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Contributions of Filtering and Attentional Allocation to Working Memory Performance in Individuals With Autism Spectrum Disorder

Kimberly E. Bodner, Nelson Cowan, and Shawn E. Christ
University of Missouri

Past findings on working memory (WM) ability in individuals with autism spectrum disorder (ASD) are mixed. The present objective was to assess not only the integrity of WM capacity, but also the potential contribution of filtering ability and attentional selection to WM performance, in individuals with ASD. A sample of 24 participants with ASD (M_{age} = 19.6 years) and 24 typically developing participants without ASD (M_{age} = 20.3 years) participated. Participants completed a computerized paradigm designed to systematically assess WM capacity, visual filtering ability, and attentional selection. In brief, participants were shown visual arrays consisting of 2–8 colored stimuli (circles and/or squares). After a short delay, memory for one of the stimuli was probed. Importantly, participants were informed beforehand that one of the shape types (e.g., circles) was more likely to be probed compared to the other shape type (e.g., squares) – thus making it strategically advantageous to focus on the high frequency shapes and to filter/ignore the low frequency shapes. Eye tracking data were simultaneously collected. The ASD group demonstrated intact WM capacity and filtering ability, but disrupted ability to efficiently allocate capacity under the demands of high WM load. Analysis of eye tracking data suggests the groups may have differed in their strategic approach to encoding stimuli which may have, in turn, contributed to the aforementioned impairment. Findings support the assertion that disruptions in secondary processes such as strategy use and attentional selection may have played a role in previous reports of WM impairment in ASD.

General Scientific Summary
Recent reviews suggest that ASD is associated with impairment in WM performance. The present study suggests that such previous findings may be attributable to disruptions in secondary processes such as strategy use and attentional selection rather than WM capacity per se.

Keywords: autism spectrum disorder, working memory, visual filtering, attention, executive function

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Individuals with autism spectrum disorder (ASD) experience impairments in social communication and display repetitive behaviors and/or restricted interests (American Psychiatric Association, 2013). In addition, there is a general consensus among researchers and clinicians that executive function is detrimentally affected in ASD, although findings are inconsistent as to what specific aspects of executive function are impacted and to what degree (Kenworthy, Yerys, Anthony, & Wallace, 2008). Executive function represents higher order cognitive processes that allow for the flexible modification of thought and behavior in response to changing cognitive or environmental contexts. Here we investigate the role of executive function in working memory (WM) for individuals with and without ASD, drawing a distinction between remembering per se and encoding information into the memory system. This distinction allows us increased precision in our analysis of the cognitive challenges faced by people with ASD. In the present study, the priority of visual objects to be remembered within an array will be manipulated to determine whether ASD is associated with (a) impaired memory of all items and/or (b) impaired ability to encode the higher priority objects preferentially into WM.

The Nature of WM

WM can itself be considered a core component of executive function (Miyake et al., 2000). WM has been viewed by some as a "multi-component system that holds and manipulates information in short term memory" (Cowan, 2008, p. 323, referring to approaches like Baddeley & Hitch, 1974). Definitions vary, but WM can be described generally as "the ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information

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Kimberly E. Bodner, Thompson Center for Autism and Neurodevelopmental Disorders, University of Missouri; Nelson Cowan and Shawn E. Christ, Department of Psychological Sciences, University of Missouri.

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Correspondence concerning this article should be addressed to Shawn E. Christ, Department of Psychological Sciences, University of Missouri, 210 McAlester Hall, Columbia, MO 65211. E-mail: christse@missouri.edu

processing" (Cowan, 2017, p. 1159). Proficient WM is critical for everyday tasks such as remembering a name while maintaining a conversational topic, navigating a novel situation/environment, or searching for objects.

WM in Individuals With ASD

Previous research on WM performance in individuals with ASD has yielded mixed results across a wide range of standardized and experimental tests of WM. Results of recent qualitative and quantitative reviews suggest that ASD is generally associated with impairment in WM performance (Barendse et al., 2013; Kenworthy et al., 2008; Kercood, Grskovic, Banda, & Begeske, 2014; Wang et al., 2017). Whereas a handful of studies have reported comparable or even superior WM performance in children and adults with ASD as compared to individuals without ASD (e.g., Chen et al., 2016; Ozonoff & Strayer, 2001), the majority of studies have reported ASD-related impairments in WM (e.g., Bodner, Beversdorf, Saklayen, & Christ, 2012; Christ et al., 2017).

Research also supports the notion that such impairments may be more readily apparent for visuospatial WM as compared to verbal WM. For example, Williams, Goldstein, Carpenter, and Minshew (2005) reported impaired performance on visuospatial WM tests (e.g., spatial span) but not verbal WM tests (e.g., letter *n*-back task, letter–number sequencing task) within groups of both children and adults with ASD. Consistent with this, a recent meta-analysis by Wang et al. (2017) reported a larger average effect size for studies employing a visuospatial WM task ($d = -0.72$) as compared to a verbal task ($d = -0.44$).

Recent qualitative reviews (Barendse et al., 2013; Kercood et al., 2014) have suggested that ASD-related impairments may also be more evident when the complexity and/or magnitude of demands on WM are increased. The results on this front, however, are much more mixed than might be anticipated. A number of studies have reported intact or even superior performance in children and adults with ASD on complex WM tasks (Koshino et al., 2008; Ozonoff & Strayer, 2001), or on certain aspects of WM tasks such as strategy but not errors (Chen et al., 2016; Landa & Goldberg, 2005). A quantitative meta-analysis by Wang et al. (2017) failed to find evidence of increased ASD-related WM impairment with increased complexity or memory load.

The diversity of tasks used across studies to assess WM and the varying degree to which tasks place demands on different aspects of WM has likely contributed to the aforementioned discrepant findings. Performance on WM tasks frequently reflects not only capacity (i.e., the number of items that can be held) but also the efficiency of several additional WM-related processes. For example, an individual's poor performance on a WM task might not reflect diminished capacity per se, but rather impaired selective attention (i.e., focusing on relevant information) and/or filtering (i.e., ignoring or suppressing irrelevant information).

Indeed, previous research points to altered attentional processing (Mottron, Dawson, Soulières, Hubert, & Burack, 2006) and impaired filtering ability (Christ, Holt, White, & Green, 2007; Christ, Kester, Bodner, & Miles, 2011) in individuals with ASD. Furthermore, impairment in these processes has previously been associated with poorer performance on WM tasks in non-ASD samples (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010). It remains unclear, however, to what extent disruptions in attentional selection and filtering ability may contribute to WM performance in individuals with ASD. For many of the WM tasks used in prior studies, as complexity and/or memory load increases, so too does the potential demand on secondary WM processes such as attentional control and filtering ability. As such, it is difficult to disentangle the relationship among these different factors based on the existing literature.

The Present Study

The goal of the present study was to provide additional insight by evaluating not only WM capacity but also the potential contribution of attentional selection and filtering ability to WM performance in individuals with ASD. To assess the aforementioned factors, we used a version of an established computerized WM paradigm which has been used in previous studies of clinical and nonclinical pediatric and adult populations (e.g., Cowan et al., 2010; Gold et al., 2006; Mall, Morey, Wolff, & Lehnert, 2014). In brief, participants were shown visual arrays consisting of two to eight colored stimuli (circles and/or squares). After a short delay, memory for one of the stimuli was probed. Importantly, participants were informed beforehand that the one of the shape types (e.g., circles) was more likely to be probed compared to the other shape type (e.g., squares)—thus making it strategically advantageous to focus on the high frequency shapes and to filter/ignore the low frequency shapes. This paradigm configuration allows us to differentiate whether potential group differences in performance may be related to (a) a deficiency in overall memory for items and/or (b) disrupted ability to focus attention on the higher priority items. For additional insight into this issue, eye tracking data were collected along behavioral results.

Based on previous WM findings, we hypothesized that ASD might be associated with decreased overall WM capacity. In addition, we anticipated that impairments in WM performance would be most evident in the presence of additional filtering and attentional demands (specifically, the need to filter out irrelevant items so that they remain unattended and the need to attend to relevant items, moreso for high-priority items). If filtering and/or attentional were deficient in participants with ASD, we further expected that they would spend a smaller proportion of encoding time looking at the relevant and higher-priority items than would non-ASD participants.

Method

Participants

A sample of 26 male participants with ASD ($M_{age} = 19.8$ years) and a comparison group of 25 typically developing male participants without ASD ($M_{age} = 20.2$ years) participated in the present study. Three participants were ultimately excluded from data analyses (two participants with ASD and one participant without ASD) due to excessive sleepiness, poor effort (i.e., participant disclosed poor effort), or computer malfunction. Additional demographic and diagnostic information for the final sample of 48 participants is included in Table 1.

Participants with ASD were recruited using a preexisting database of previously diagnosed individuals with ASD from the

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Table 1
Sample Characteristics

Variable	ASD (n = 24)		Non-ASD (n = 24)			
	M (SD)	Range	M (SD)	Range	t^{a}	p
Age (years)	19.6 (2.2)	16–24	20.3 (2.2)	16–23	1.11	.27
FSIQ[b]	112.2 (9.4)	83–130	108.1 (8.3)	89–127	1.58	.12
VIQ[b]	106.3 (9.1)	75–126	104.8 (8.2)	86–124	.63	.53
PIQ[b]	115.8 (13.2)	94–148	109.8 (11.1)	89–138	1.70	.10
SRS total score	62.7 (10.1)	40–82	47.9 (6.1)	40–64	6.16	<.001
ADI-R (n = 18)[c]						
A (social interaction)	22.2	9–29	—	—		
B (communication)	18.1	8–23	—	—		
C (restricted/repetitive behavior)	8.1	3–18	—	—		
D (abnormal development)	3.2	2–5	—	—		
ADOS-G (n = 7)[c]						
Social	9.1	6–12	—	—		
Communication	3.1	2–5	—	—		
ADOS-2 (n = 14)[c]						
Social affect	8.7	4–14	—	—		
Restricted, repetitive behavior	2.6	1–4	—	—		

Note. ASD = autism spectrum disorder; FSIQ = full-scale IQ; VIQ = verbal IQ; PIQ = performance IQ; SRS = Social Responsiveness Scale; ADI-R = Autism Diagnostic Interview–Revised; ADOS-G = Autism Diagnostic Observation Schedule–Generic; ADOS – 2 = Autism Diagnostic Observation Schedule–2.
[a] df = 46. [b] Estimated based on the Wechsler Abbreviated Scale of Intelligence–II (Wechsler, 2011). [c] Note that some individuals (n = 14) received both the ADI-R and ADOS.

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University of Missouri Thompson Center for Autism and Developmental Disorders, Columbia, Missouri. They had been diagnosed with ASD by qualified clinical personnel based on diagnostic interviews, caregiver questionnaires, and observation focused on *Diagnostic and Statistical Manual of Mental Disorders* (*DSM*)*–IV* criteria (American Psychiatric Association, 2013). The diagnosis of ASD was further confirmed using the Autism Diagnostic Observation Schedule (Lord et al., 2012) and/or the Autism Diagnostic Interview–Revised (Lord, Rutter, & Le Couteur, 1994). Typically developing participants were recruited from the Columbia area.

Individuals with color blindness, severe cognitive impairment, or major medical history unrelated to ASD were excluded from the study. Four ASD participants were prescribed attention-related medications or other medications known to affect WM/cognitive performance (e.g., lisdexamfetamine, propranolol). They were able to safely refrain (per their treating physicians) from taking the relevant medication for 24 hr prior to testing and thus were included in the study.

Procedure

The present study was approved by the University of Missouri Internal Review Board (Review ID 1213704). Informed consent was obtained for all individuals prior to participation. The task procedures were similar to what has been described previously (Cowan et al., 2010, 2011; Mall et al., 2014). Participants were seated in front of a computer monitor in a well-lit, sound-attenuated room. The sequence of trial events is shown in Figure 1.

Each trial began with a fixation point (represented by a small shape) presented in the center of the display for 1,000 ms. The fixation shape reminded participants as to what shape stimulus (circle or square) was most likely to be probed/tested and thus should be attended during the experimental session (henceforth referred to as the high-frequency [HF] target shape). The HF target shape and low-frequency (LF) target shape designations remained constant for a given participant throughout the experiment and were counterbalanced across individuals.

After removal of the initial fixation point, a sample array of colored objects was presented. Each object consisted of a small circle or square that subtended approximately 0.5° vertically and 0.5° horizontally. Each object appeared at one of eight possible locations arranged equidistant (first location = 22.5° from vertical) around an imaginary circle 2.7° in radius and centered on the middle of the display. Each object's specific location was determined randomly, and all empty locations were marked with a small placeholder ("+").

After 1,500 ms, all objects were removed and replaced with placeholders. Following a 2,000-ms delay, a single probe object was presented. Participants were asked to respond whether the probe's color was the same or different from the color of the object that was presented in the same spatial location during the initial sample array. Participants were instructed to respond as quickly as possible by pressing a button with their right or left index finger (via pressing the "/"or "z" keys, respectively) to indicate whether the probe color was the same or different (i.e., unchanged or changed) from earlier. The response probe remained on the display until the participant made a response. The next trial was presented after an intertrial interval of 3,000 ms.

For all task conditions, trial presentation was balanced such that probe color was equally likely to change or not change (50% different; 50% same). The color of shapes in the initial memory array was drawn randomly from a set of 10 possibilities without replacement (black, white, red, blue, yellow, green, orange, purple, brown, and pink). For "change/different" trials, the color of the memory probe was drawn randomly from colors not previously displayed in the initial memory array. The target-to-response key mapping (e.g., left button = change; right button = no change) was counterbalanced across participants. Response time and accuracy were recorded.

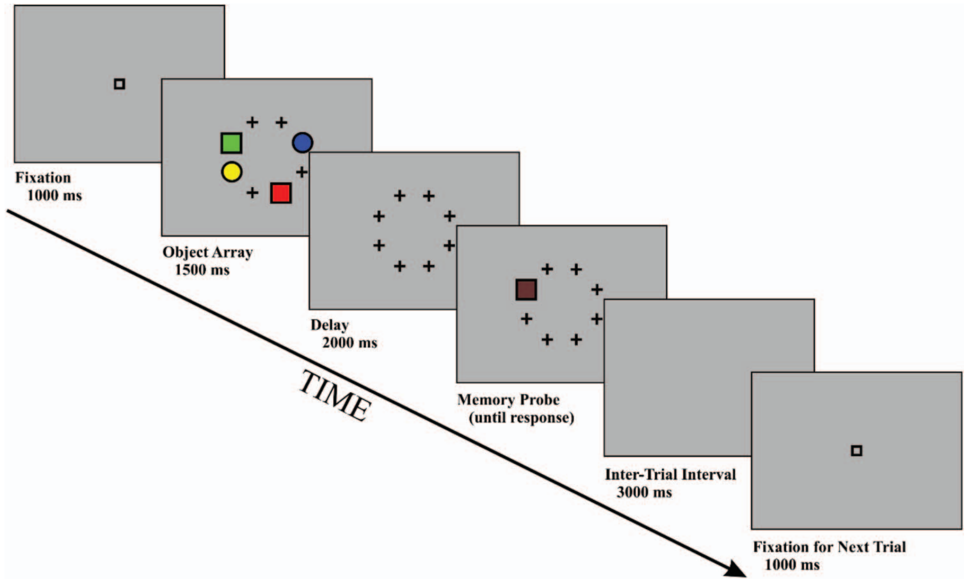

Figure 1. Sequence of events on a task trial. Note that stimuli are enlarged for illustrative purposes. Prior to the start of each block of trials, the participant was explicitly informed as to the relatively likelihood that they would be tested on each object shape (e.g., if squares were the high-frequency shape, prior to the high-frequency-100% trial blocks, a participant would be told that they would be tested on squares only). In the example trial illustrated here, the correct answer to the memory probe would be "different." If the probe had been green at the same location, the correct answer would be "same." See the online article for the color version of this figure.

Four different trial types were administered across three block types:

(1) On HF-only trials, the sample array comprised two, three, four, or six HF shapes and no LF shapes. (e.g., if the HF shape was circle, then the sample array was made entirely of circles with no squares.) Given that no LF shapes were present in the sample array, the probe shape was always HF. Two blocks of 48 trials each of HF-only trials were administered.

(2) On HF-100% trials, the sample array comprised two, three, or four HF shapes and an equal number of LF shapes. (e.g., if there were three HF shapes in the sample array, then there were also three LF shapes.) The probe shape was always HF—as such, the LF shapes could be completely ignored on these trials. Two blocks of 48 trials each of HF-100% trials were administered.

(3) On HF-75%/LF-25% trials, the sample array comprised two, three, or four HF shapes and an equal number of LF shapes. On 75% of the trials, the probe shape was a HF shape object. On the remaining 25% of trials, the probe shape was a LF shape object. Three blocks of 48 trials each of mixed HF-75% and LF-25% trials were administered.

Importantly, prior to the start of each block, the participant was explicitly informed of the nature of the upcoming block and the relative frequency of the probe shape. For example, prior to the HF-100% trial blocks, they were told that they would be tested on HF shape objects only. Prior to the HF-75%/LF-25% trial blocks, they were told that most of the time they would be tested on HF shape objects but sometimes on the LF shape objects.

Consistent with previous research (Mall et al., 2014), participants were administered a short practice block (i.e., 24 trials) of HF-100% trials. This allowed participants to become familiar with the task procedure and stimuli. Following practice, participants completed 7 blocks of 48 experimental trials each (two blocks of HF-only trials, two blocks of HF-100% trials, and three blocks of mixed HF-75% and LF-25% trials). Trial block order was randomly determined. Participants were given the opportunity to take breaks between blocks (i.e., every 48 trials).

Preliminary analyses were conducted on the present data to confirm the internal consistency and reliability of the WM task. The split-half reliabilities (odd–even, Spearman–Brown corrected) of the response time and error rate measures from the task were .99 and .87, respectively.

During task performance, eye position was recorded using an Eye-Trac R6 remote eye-movement monitor with video head tracking (Applied Sciences Laboratories, Bedford, MA). Eye position data was collected at a rate of 60 Hz, and fixations lasting longer than 50 ms were recorded. (Shorter fixations were assumed to reflect saccade-related eye movements and were thus excluded from analysis.) The resulting data was utilized to calculate the proportion of time during encoding (i.e., sample array presentation) that was spent fixating on (a) HF target shapes, (b) LF target shapes, and (c) other locations (e.g., the central fixation point).

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Results

The primary dependent variable of interest was Cowan's *k*, which represents an estimate of the number of array items encoded in WM. The *k* estimate is considered theoretically more meaningful measure than accuracy rate. Accuracy inevitably declines across set sizes, but *k* is theoretically constant across set sizes (except for variability) once capacity is reached. There is no interpretability of accuracy in terms of underlying processes, as there is for *k* (even though *k* is only a rough approximation of those processes).

The *k* estimate was calculated according to a commonly used formula (Cowan, 2001; Cowan et al., 2010) that takes into account guessing, $k = A(hits - false\ alarms)$, where *A* represents the number of sample array objects in the target shape (i.e., if the probe was a circle object, then *A* would be equal to the total number of circle objects originally presented in the sample array), *hits* means the proportion of new/changed probes correctly judged to have changed, and *false alarms* means the proportion of same/unchanged probes incorrectly judged to have changed. The formula arises from the assumption that, if the probe represents one of *k* items in WM, then the participant will know the correct response, otherwise he or she will guess.

Note that a similar pattern of results was found when the analyses described below were repeated with proportion correct as the dependent variable (instead of Cowan's *k* estimates). Descriptive statistics (mean, standard deviation) for performance in each task condition are included in Table 2.

Basic WM Capacity

Performance on HF-only trial blocks (i.e., trials where the sample array comprised only HF shapes and no LF shapes) was examined as a measure of "pure" WM capacity when filtering demands were as low as possible. Estimates of *k* for the HF-only trial blocks are included in Figure 2. Data were entered into a mixed-model analysis of variance (ANOVA) with sample array size (two, three, four, and six HF items) serving as the within-subjects factor and group (ASD and non-ASD) serving as the between-subjects factor. Overall, *k* estimates increased as the sample array size increased, $F(3, 138) = 81.04$, $p < .001$, $\eta_P^2 = 0.64$. There was no main effect of group, $F(1, 46) < 1$, $p = .44$, $\eta_P^2 = 0.01$, nor interaction between array size and group, $F(3, 138) < 1$, $p = .85$, $\eta_P^2 = 0.006$. In the absence of filtering demands, the ASD group demonstrated equivalent WM capacity compared to the non-ASD group. The mean *k* estimate levels off at about four items, comparable to past work (e.g., Cowan, 2001).

Table 2
Means and Standard Deviations for Capacity Estimate (Cowan's k) and Proportion Correct for Each Task Condition

	Capacity estimate (*k*)				Proportion correct			
	ASD		Non-ASD		ASD		Non-ASD	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
HF-only condition								
Array Size 2	1.94	.11	1.93	.12	.98	.03	.98	.03
Array Size 3	2.79	.25	2.86	.21	.97	.04	.98	.03
Array Size 4	3.42	.46	3.64	.31	.93	.06	.95	.04
Array Size 6	3.81	1.30	3.88	1.30	.82	.11	.82	.11
HF-100% condition								
Array Size 2	1.89	.15	1.93	.12	.97	.04	.98	.03
Array Size 3	2.59	.33	2.70	.28	.93	.06	.95	.05
Array Size 4	3.06	.62	3.28	.52	.88	.08	.91	.07
HF-75% condition								
Array Size 2	1.67	.28	1.78	.19	.92	.07	.95	.05
Array Size 3	2.02	.58	2.22	.51	.84	.10	.87	.08
Array Size 4	2.17	.71	2.39	.97	.77	.09	.80	.12
LF-25% condition								
Array Size 2	1.35	.36	1.57	.43	.84	.09	.89	.11
Array Size 3	1.33	.84	1.56	.84	.71	.16	.76	.14
Array Size 4	1.53	1.01	1.00	1.15	.69	.13	.60	.17

Note. ASD = autism spectrum disorder; HF = high frequency; LF = low frequency.

Visual Filtering

Task performance. Like in HF-only trials, the probe in HF-100% trials was always a HF shape object. However, the sample array for HF-100% trials also included LF shape objects, thus adding the task demand of needing to filter/ignore these irrelevant shapes. Data from this condition were entered into a mixed-model ANOVA with sample array size (two, three, and four HF items) serving as the within-subjects factor and group (ASD and non-ASD) serving as the between-subjects factor. Overall, there was a main effect of array size, with greater *k* estimates associated with larger sample array sizes, $F(2, 92) = 487.84$, $p < .001$, $\eta_P^2 = .79$. There was no main effect of group, $F(1, 46) = 2.58$, $p = .12$, $\eta_P^2 = 0.05$, nor interaction between array size and group, $F(2, 92) < 1$, $p = .44$, $\eta_P^2 = 0.02$, suggesting comparable WM performance for the two groups in the presence of filtering demands.

Notice that there is some effect of the irrelevant objects, given that capacity was somewhat lower for HF-100% trials compared to HF-only trials (cf. Figure 2 and the left-hand panel of Figure 3). To further test for group differences in filtering, we examined the magnitude of the difference between trial types ($k_{\mathrm{HFonly}} - k_{\mathrm{HF100\%}}$), which represents a measure of filtering ability. Data were entered into a mixed-model ANOVA with sample array size and group serving as within- and between-subjects factors, respectively. No effect of group nor interaction was observed [$F < 1$, $p > .74$, $\eta_P^2 < .003$ in both instances]. The magnitude of trial difference ($k_{\mathrm{HFonly}} - k_{\mathrm{HF100\%}}$) was comparable across setsizes for the two groups ($M_{\mathrm{ASD}} = 0.20$; $M_{\mathrm{TYP}} = 0.17$).

Ocular fixation data. Additional insight regarding filtering ability may be gained by examining the proportion of time that participants spent foveating HF and LF shapes during presentation of the sample memory array in the HF-100% condition. Fixation data were entered into a mixed-model ANOVA with stimulus shape (HF and LF) and sample array size (two, three, and four HF items) serving as the within-subjects factor, and group (ASD and non-ASD) serving as the between-subjects factor. As could be anticipated, there was a main effect of stimulus shape, with participants spending significantly more time fixating the HF shapes compared to the LF shapes [$M_{\mathrm{HF}} = 0.45$; $M_{\mathrm{LF}} = 0.07$; $F(1, 46) = 295.17$, $p < .001$, $\eta_P^2 = 0.87$]. No main effect of array size [$F(2, 92) < 1$, $p = .38$, $\eta_P^2 = 0.02$], main effect of group [$F(1, 46) = 2.46$, $p = .12$, $\eta_P^2 = .05$] or two-way interactions [$F < 2.11$, $p > .15$, $\eta_P^2 < .05$ in all instances] were found.

Interestingly, the three-way interaction between shape, size, and group was significant [$F(2, 92) = 4.43$, $p = .015$, $\eta_P^2 = .09$]. As

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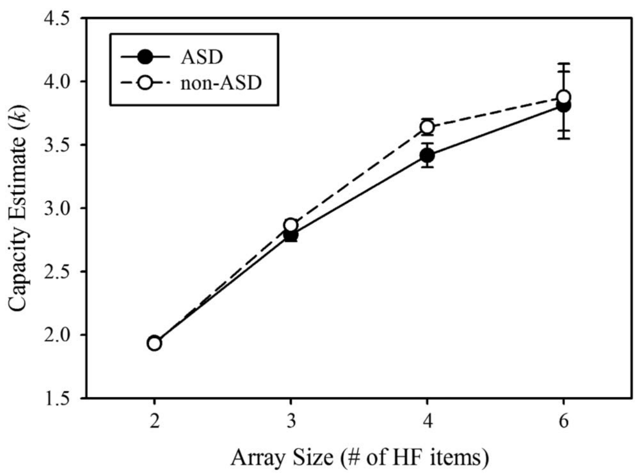

Figure 2. Basic working memory capacity. Data from the high-frequency (HF)-only trials. Working memory capacity estimate (Cowan's *k*) is shown separately for each array size (two, three, four, and six HF items) and group (autism spectrum disorder [ASD] and non-ASD). The *k* parameter indicates the number of items in working memory, and the individual's capacity can be estimated from the asymptotic or maximal level of *k* as *A* increases. Error bars represent the standard error of the mean.

can be seen in the right-hand panel of Figure 3, the interaction appears to be driven by two concurrent patterns in the data. Whereas the two groups spent a similar proportion of time fixating LF shapes, the ASD group appeared to fixate HF shapes for proportionally less time than the non-ASD group did. In addition, for the non-ASD group, the proportion of time spent fixating HF shapes increased from array size 2 to the larger array sizes (3–4). This was not the case for the ASD group, whose fixation time remained largely comparable across array sizes.

Attentional Allocation

Task performance. The sample array for trials in both the HF-100% and HF-75%/LF-25% blocks included HF and LF shapes. However, in the latter blocks, the LF shapes could potentially be probed and thus optimal performance on these trials required participants to disproportionally divide attention between the two shapes. To examine WM performance under these conditions, data were entered into a mixed-model ANOVA with stimulus shape (HF and LF) and sample array size (two, three, and four HF items) serving as within-subjects factors, and group (ASD and non-ASD) serving as a between-subjects factor.

Overall, *k* estimates were greater for HF as compared to LF items, $F(1, 46) = 42.32$, $p < .001$, $\eta_p^2 = .48$, suggesting that participants overall were devoting more WM capacity to HF as compared to LF shapes. There was also a significant two-way interaction between stimulus shape and array size, $F(2, 92) = 8.37$, $p < .001$, $\eta_p^2 = .15$, and a three-way interaction between stimulus shape, array size, and group, $F(2, 92) = 3.41$, $p = .04$, $\eta_p^2 = .07$. As can be seen in left panel of Figure 4, these interactions were largely driven by group differences at the largest (and most demanding) array size. Specifically, the ASD group as compared to the non-ASD group devoted disproportionally more WM capacity to the LF shapes for arrays with four HF items.

To further explore this data pattern, we calculated an attentional allocation index, which is defined as the proportion of WM capacity devoted to the "to-be-attended" HF shapes, $k_{HF}/(k_{HF} + k_{LF})$, and reflects an individual's ability to effectively allocate attention to the HF shapes relative to the LF shapes (Cowan et al., 2010). As illustrated in Figure 5, as array size increased, the non-ASD group continued to increase the proportion of WM capacity devoted to HF shapes (presumably so as to accommodate the increased memory load). In contrast, the proportion of capacity devoted to HF shapes for the ASD group did not show a similar increase for the largest array size (which included four HF shapes and four LF shapes).

Ocular fixation data. The proportion of time that participants spent foveating HF and LF shapes during presentation of the sample memory array for the HF-75%/LF-25% blocks was also examined. Data were entered into a mixed-model ANOVA with stimulus shape (HF and LF) and sample array size (two, three, and

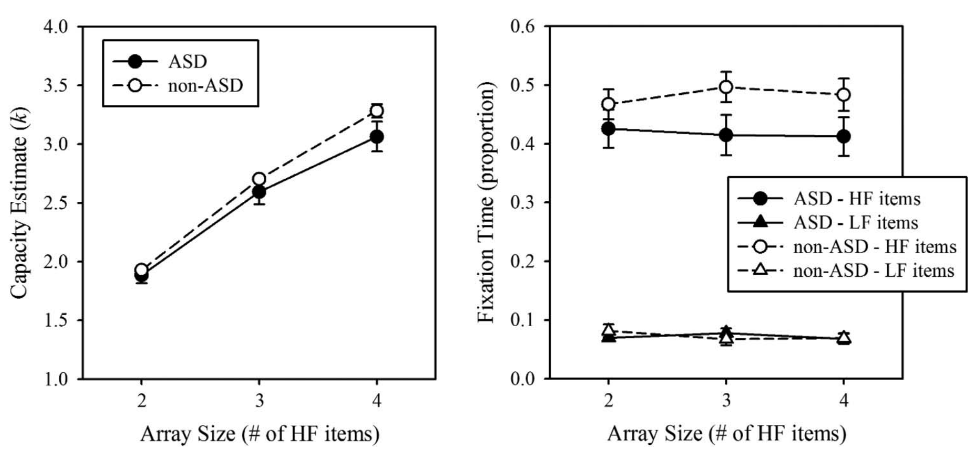

Figure 3. Visual filtering. Data from the high-frequency (HF)-100% trials. In the left panel, working memory capacity estimate (Cowan's *k*) is shown separately for each array size (two, three, and four HF items) and group (autism spectrum disorder [ASD] and non-ASD). In the right panel, ocular fixation time is shown separately for each array size (two, three, and four HF items), item type (HF and low frequency [LF]), and group (ASD and non-ASD). Error bars represent the standard error of the mean.

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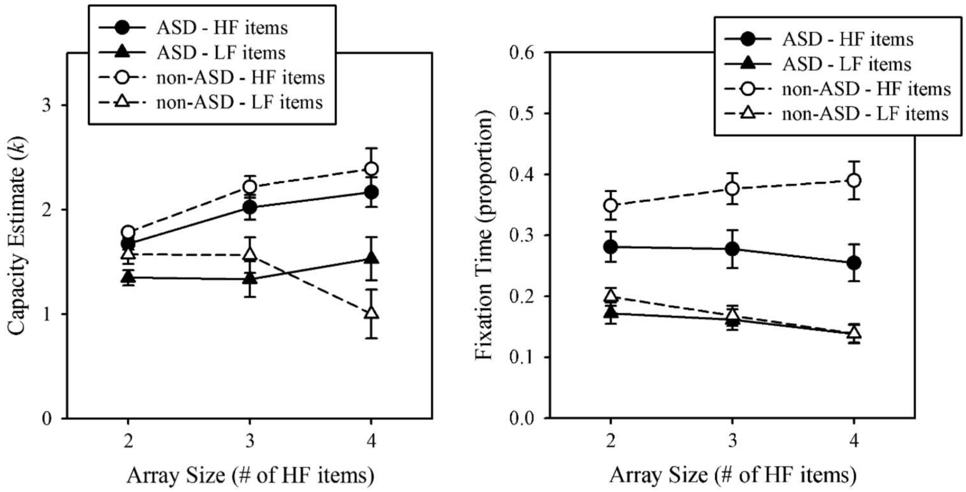

Figure 4. Attentional allocation. Data from the high-frequency (HF)-75%/low-frequency (LF)-25% trials. In the left panel, working memory capacity estimate (Cowan's *k*) is shown separately for each array size (two, three, and four HF items), item type (HF and LF), and group (autism spectrum disorder [ASD] and non-ASD). In the right panel, ocular fixation time is shown separately for each array size (two, three, and four HF items), item type (HF and LF), and group (ASD and non-ASD). Error bars represent the standard error of the mean.

four HF items) serving as within-subjects factors, and group (ASD and non-ASD) serving as a between-subjects factor.

Main effects of array size and stimulus shape were evident, $F > 8.9$, $p < .001$, $\eta_P^2 > .15$, in both instances. Overall participants fixated longer on HF shapes as compared to LF shapes. There was also a significant interaction between array size and stimulus shape, $F(2, 92) = 8.31$, $p < .001$, $\eta_P^2 = .15$, with the difference in fixation time between HF and LF shapes increasing with larger array sizes. Of particular relevance, there was also a significant main effect of group, $F(1, 46) = 6.33$, $p = .015$, $\eta_P^2 = .12$, a two-way interaction with group and stimulus shape, $F(1, 46) = 4.45$, $p = .04$, $\eta_P^2 = .09$, and a three-way interaction with group, stimulus shape, and array size, $F(2, 92) = 6.13$, $p = .003$, $\eta_P^2 = .12$.

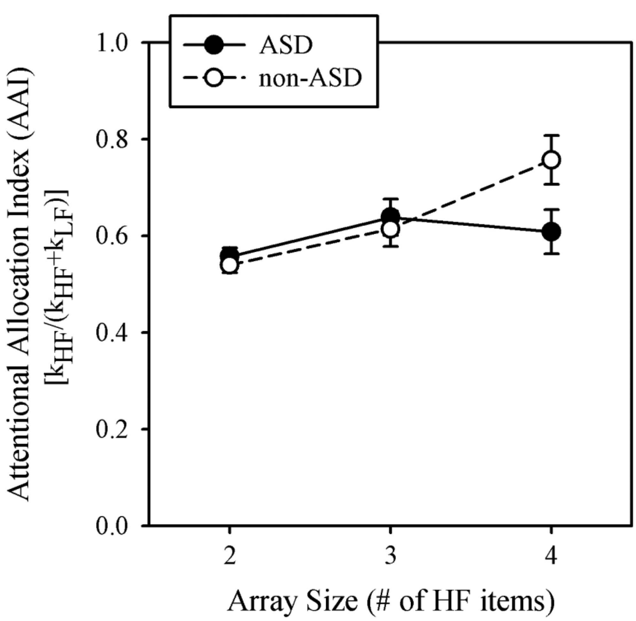

Figure 5. Data from the high-frequency (HF)-75%/low-frequency (LF)-25% trials. Attention Allocation Index—reflecting the proportion of working memory capacity devoted to HF items—is shown separately for each array size (two, three, and four HF items) and group (autism spectrum disorder [ASD] and non-ASD). Error bars represent the standard error of the mean.

As can be seen in right panel of Figure 4, these effects are all primarily driven by group differences in the proportion of time spent fixating the HF shapes. When faced with larger array sizes (and thus more to encode), non-ASD participants increased their proportion of time spent fixating HF shapes ($M_{SS2} = 0.35$; $M_{SS3} = 0.38$; $M_{SS4} = 0.39$). In contrast, the ASD group demonstrated constant or slightly decreased HF fixation time for larger array sizes ($M_{SS2} = 0.28$; $M_{SS3} = 0.28$; $M_{SS4} = 0.25$). Taken together with the task performance data described earlier, these findings suggest that the ASD participants had difficulty efficiently allocating attention (and thereby WM capacity) under the most demanding conditions (i.e., largest set size).

Discussion

Findings from past studies have been mixed, with some studies reporting intact (or even superior) WM performance for individuals with ASD (e.g., Koshino et al., 2008; Ozonoff & Strayer, 2001) and others reporting impaired performance (e.g., Christ et al., 2017; Williams et al., 2005). Within this context, it is likely that the diversity of tasks used to assess WM and the degree to which they place demands on different aspects of WM have contributed to the aforementioned variability in study outcomes. To examine this issue further, we presently evaluated WM performance in a sample of individuals with and without ASD under conditions in which the demands on related secondary processes such as visual filtering and attentional selection were systematically varied. We hypothesized that ASD would be associated with

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decreased WM performance—particularly in the presence of additional filtering and/or attentional demands. Consistent with this, the ASD group demonstrated intact "pure" WM capacity (i.e., in presence of minimal secondary demands) but impaired ability to efficiently allocate WM capacity under the most demanding of conditions (i.e., a large memory load combined with a need to strategically allocate attention).

Participants with ASD performed comparable to non-ASD participants on the WM task when filtering and other secondary demands were as low as possible (i.e., the HF-only condition). This was true even in the presence of relatively high memory load (i.e., array size 6). The present finding supports intact basic WM capacity in older adolescents and adults with ASD. This finding is also consistent with results from a recent meta-analysis (Wang et al., 2017) suggesting that increases in memory load alone may be insufficient to reveal ASD-related differences in WM performance.

The result, however, does appear to potentially contradict with past findings on another well-established basic visuospatial WM task—the forward spatial (or block) span task. For this task, participants are shown a board upon which several blocks are randomly positioned. The examiner taps a sequence of blocks one-at-a-time. The participant then attempts to reproduce the sequence and tap the same blocks in the identical order. The task is repeated with increasing sequence lengths. ASD-related impairments on this task have been reported across the life span (e.g., Christ et al., 2017; Cui, Gao, Chen, Zou, & Wang, 2010; Geurts & Vissers, 2012). Of note, a major distinction between the aforementioned spatial span task and our present paradigm relates to the nature of the to-be-remembered information. Both tasks involve information on spatial location, but the present paradigm also involves color attributes while the spatial span task involves temporal order information. Past research suggests that the latter (i.e., serial order recall) may represent a particular area of weakness for individuals with ASD (Bowler, Poirier, Martin, & Gaigg, 2016; Poirier, Martin, Gaigg, & Bowler, 2011) and thus may help explain the discrepancy in findings between the current study and those past studies using the spatial span task.

Another of the current task conditions focused on WM performance in the presence of the additional task demand of needing to filter/ignore irrelevant nontarget shapes (i.e., HF-100% condition). While performance of both groups decreased with the additional task demand, the introduction of visual filtering demands did not disproportionally affect performance in the ASD group as compared to the non-ASD group. The ASD group appears to have been as equally effective as the non-ASD group at filtering/suppressing the irrelevant items and associated information. Upon first glance, this finding may appear inconsistent with past studies documenting visual filtering impairments in individuals with ASD (e.g., Christ et al., 2007). More recent reports, however, suggest that such filtering impairments may be most prominent in childhood, with deficits decreasing by adolescence (Boland, Stichter, Beversdorf, & Christ, 2019; Christ et al., 2011). A possible explanation for this pattern is that the underlying neurocognitive disruption does not resolve per se, but rather that as the children grow older, they engage compensatory cognitive strategies to overcome the impairment and better match the task performance of their non-ASD peers. Additional support for this possibility comes from studies such as one by Koshino et al. (2008), which found differences in brain activation patterns but not behavioral performance between adults with and without ASD performing an *n*-back WM task.

In terms of the present study, analyses of the eye tracking data further support the potential engagement of alternate strategies/approaches by the ASD group. During encoding, the ASD group fixated on the HF shapes for disproportionally less time than the non-ASD group. In addition, the proportion of time that the ASD group devoted to fixating on HF shapes remained fairly constant across array sizes. In contrast, the non-ASD group increased its fixation time on HF shapes as the array size grew (note that a similar pattern was observed for the HF-75%/LF-25% blocks as well). These fixation patterns may reflect different strategic approaches to the encoding of the stimuli arrays. For example, the pattern observed for the non-ASD group may reflect a "focused serial" approach to encoding, whereby participants tended to foveate and process stimuli in turn. In contrast, the pattern observed for the ASD group appears more consistent with a "diffuse simultaneous" approach whereby they relied on diffuse/peripheral vision and concurrent processing of multiple stimuli at once. Although highly speculative, the adoption (and effectiveness) of this approach may relate to reports of enhanced perceptual capacity in individuals with ASD (Remington, Swettenham, Campbell, & Coleman, 2009). Additional research is needed to better understand the nature of the different ocular fixation patterns and how they may relate to individual differences in strategic approach and task performance.

Lastly, we examined WM performance under conditions where one set of items (HF shapes) was much more likely to be probed than another (LF shapes; i.e., HF-75%/LF-25% blocks). Optimal performance required participants to distribute attention unequally between the two item groups. The ability to allocate attention efficiently represents a critical aspect of WM, with past studies suggesting that it serves a major contributor to observed individual differences in WM performance (e.g., McNab & Klingberg, 2008; Vogel, McCollough, & Machizawa, 2005). Presently we found that, for smaller array sizes, the ASD and non-ASD groups allocated attention and capacity similarly. Group differences in attentional allocation, however, were apparent under higher WM loads. For the largest array size (4 HF + 4 LF items), the ASD group devoted a significantly smaller proportion of capacity to HF items as compared to the non-ASD group ($M_{\text{ASD}} = 60.8\%$; $M_{\text{TYP}} = 75.5\%$). Importantly, this reflected differences in attentional allocation and not overall WM capacity per se. Indeed, the overall number of items recalled ($k_{\text{HF}} + k_{\text{LF}}$) in this condition was comparable for the two groups ($M_{\text{ASD}} = 3.69$; $M_{\text{TYP}} = 3.39$; $t < 1$, $p = .44$).

This finding may begin to provide insight into some of the mixed findings in the literature. For example, a recent meta-analysis of ASD and executive function by Lai et al. (2017) found a significant effect ($g = 0.67$, $p < .001$) for the CANTAB's visuospatial WM task but not for spatial *n*-back WM tasks ($g = .099$, $p = .46$). Stimuli in an *n*-back task are typically presented one-at-a-time, thus placing minimal demands on attentional selection (i.e., there is no need to allocate attention among multiple simultaneous stimuli). In contrast, much like for the HF-75%/LF-25% blocks of the present study, optimal CANTAB WM task performance depends on effective attentional allocation. In the task, participants are shown several colored boxes on the screen. They must search the boxes (by clicking on them) to locate a specified number of "tokens" hidden in the boxes. Proficient performance requires participants to allocate attention to boxes that have not yet been searched and to ignore boxes that have already been searched. Also consistent with the present findings, Steele, Minshew, Luna, and Sweeney (2007) found that differences in performance between individuals with and without ASD on the CANTAB task were most apparent under higher memory loads and attentional demands.

It is further interesting to note that the present pattern of findings (i.e., intact attentional allocation with lower WM loads, but inefficient allocation with higher loads) mirrors earlier findings by Cowan et al. (2010) when comparing typically developing young children (7–8 years old) with adults (18–22 years old). With a small array size (two HF items), both adults and young children devoted a significantly greater proportion of capacity to HF items compared to LF items. At a larger array size (three HF items), however, only the adults continued to show an attentional/WM benefit for the HF items. The researchers postulated that attentional resources are generally shared between selection and maintenance of items in WM. For the young children, the additional demands associated with maintenance of a high WM load left fewer resources to support efficient attentional selection. A similar explanation may underlie the present findings. As noted earlier, the eye tracking data suggests that the ASD group was utilizing a different approach to encoding than the non-ASD group. Specifically, the data were consistent with the ASD group relying on a diffuse attentional set whereby they processed/encoded multiple stimuli at once. It may be that this approach, while effective with smaller array sizes, placed higher-than-usual demands on attentional resources. Within this context, when faced with larger arrays, the attentional demands of this approach were too high thus leaving fewer attentional resources to support selection operations. Future research examining the interplay between WM capacity and attentional allocation in individuals with and without ASD will be critical in evaluating this possibility.

Additional Limitations and Future Directions

The present sample size provided sufficient statistical power to detect the aforementioned group differences in task performance. However, future studies employing a larger sample size (thus providing greater statistical power and ability to generalize) may reveal additional, more subtle effects that otherwise went undetected in the current study. A larger (and more diverse) sample would also allow us to explore to what extent factors such as sex, age, and overall level of cognitive functioning may influence the current pattern of results. Indeed there is growing evidence of sex-related differences in individuals with ASD in overall cognitive profile as well as specific cognitive domains including WM (e.g., Kiep & Spek, 2017; M.-C. Lai et al., 2012).

Recent meta-analyses (C. L. E. Lai et al., 2017; Wang et al., 2017) failed to find significant age- or IQ-related effects when comparing WM findings across ASD studies. However, the vast majority of studies (including the present one) have focused on higher functioning individuals, and additional research is needed to fully evaluate whether the present findings generalize across different levels of overall intellectual ability. With regards to age, results from other studies suggest trajectory differences in WM development across the life span—continuing from early childhood through to older adulthood (e.g., Andersen et al., 2015; Lever, Werkle-Bergner, Brandmaier, Ridderinkhof, & Geurts, 2015). For example, Luna, Doll, Hegedus, Minshew, and Sweeney (2007) compared WM performance in three age groups (child, adolescent, and adult) of individuals with and without ASD. They found evidence of WM impairment across all three age groups as well as a delayed age at which the ASD participants reached adult-levels of performance, thus suggesting the presence of a persistent impairment combined with delayed development. Future research focused on potential developmental changes in specific aspects of WM (e.g., capacity, filtering ability, attentional allocation) may provide valuable insight into the nature of the aforementioned changes in overall WM performance observed across the life span in ASD.

It is also worth considering to what extent the present findings may relate to more general attentional difficulties in individuals with ASD. An alternate explanation for the group differences in fixation patterns is that the participants with ASD were simply more likely to let their attention wander away from the high-priority array items and presumably toward other environmental or internal events. Such tendency to mind-wander during task performance is associated with relatively low span on complex, storage-and-processing tasks in typical non-ASD adults (Kane et al., 2007). The present participants with ASD did not exhibit a low span on array memory (see Figure 2) but perhaps they might on more complex WM tasks.

To explore the issue of attentional problems further, we examined the potential association between performance in the critical condition (i.e., attentional allocation index for the 4HF + 4LF array condition) and scores on the Conners' Adult ADHD Rating Scales (CAARS; Conners, Erhardt, & Sparrow, 1999) in our ASD sample. (Note that CAARS data was unavailable for 6 participants who fell under the test's age limit [<18 years old].) No significant correlations were found with either the *DSM–IV* Inattentive Symptoms Score or *DSM–IV* Hyperactive–Impulsive Symptoms Score ($p > .05$ in all instances). Regardless, additional research utilizing a broader, more comprehensive assessment of attentional abilities and symptomatology (e.g., third-party report; direct behavioral assessment) is needed to fully evaluate this issue. Future studies will also be vital in better characterizing WM performance in ASD more generally. The conceptual model of WM originally proposed by Cowan (1988) and adopted for the present study is not modality specific and thus may provide a viable framework for examining and understanding ASD-related differences in WM and related cognitive factors such as inhibition and attention across different modalities (visuospatial, auditory, etc.).

Summary and Conclusions

In summary, the present study found comparable "pure" WM capacity in a sample of individuals with and without ASD. The ability to efficiently allocate such capacity under the demands of a high WM load, however, was poorer in the ASD group compared to the non-ASD group. We believe that this disruption may be related to implementation of an atypical strategy at encoding (as evidenced by eye tracking data) whereby the ASD group adopted a diffuse attentional set and processed multiple stimuli at once. This approach proved effective with smaller array sizes but may have overwhelmed available attentional resources under condi-

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tions with higher WM loads. Additional research is needed to fully understand the nature of this finding and its implications for the existing literature on autism, WM, and attention.

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