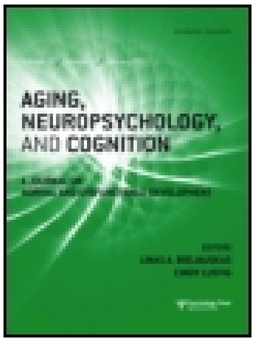

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Improving visual spatial working memory in younger and older adults: effects of cross-modal cues

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ABSTRACT
Spatially informative auditory and vibrotactile (cross-modal) cues can facilitate attention but little is known about how similar cues influence visual spatial working memory (WM) across the adult lifespan. We investigated the effects of cues (spatially informative or alerting pre-cues vs. no cues), cue modality (auditory vs. vibrotactile vs. visual), memory array size (four vs. six items), and maintenance delay (900 vs. 1800 ms) on visual spatial location WM recognition accuracy in younger adults (YA) and older adults (OA). We observed a significant interaction between spatially informative pre-cue type, array size, and delay. OA and YA benefitted equally from spatially informative pre-cues, suggesting that attentional orienting prior to WM encoding, regardless of cue modality, is preserved with age. Contrary to predictions, alerting pre-cues generally impaired performance in both age groups, suggesting that maintaining a vigilant state of arousal by facilitating the alerting attention system does not help visual spatial location WM.

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Vibrotactile cues; auditory cues; spatial working memory; cognitive aging; cross-modal cues

Working memory (WM) is defined as the short-term maintenance and manipulation of information (Baddeley, 1981; Hitch & Baddeley, 1976; Kiyonaga & Egner, 2012). Visual features and spatial locations are stored within a cognitive system called the visuospatial sketchpad (Baddeley, 1981). 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 allocates attentional resources to help maintain a durable memory representation (Awh, Anllo-Vento, & Hillyard, 2000).

Compared with 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

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information such as location (e.g., Kessels, Meulenbroek, Fernández, & Olde Rikkert, 2010) and feature information such as object identity (e.g., Gilchrist, Duarte, & Verhaeghen, 2015; 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 (e.g., Craik, 1994; Jost, Bryck, Vogel, & Mayr, 2011; McIntosh et al., 1999; Schwarzkopp, 2016). Therefore, it is important to investigate the effects of strategies that are known to help focus attention and enhance control on subsequent cognitive processing such as that carried out during WM performance.

One strategy that can facilitate attention is to use cues. There is extensive evidence showing how spatially informative visual (i.e., uni-modal) cues that engage and focus spatial attention and predict the location of an upcoming visual stimulus can decrease response time in target detection tasks (e.g., Driver & Spence, 1998; Mcdonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Posner, 1980; Spence & Driver, 1997). In addition, cue modality has been shown to moderate the effectiveness of the cue in certain attention tasks. Research has shown that spatially informative auditory cues improve performance (relative to invalid cues that incorrectly predict target location) to a similar degree as uni-modal cues in visual target localization discrimination (Schmitt, Postma, & De Haan, 2000, 2001). In addition, vibrotactile cues have been found to quicken response times to a greater degree than uni-modal cues during a visual change detection task (Sklar & Sarter, 1999).

Moreover, determining effective cross-modal cues for real-world applications (i.e., outside of the laboratory) may provide important advantages. For example, relative to uni-modal visual cues, cross-modal cues could arguably prove to be of greater benefit while driving, where engaging visual attention is particularly challenging due to the wide variety of visual distracters competing to grab one's attention (e.g., billboards, traffic lights, and signs). Additionally, designing real-world cross-modal cueing paradigms lends itself to greater flexibility when incorporating their use in the lab and real-world scenarios. For instance, 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). The question remains whether different types of cues under varying conditions impact visual spatial WM performance in OA differently than in younger adults (YA).

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 that assess feature WM performance in YA. For instance, it has been shown that visual pre-cues (i.e., presented prior to encoding) that are spatially informative and predict the location of an upcoming target can improve the accuracy of remembering simple colored shapes (Griffin & Nobre, 2003; Schmidt, Vogel, Woodman, & Luck, 2002; Souza, 2016) in YA. Similarly, Murray and colleagues (2011) reported that presenting a centrally located visual pre-cue (arrow pointing left or right) to YA increased the probability that cued targets (arrows with varying orientations) would be encoded into WM and subsequently recalled. A favorable impact of uni-modal visual cues in a WM task in OA has also been reported. To illustrate, Souza (2016) found that OA and YA received similar benefits of spatially informative visual pre-cues in improving visual feature (color) WM relative to a non-cued condition.

Bays and Husain (2008) suggest that these results occur because when attention is selectively focused, more resources are devoted to the creation of a memory representation, and thus more information is stored and recalled.

The present study employs a similar paradigm as Souza (2016), but extends the author's results by also determining the benefits of auditory and vibrotactile (i.e., cross-modal) pre-cues to spatial location WM in order to examine whether cross-modal pre-cues provide additional benefit to WM performance relative to uni-modal visual pre-cues. 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 suggested that spatially informative auditory pre-cues did not increase the accuracy of feature WM (color of square in a spatial array; Botta et al., 2011). However, in a follow-up study by Botta and colleagues (2013), it was found that these spatially informative auditory pre-cues were only effective when they were associated with visually distinct hemifields (Botta et al., 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 the center on the computer screen, thereby cueing participants to distinct left and right hemifields. We extend the results of Botta and colleagues (2013) by comparing auditory cues to vibrotactile and visual cues, and including both YA and OA participants. 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 sum, we investigated the effect of spatially informative cross-modal (auditory, vibrotactile) and uni-modal (visual) pre-cues relative to no cues on visual spatial location WM recognition performance for YA and OA. We also compared these pre-cues (relative to no cues) to the effects of nonspatially informative alerting cues, which, for the visual modality, have been shown to quicken target detection in an attentional flanker task relative to no cues (Jennings, Dagenbach, Engle, & Funke, 2007). We wished to determine whether the pre-cue benefit to visual spatial WM depends on the spatial information provided by the cue. We predicted that in general, pre-cues would improve visual spatial location WM performance compared with 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 to WM performance relative to no cues. To better understand the nature of any observed spatially informative 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 relative to no cues, spatially informative pre-cues would help maintain memory performance as array size increased, and across longer delay periods. Finally, similar to the findings by Souza (2016), we expected OA to be able to use the spatially informative pre-cues to improve spatial location WM performance. We also sought to determine whether OA receive any additional cue benefit relative to YA, a finding that has been previously reported for target detection (Thornton & Raz, 2006) and visual search paradigms (McLaughlin & Murtha, 2010), suggesting that OA rely on external environmental support to a greater degree than YA to enhance attentional performance. In WM paradigms, support for increased cue benefit in OA has not been established. Although Souza (2016) reported similar cue benefits overall relative to no cues for OA and YA in a visual WM task, they did observe a higher cue benefit for OA in high WM load (i.e., five-item arrays) trials. Therefore, it is possible that relative to YA, OA might show increased benefit of pre-cues when their WM resources are taxed, suggesting a greater reliance of environmental support to perform the task. Given that we utilized moderate to large array sizes (four items and six items), we predicted that OA would show a greater cue benefit (relative to no cues) than that observed for YA in a visual spatial WM task.

The results of the present study help us better understand the cognitive underpinnings of the cross-modal spatial pre-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 visual spatial 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, Guidetti, Baldari, Tessitore, & Capranica, 2005). Ultimately, 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 was recruited from the York University undergraduate research participant pool, and received course credit for their participation. The OA group was 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 cutoff for possible memory impairment (Knopman et al., 2010). All other neuropsychological tests were administered to both age groups 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, and visual spatial location WM.

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)

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: *$p < .05$. **$p < .01$. ***$p < .001$.

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 4 cm, 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 19.5 cm 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 1500 Hz tone, presented at 80 db, for a time interval of 100 ms, 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 19 cm 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 the 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.

Procedure

To control for time of day, which has been shown to affect the 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 in which auditory 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 indicating the location (left, right, both, or none) of the tone or vibration. All participants were able to correctly localize the cues 100% of the time.

Spatially informative cue task

As illustrated in Figure 1, each trial began with participants fixating on a central cross-hair for 500 ms 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

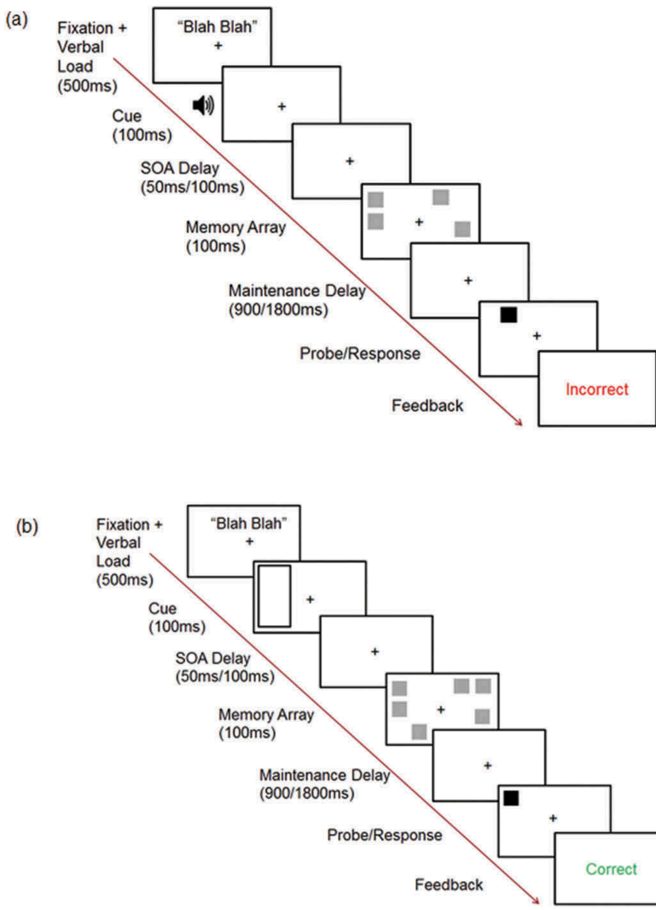

Figure 1. Schematic representation of the experimental procedure. A spatially informative auditory pre-cued four-item array trial requiring a "no" response (a) and visually pre-cued six-item array requiring a "yes" response (b) are depicted. Target stimuli/probes are for illustration only and are not drawn to scale. [To view this figure in color, please see the online version of this journal.]

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 500 ms, 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 spatially informative cue (100 ms) or a blank interval (100 ms; non-cued trial) was presented. Cues were 100% valid, as they always correctly predicted the location of the target rectangles (i.e., right visual cue/targets in right hemifield; right auditory cue/ targets in right hemifield, etc.). To eliminate temporal cueing, a blank delay of either 50 ms or 100 ms was then presented. This ensured varying stimulus onset asynchronies (SOAs) of 150 ms and 200 ms, respectively. Memory arrays were then presented (random presentation of either four- or six-item arrays) for 100 ms (Schmidt et al., 2002), followed by a blank maintenance delay period of either 900 ms (short delay) or 1800 ms (long delay). Finally, a probe (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 whether 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 to begin. The participant viewing distance was approximately 57 cm from the computer screen. To minimize eye movements, participants were instructed to remain fixated on the central crosshair for the duration of each trial.

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 (four blocks per modality) to reduce fatigue. Each block took approximately 3 min 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 (900/1800 ms). 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 versus non-cued trials. All visual stimuli and responses required remained the same, and four blocks of trials were 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 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. There were eight alerting cued trials per block and 24 non-cued trials.

Data analysis

Our outcome variable of interest was WM recognition performance. This was calculated using d prime (d'), which represents the 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 or "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 pre-cues and the WM task with alerting pre-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: 900 ms vs. long: 1800 ms). 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

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. 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 complete set of the ANOVA results is provided in Table 2.[3] The d′ values (higher d' means better visual spatial location WM recognition) for all conditions and for each age group are presented in Figure 2. Overall, we observed a main effect of cue type (F (1.0, 32.0) = 35.1, $p < .001$, $\eta_p^2 = .51$, and a main effect of array size (F (1.0, 34.0) = 43.7, $p < .001$, $\eta_p^2 = .56$. These main effects were further qualified by a significant interaction between cue type and array size (F (1.0, 34.0) = 10.2, $p = .003$, $\eta_p^2 = .23$(see Figure 3). Unexpectedly, scores on

Table 2. Mixed-model analysis of variance of d' values on spatial location WM task (alerting cue).

Source	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Age group	10.67	1.00	10.67	1.72	.198	.048
Error (Age group)	210.98	34.00	6.205			
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			

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

alerting cued trials were significantly lower compared with non-cued trials for both four-item (mean difference (md) = .43, *SEM* = .06, $p < .001$) and six-item (md = .18, *SEM* = .07, $p = .013$) arrays.

We did not observe a main effect of age group (F (1.0, 34.0) = 1.72, $p = .20$, η_p^2 = .05. However, we did observe a two-way interaction between age group and array size (F (1.0, 34.0) = 6.12, $p = .019$, η_p^2 = .15. 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

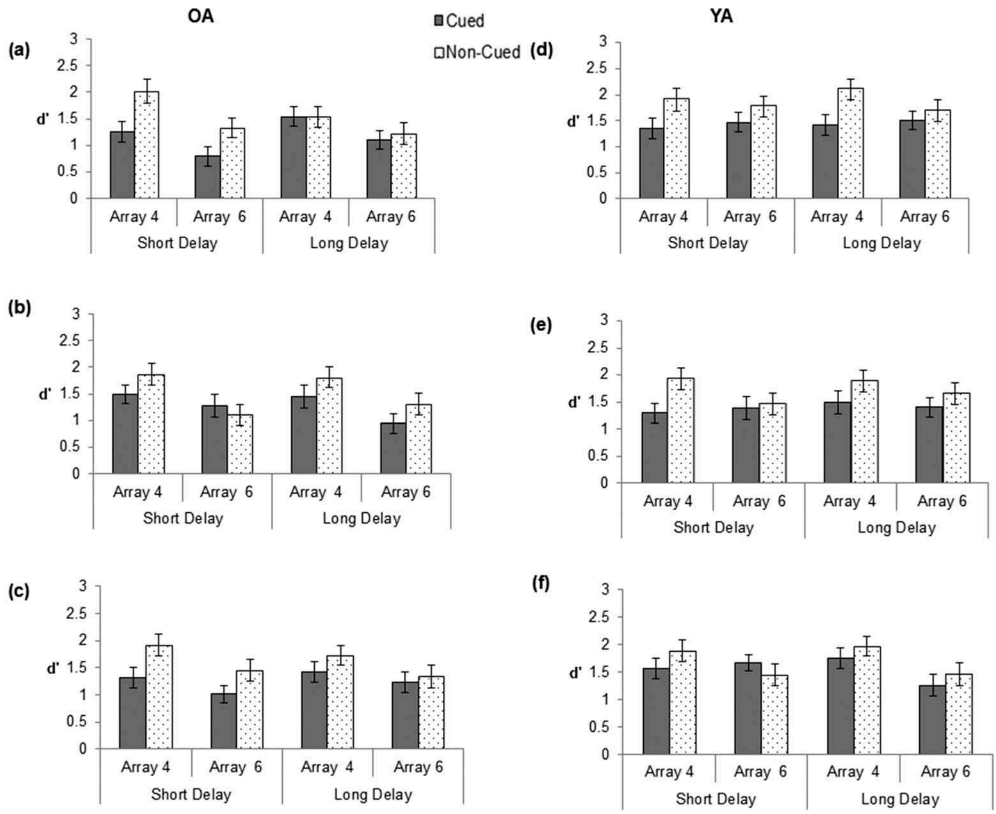

Figure 2. Full experimental results of the alerting pre-cue task. Mean d′ values ± *SEM* (error bars) for both younger (right panel) and older (left panel) adults across cued (dark gray bars) and non-cued (white dotted bars) trials, four-item and six-item arrays, short and long maintenance delays in (a) auditory cue blocks, (b) vibrotactile cue blocks, and (c) visual cue blocks.

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 ($p > .05$).

Spatial WM task: spatially informative cue

A complete set of the ANOVA results is presented in Table 3.[4] The d′ values for all conditions for each age group are shown in Figure 4. Age group and modality type did not moderate our results (see Table 3 and Figure 4). In other words, we observed similar cueing effects for both YA and OA across all modalities. Most notably, we observed a significant three-way interaction between cue type, array size, and delay (F (1.0, 34.0) = 6.04, p = .019, η_p^2 = .15. As shown in Figure 5, collapsed across age group and modality type, in general performance on cued trials was significantly higher than performance on non-cued trials.

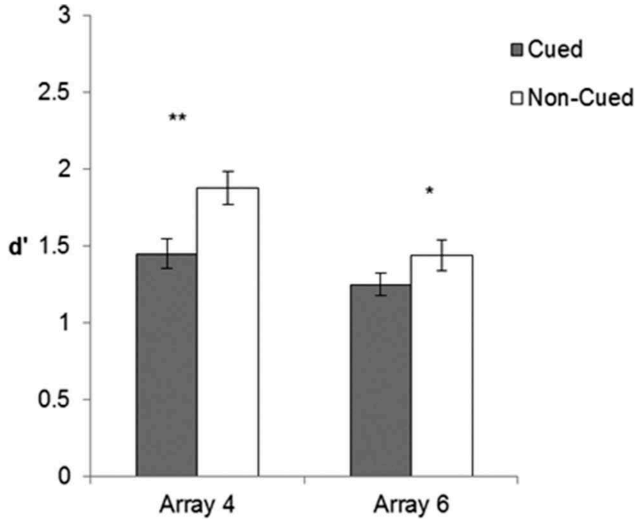

Figure 3. Cue type x Array size interaction. Mean d' values +/- *SEM* (error bars) for younger and older adults on visual spatial location WM task during alerting cued (dark gray bars) and non-cued (white bars) trials. *$p < .05$; **$p < .01$.

For the four-item array, the cue significantly improved spatial WM performance over non-cued trials for the short (900 ms) delay, md = .27, *SEM* = .09, $p = .004$. Furthermore this cue benefit increased nearly twofold in the longer (1800 ms) 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 visual 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 = .25, *SEM* = .06, $p < .001$, relative to non-cued trials, md = .25, *SEM* = .06, $p < .001$.

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 (1.0, 34.0) = 6.70, $p = .014$, $\eta_p^2 = .17$. Overall, OA visual

Table 3. 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
Age Group	3.40	1.00	3.40	0.44	.511	.013
Error	261.59	34.00	7.69			
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			

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

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 (1.0, 34.0) = 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.

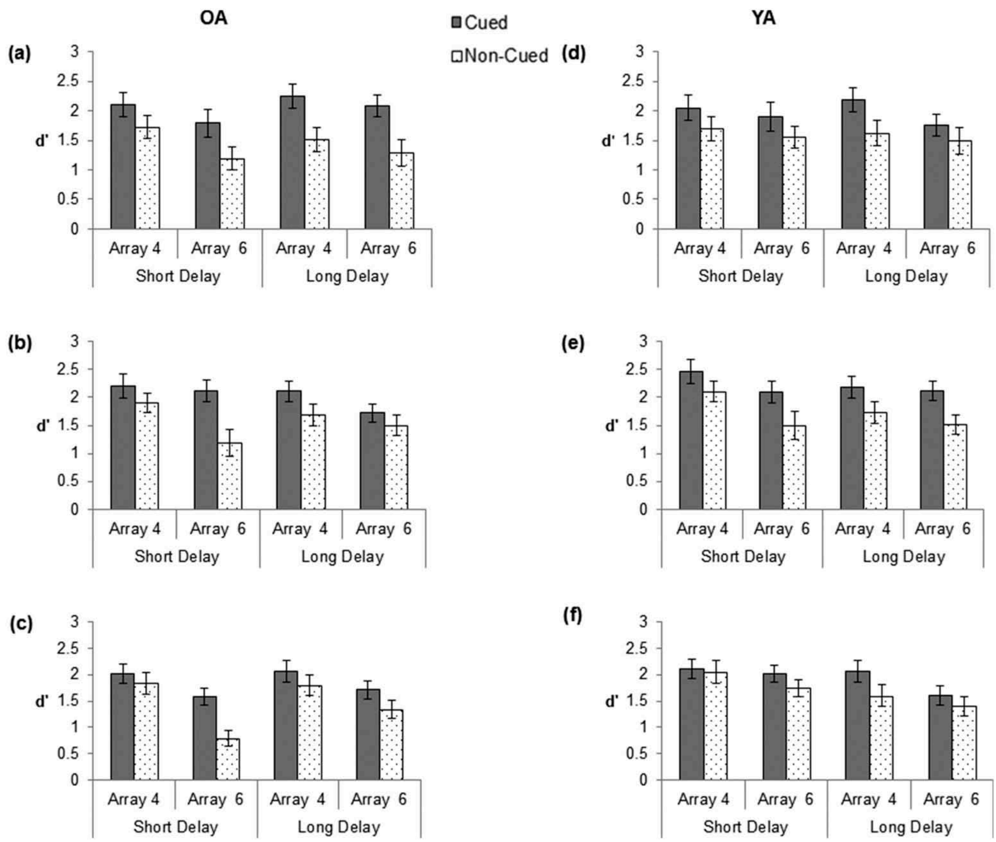

Figure 4. Full experimental results of the spatially informative pre-cue task. Mean d' values +/- *SEM* (error bars) for both younger (right panel) and older (left panel) adults across cued (dark gray bars) and non-cued (white dotted bars) trials, four-item and six-item arrays, short and long maintenance delays in (a) auditory cue blocks, (b) vibrotactile cue blocks, and (c) visual cue blocks.

We also observed a main effect of cue modality, $F\ (1.91, 64.8) = 3.34$, $p = .04$, $\eta_p^2 = .09$. Overall, when collapsed across age, cue type, array size, and delay, performance in the vibrotactile cue blocks ($M = 1.88$, $SEM = .09$) was higher ($p = .03$) than visual cue blocks ($M = 1.73$, $SEM = .09$). Performance in auditory cue blocks did not differ from either of the other two modalities.

Discussion

Visual, auditory, and vibrotactile spatially informative pre-cues have been shown to facilitate visual attention in younger and older individuals (e.g., Ho et al., 2005; Hopkins, Kass, Blalock, & Brill, 2016; McLaughlin & Murtha, 2010; Spence & Driver, 1997). However, research on the effects of both spatially informative and alerting cross-modal pre-cues on WM for both YA and OA is limited. Prior research has found that spatially informative visual uni-modal pre-cues help facilitate the focusing of attention during encoding (e.g., Bays & Husain, 2008) and WM maintenance (e.g., Awh,

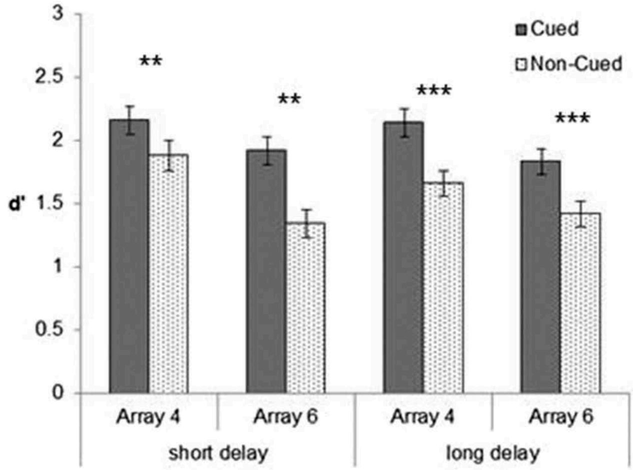

Figure 5. Cue x array size x delay interaction. Mean d′ values +/- SEM (error bars) on visual spatial location WM task during spatially informatively cued (dark gray bars) and non-cued (dotted pattern bars) trials, as a function of array size (four or six-items) and delay period (short- 900 ms and long – 1800 ms). $^{*}p < .05$;$^{**}p < .01$; $^{***}p < .001$.

Jonides, & Reuter-Lorenz, 1998; Pan & Soto, 2010; Schmidt et al., 2002). Additionally, WM performance for feature information can be improved through the use of both uni-modal visual (e.g., Griffin & Nobre, 2003; Schmidt et al., 2002) and auditory cross-modal (Botta et al., 2013) pre-cues in YA and visual (Souza, 2016) pre-cues in OA. The present study investigated the effects of spatially informative uni-modal visual, and cross-modal auditory and vibrotactile cues, relative to no cues on visual spatial location WM performance of both YA and OA. We also compared these cues to alerting pre-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 the spatially informative pre-cues would improve visual spatial WM, and the benefit would be the greatest for cross-modal cues. 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, 1997), in the present study, auditory, visual, and vibrotactile spatially informative pre-cues facilitated visual spatial WM, compared with non-cued conditions. Auditory cue findings agree with the results from Botta and colleagues (2013), in which auditory cues improved WM for visual features. Our results extend these findings by showing that vibrotactile pre-cues that are spatially informative improve visual spatial WM to a similar degree as auditory and visual spatially informative pre-cues. Thus, contrary to our prediction, all cue modalities were equally effective in terms of improving accuracy on a visual spatial WM task.

Consistent with our prediction, we found that spatially informative pre-cues were more helpful to visual spatial WM performance than alerting cues. In fact, we found that alerting cues generally impaired visual spatial location WM performance, across both memory array sizes. Alerting cues also equally impaired the visual spatial location WM performance of OA compared with YA, suggesting that both YA and OA did not use alerting attention cognitive mechanisms to improve visual spatial location WM performance. Thus, it appears that maintaining an alert or state of high-level arousal does not improve visual spatial location WM. However, given that the SOAs in the present study were quite short (50/100 ms), and many previous findings of alerting cue benefit were under conditions of strong temporal uncertainty (e.g., Fuentes & Campoy, 2008), it is possible that the processing of the alerting cue interfered with the processing of the memory array at encoding. Therefore, future research should explore alerting cue effects at longer SOAs in order to determine the extent to which spatially non-informative pre-cues might influence WM processes.

Overall, we showed that spatial WM can be enhanced 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 visual spatial WM, especially in scenarios where this ability is challenged, such as while driving.

We also explored whether cue benefits in visual spatial location WM differ for OA relative to YA. Prior studies have shown that relative to YA, OA experience greater pre-cue benefits relative to invalid cues in target detection (Thornton & Raz, 2006) and relative to no-cues in visual search (McLaughlin & 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). Therefore, in the present study, we predicted that OA would be more reliant on pre-cues and, compared with YA, would show a greater cue benefit relative to no cues. However, this initial hypothesis was not supported, as we found that OA showed the same cue benefit (for spatially informative pre-cues relative to no cues) to visual spatial WM performance as YA. This agrees with previous findings on the pre-cueing of feature WM, where OA and YA benefitted similarly (Souza, 2016). The finding that OA can use the spatially informative cues presented in our study is an important one for several reasons. First, this provides further support for the suggestion that the orienting attention system remains intact with aging (e.g., Gamboz, Zamarian, & Cavallero, 2010). Furthermore, our results suggest that cues that automatically orient attention across various modalities could be of greater use than cues that do not provide spatial information (i.e., alerting cues) in real-world applications aimed at improving WM in OA.

Another objective of the present study was to understand the nature of the spatially informative cue benefit. We expected that the spatially informative cues would focus visual spatial attention more quickly and on fewer items in the targeted hemifield and these attended items would presumably receive priority for entry into visual spatial WM (Awh et al., 2006; Schmitt et al., 2001), and be encoded more effectively than non-cued items. Therefore, we predicted that relative to no-cues, spatially informative cues would help maintain memory performance across increasing array sizes, and across short and long maintenance delays. This hypothesis was generally supported, with several caveats and areas for future research identified. We found that spatially informative pre-cues improved visual spatial location WM recognition relative to non-cued trials across both array sizes. Additionally, for the four-item arrays, visual spatial location WM recognition declined when the delay period increased from 900 ms to 1800 ms in non-cued trials, but was maintained in cued trials. This particular result suggests that the cues that prioritize locations of items into WM at encoding might also help maintain locations and prolong their decay, supporting previous suggestions that spatially informative cues might contribute to the rehearsal of spatial locations during WM maintenance (Awh et al., 2006; Silk, Bellgrove, Wrafter, Mattingley, & Cunnington, 2010). However, we are cautious in generalizing these results, given that we found that 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. Although it is possible that this maintenance of WM performance even in non-cued trials could be due to floor effects [e.g., Simons (1996) suggested a spatial location capacity of five, and therefore a memory array size of six in the present study could be at the limits of or exceed capacity], more research is needed to determine whether pre-cues actually assist WM maintenance.

We observed several interesting results regarding cue benefits (improvement in performance relative to non-cued trials) across varying task demands. In fact, it has been suggested that auditory cues interact more effectively with visual targets when focused attention is required relative to when automatic processing occurs (Dufour, 1999). Our finding of greater cue benefit in six-item arrays relative to four-item arrays might provide support for this interpretation. It is possible that in situations of high attentional demand (e.g., memory arrays with a greater number of items), participants rely more heavily on the pre-cue to help them perform the WM task. Future research should explore this possibility by examining cue benefits under various task demands (e.g., larger arrays, presenting distracting interference at encoding and/or maintenance).

There are several limitations in the present study that reduce 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 of 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 should consider modifying task demands in order to maximize the potential of observing 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, suggesting that maintaining a vigilant state of arousal by facilitating the alerting attention system does not help visual spatial location WM. We also showed that OA are able to use spatially informative cues in all modalities to aid performance to a similar degree as YA. Our results are consistent with Souza's (2016) findings for spatially informative visual pre-cues, but extend the author's findings by showing that OA performance was aided by cross-modal pre-cues. Array size and maintenance delays also moderate cue effects. The spatially informative pre-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. 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 pre-cue benefit. Future research should investigate whether similar benefits are observed for retro-cues presented during WM maintenance. It will also be important to examine underlying neural mechanisms mediating cue use, in order to complement the present behavioral findings and determine any functional differences between younger and older individuals.

Notes

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).
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.
3. Note, we tested the effects of time of day by entering this factor as a between-subjects variable and rerunning our ANOVA. Time of day did not moderate any main effect or interactions ($p > .05$), and thus is not discussed further.
4. We also conducted an ANOVA with time of day as a between-subjects variable. The analysis revealed that time of day did not moderate any main effects or interactions ($p > .05$) and thus is not discussed further.

Disclosure statement

No potential conflict of interest was reported by the authors.

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