Non-cued	O	Y	.253*	0.08	0.003
				Y	O	-.253*	0.08	0.003
	Ignore	4-item	Cued	O	Y	0.08	0.048	0.105
				Y	O	-0.08	0.048	0.105
			Non-cued	O	Y	.118*	0.053	0.034
				Y	O	-.118*	0.053	0.034
		6-item	Cued	O	Y	.132*	0.055	0.021
				Y	O	-.132*	0.055	0.021
			Non-cued	O	Y	.135*	0.06	0.03

				Y	O	-.135*	0.06	0.03
Visual	Compare	4-item	Cued	O	Y	.160*	0.053	0.005
				Y	O	-.160*	0.053	0.005
			Non-cued	O	Y	0.042	0.062	0.504
				Y	O	-0.042	0.062	0.504
		6-item	Cued	O	Y	.167*	0.071	0.025
				Y	O	-.167*	0.071	0.025
			Non-cued	O	Y	0.003	0.063	0.956
				Y	O	-0.003	0.063	0.956
	Ignore	4-item	Cued	O	Y	.149*	0.06	0.018
				Y	O	-.149*	0.06	0.018
			Non-cued	O	Y	.170*	0.066	0.015
				Y	O	-.170*	0.066	0.015
		6-item	Cued	O	Y	.191*	0.059	0.003
				Y	O	-.191*	0.059	0.003
			Non-cued	O	Y	.163*	0.058	0.008
				Y	O	-.163*	0.058	0.008

Based on estimated marginal means

* The mean difference is significant at the .05 level.

b Adjustment for multiple comparisons: Bonferroni.