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ORIGINAL PAPER

Circumscribed Interests and Attention in Autism: The Role of Biological Sex

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Abstract
Recent studies suggest that circumscribed interests (CI) in females with Autism Spectrum Disorder (ASD) may align more closely with interests reported in *typical* female development than those typically reported for ASD males. We used eye-tracking to quantify attention to arrays containing combinations of *male, female* and *neutral* images in elementary-aged males and females with and without ASD. A number of condition × sex effects emerged, with both groups attending to images that corresponded with interests typically associated with their biological sex. Diagnostic effects reported in similar studies were not replicated in our modified design. Our findings of more typical attention patterns to *gender-typical* images in ASD females is consistent with evidence of sex differences in CI and inconsistent with the "Extreme Male Brain" theory of ASD.

Keywords Eye-tracking · Circumscribed interests · Sex differences · Females · Extreme Male Brain theory

Introduction

Sex differences in the prevalence of Autism Spectrum Disorder (ASD) have remained consistent despite changes in diagnostic criteria and early screening. Based on national prevalence estimates, four boys to one girl receive a diagnosis of ASD (Christensen et al. 2016; Loomes et al. 2017). As a result, much less is known about the development and clinical profile of females on the autism spectrum. Research has indicated differences between males and females with ASD in a number of areas, including social motivation (Dean et al. 2017; Hiller et al. 2014; Sedgewick et al. 2016) and fewer and/or different restricted and repetitive behaviors (RRBs; Frazier et al. 2014; Van Wijngaarden-Cremers et al. 2014). This study focuses on a subset of RRBs—circumscribed interests (CI)—and adapts a validated eye-tracking paradigm to understand whether patterns of attention to images differ between males and females with ASD.

Circumscribed Interests in ASD

Differences in CI have emerged as a potential area of distinction between males and females with ASD. CI are defined as an intense and focused interest in a narrow range of subjects. The content and focus of CI often overlap with interests observed in typical development, particularly in males (DeLoache et al. 2007). Examples include Legos®, trains, cars and computers (South et al. 2005). However, CI in ASD are often idiosyncratic, such as interests in watches and clocks, road signs, historical facts and timetables (Mercier et al. 2000; South et al. 2005), and can be less functional and less age-appropriate (Turner-Brown et al. 2011).

Reports suggest that over 75% of individuals with ASD have at least one CI, with a high proportion of individuals having multiple CI (Klin et al. 2007; Turner-Brown et al. 2011). Individuals with ASD frequently organize their activities around their CI (Klin et al. 2007; South

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et al. 2005) and these interests can have a negative effect on social activities, learning and adaptive behaviors (Koegel and Covert 1972; Koegel et al. 1974; Pierce and Courchesne 2001). Children with ASD often engage with their CI in inflexible ways, resist when interrupted and require accommodation around their interests (Turner-Brown et al. 2011), supporting the clinical importance of these behaviors. Further, CI seem to be specific to ASD compared to other RRBs that are frequently observed in other neurodevelopmental disorders. As such, researchers have sought to understand the mechanisms that underlie CI and their potential impact on learning and social opportunities.

Importantly, however, CI in ASD can also confer significant benefit for individuals with ASD. Not only can they be a great source of pleasure (Sasson et al. 2012), but they also can serve as an area of strength and expertise (Mercier et al. 2000) that is observable at the neurobiological level (Grelotti et al. 2005; Foss-Feig et al. 2016) and in some cases lead to specialized skills and abilities (Koenig and Hough 2017). CI also can provide opportunities for individuals with ASD to socially engage with others (Mercier et al. 2000), a phenomenon which may be particularly relevant to females with ASD, as they often report their CI as a defining feature of their identity (Bargiela et al. 2016). CI in such cases may serve as a *protective effect* (Bargiela et al. 2016).

Eye-Tracking Studies of Circumscribed Interests

Eye-tracking studies have been used to understand how CI relate to attention and motivation in ASD. In two studies using a paired-preference task, young children with ASD fixated on images of common CI at the expense of attending to faces to a greater degree than did typically developing (TD) children (Sasson and Touchstone 2014; Unruh et al. 2016). Using arrays of images varying in content, Sasson and colleagues found that when presented with images of common CI that are of high salience to individuals with ASD (termed *high autism interest* objects, e.g. Lego®, trains, cars), attention to social stimuli and other images (termed *low autism interest* objects) is reduced (Sasson et al. 2008, 2011). When presented with common CI, individuals with ASD had a tendency to explore fewer items within the arrays, perseverate on CI images, and explore them in a more detail-orientated manner. These studies demonstrated that relative to TD controls, attention in individuals with ASD is reduced to social stimuli when paired with items of high salience, like CI objects. However, these studies were underpowered to examine sex differences and recent findings suggest that CI content and intensity may differ between males and females with ASD; therefore, it is unclear whether these patterns of attention extend to females.

Circumscribed Interests in ASD Females

A number of recent studies have indicated lower incidences of CI in females with ASD and differences in their content. For example, in a large study examining behavioral and cognitive characteristics of ASD females (N = 304, mean age = 9 years), Frazier et al. (2014) reported lower CI scores on standardized measures of RRBs in females compared to males, and that these differences were not mediated by cognitive abilities. This study raised questions as to whether these types of *higher order* RRBs (RRBs considered to be more cognitively complex) are as prevalent in females, or perhaps that CI observed in females are not as readily observed using existing measurement tools which have been predominately developed using male samples (Lai et al. 2011).

A handful of studies implementing parent report and direct observation have suggested that the content of these interests may differ with more focus on interests that are commonly observed in typical development. In two studies, Hiller and colleagues reported that parents and teachers described both lower levels of RRBs but also differences in the content of CI (Hiller et al. 2014, 2016). Namely, girls were more likely to have “seemingly random” interests and less likely to be interested in wheeled toys and gaming. Girls were also more likely to share their interests with others, suggestive of lower levels of social impairment stemming from these intense interests.

Using observations of parent–child play, Harrop et al. (2017) reported that while preschool-aged ASD females played to a similar level of complexity as ASD males, they played with different toys. Specifically, both groups played with toys commonly associated with sex differences in typical development. For example, females with ASD were more likely to play with such toys as tea sets, dolls and cooking items; whereas ASD males tended to play with toys associated with *male typical*—building toys, computers and cars. These results suggest that sex differences observed in typical development may extend to ASD.

These findings, together with reports of heightened social motivation in females with ASD (Sedgewick et al. 2016), do not align with the predictions of the Extreme Male Brain (EMB) theory of ASD (Baron-Cohen 2002). The EMB theory of ASD postulates that autism represents an extension of typical sex differences in the domains of empathizing and systemizing (Baron-Cohen 2009) and thus would predict more *male-typical* interests among females with ASD rather than female-typical interests, as has been shown in prior studies (Harrop et al. 2017; Hiller et al. 2014, 2016). Based on this theory, females and males with ASD should demonstrate similar attention patterns to similar images—those reflecting common CI that are *male-typical*. This, however, has not yet been empirically investigated.

Unfortunately, given findings that CI in ASD appear to fall along traditional gender lines (Hiller et al. 2014, 2016; Sutherland et al. 2017), the applicability of previously validated eye-tracking paradigms may not truly reveal differences between males and females with ASD because of an over-reliance on more *male-specific* CI (e.g. Lego®, trains, computers) using predominantly male samples. To this end, we adapted the visual search arrays that Sasson et al. (2008, 2011) developed to include images of interests that that reflect commonly reported gender differences. The inclusion of more *gender typical* images may provide a more sensitive measure of attention in ASD as these stimuli may be more likely to capture attention than typical CI images that have not considered the role of gender. The goal of this study was to understand patterns of visual attention to CI-related stimuli in school-aged ASD females. Based on previous literature and clinical descriptions of ASD females, we predicted that overall attention in females with ASD would be comparable to males with ASD (i.e. more circumscribed and perseverative), but to different types of images. Specifically, females with ASD would demonstrate these visual attention patterns to images representative of interests reported in TD females but not to the male-typical CI images used in prior research (Sasson et al. 2008, 2011).

Methods

Participants

Four groups of participants were recruited to participate based on diagnosis and biological sex: (1) 27 ASD males; (2) 27 ASD females; (3) 16 TD males; and (4) 17 TD females. All participants met the following general inclusion criteria: between 6 and 10 years of age; absence of seizure disorder, acute medical or genetic condition; and absence of any visual impairment uncorrectable with eyewear. The age range was 6–10 years based on the findings of a recent meta-analysis suggesting that, prior to the age of 6, very few differences in core symptoms were observed between males and females, however at age 6, higher rates of RRBs were reported in males (Van Wijngaarden-Cremers et al. 2014). We also included a narrower age range than Sasson et al. (2008) to ensure the developmental appropriateness of the images selected for our paradigm.

We did not exclude participation based on IQ or level of functioning. However, we collected data on child cognitive ability using the Differential Ability Scales (DAS-II; Elliot 2007). We did not exclude any children based on severity or functioning due to the inherent difficulty of recruiting an adequate sample size of ASD females and the fact they often fall at the lower end of the spectrum and require additional behavioral problems and/or co-occurring intellectual disability to warrant a diagnosis of ASD (Dworzynski et al. 2012). However, any cognitive or functional differences were co-varied in all analyses—an approach common in ASD research and eye tracking studies (Chevallier et al. 2015; Fletcher-Watson et al. 2009; Sasson and Touchstone 2014).

Participants with ASD were recruited via the (University of North Carolina at Chapel Hill) Autism Research Registry in conjunction with regional diagnostic and treatment centers. Inclusion in the registry required a previous Diagnostic and Statistical Manual of Mental Disorders diagnosis of ASD made by a licensed clinician experienced in the assessment and diagnosis of autism, and based on parent interview and direct observation for the completion of one or more standardized autism diagnostic assessment instruments [Autism Diagnostic Interview-Revised (ADI-R; Rutter et al. 2003b), Social Communication Questionnaire (SCQ; Rutter et al. 2003a), Autism Diagnostic Observation Schedule (ADOS; Lord et al. 2000), Childhood Autism Rating Scale (CARS-2; Schopler et al. 2010)]. Study staff verified the diagnosis via a phone screen with families, and parents/caregivers also completed the Social Communication Questionnaire (SCQ; Rutter et al. 2003a) at their first study visit.

TD children were recruited via an email sent to the (University of North Carolina at Chapel Hill) Child Development Research Registry, advertisements on social media and word of mouth. TD children were excluded if they had a history of neurodevelopmental disorders or had an immediate relative with a diagnosis of ASD. Parents completed the SCQ to rule out elevated behaviors indicative of ASD. We did not purposefully match on developmental age due to the low task demands of the eye-tracking task; however, any differences in mental age (MA) were controlled for in the analysis.

All subjects were reimbursed with a gift card for their study participation. Parents provided informed written consent and, when developmentally appropriate, children provided written assent to participate. The research protocol was approved by the Institutional Review Board at (University of North Carolina at Chapel Hill).

All children completed the DAS-II (Elliot 2007). The DAS-II is an established measure of cognitive abilities from 30 months to 17 years, 11 months. It has been implemented in several studies of children with ASD (e.g. Bishop et al. 2011; Joseph et al. 2002). In this study, we administered six scales that comprise the Core Battery to derive nonverbal, verbal, and spatial ability scores and age equivalents. These core subscales are comparable across the Early and School Years protocols, and both protocols allow for out-of-level testing, allowing for administration based on ability level. The majority completed the School Years Form (ages 7–17); however, four children with ASD and one control completed the Early Years protocol.

To measure the degree of repetitive behaviors in our sample, parents completed the Repetitive Behavior Scales-Revised (RBS-R; Bodfish et al. 1999). The RBS-R is a 43-item parent-report rating scale that rates the occurrence of RRBs on a 4 point Likert scale from (0) does not occur to (3) occurs frequently and/or is severe. Ratings are based on (a) the frequency of the behavior, (b) how difficult the behavior is to interrupt, and (c) the degree of interference caused by the behavior. The RBS-R generates six subscale scores, which were summed to create a cumulative score for analysis.

Parents also completed the Interests Scale (Bodfish 2003) to measure the presence and severity of CI. The scale consists of a checklist of interests that are summed to provide a score of current and past interests in their child. Seven additional questions ask the parent to select the child's primary interest and rate the severity of this interest (frequency, social involvement, interference and accommodation). Higher scores indicate more interference/greater severity, with scores ranging from 0 to 23.

Of the 87 subjects recruited for the study, two ASD participants (both male) did not complete the eye-tracking task due to behavioral or attention issues during the testing procedure. Of the 85 subjects who completed the eye tracking paradigm, two children (1 ASD female, 1 TD female) did not have sufficient data (criteria set at > 20% overall fixation time to the screen). The final sample included 25 ASD males, 26 ASD females, 16 TD males and 16 TD females. Sample characteristics are reported in Table 1.

Despite recruitment efforts, the ASD and TD groups differed in chronological age (CA; $F = 13.37$, $p \leq .01$) with the ASD group being older. There also was a diagnosis by sex effect, with ASD males being older than both TD males and females ($F = 3.57$, $p \leq .01$). There was a marginal difference in MA between the diagnostic groups ($F = 3.51$, $p = .06$) and sexes ($F = 3.47$, $p = .06$). As a result, CA and MA were entered as co-variates in the main analysis adopting a similar approach to other eye tracking studies (Chevallier et al. 2015; Fletcher-Watson et al. 2009; Sasson and Touchstone 2014). There were no differences between the ASD males and females in SCQ and other parent reported variables.

Eye-Tracking Stimuli

Visual Exploration Task

The visual exploration task used in this study was based on the paradigm Sasson et al. developed (2008, 2011). However, rather than use the original visual search arrays, these were modified to include either *male, female or neutral* images. Participants viewed 18 static, high-quality color picture arrays consisting of 24 images each (for examples, see Fig. 1). Six of the arrays were comprised of "male vs. female" arrays. These arrays contained images of toys, objects and common interests frequently reported as male or female *typical*. Six of the arrays were comprised of "male vs. neutral" arrays, containing images of either common male or neutral toys, objects or interests. Six of the arrays contained "female vs. neutral" images.

All images were public domain photographs obtained via the internet and were selected because of their similarity in size. Images were determined as common *male, female* or *neutral* based on previous literature (Caldera et al. 1989; Cherney and London 2006; DeLoache et al. 2007; Robinson and Morris 1986) and searching categories of *male and female* toys within our age range on various online stores. Our research group also met to discuss the *gender* of the images selected. Prior to data collection, we conducted a small (n = 20) online survey distributed via social media and email to parents of TD children (ages 6–10). This survey was designed to ensure that the images selected for each category (male, female, neutral) were representative of those

Table 1 Sample characteristics

	Boys		Girls		Diagnosis effects (ASD vs. TD)	
	ASD (n = 25)	TD controls (n = 16)	ASD (n = 26)	TD controls (n = 16)	F	p
Chronological age (months)	113.12 (10.09)	93.50 (17.85)	102.00 (17.45)	95.75 (17.50)	13.37	< .001**
Mental age (months)	115.23 (31.69)	124.30 (40.88)	96.75 (32.48)	115.31 (24.31)	3.51	.06
SCQ score	14.80 (5.80)	3.50 (2.58)	13.88 (4.92)	2.19 (2.88)	125.43	< .001**
RBS-R score	28.80 (16.91)	3.12 (2.87)	34.38 (23.03)	5.25 (8.85)	54.45	< .001**
Current interests	12.92 (5.62)	11.87 (6.15)	14.23 (3.53)	13.87 (4.91)	.27	.60
CI intensity	14.36 (3.29)	9.94 (2.23)	14.81 (3.53)	9.19 (3.58)	46.66	< .001**

Mean (SD) unless otherwise noted

**Significant to p = .01 level

SCQ Social Communication Questionnaire, *RBS-R* Repetitive Behavior Scales-Revised, *CI* circumscribed interests

Fig. 1 Examples of visual search arrays

categories. Parents were asked to rate whether they thought images were "male, female or neutral" toys or interests. Results confirmed the assigned categories (male, female or neutral) of images.

Male images included common characters (Star Wars®), building toys (Lego®) and game consoles. *Female* images included dress up toys, make up, dolls, tea sets and popular characters (Shopkins®, My Little Pony®). *Neutral* images included playground equipment, board games and gender *neutral* characters (Mickey Mouse®). As *female* toys are often more socially orientated than males (i.e. more dolls and characters), we ensured that the number of *social* images (images of characters/faces) in each category were balanced according to the ratio of the visual arrays.

Each of the picture arrays contained 24 total images. The mixture of categories within each array was determined by a set of image-type ratios designed to counter-balance the image contents of the arrays. Within each *pairing* of categories (i.e. male vs. female, male vs. neutral, female vs. neutral) the image ratios were as follows; 12:12, 12:12, 16:8, 8:16, 20:4, 4:20. This counter-balancing of ratios of image categories (male, female, neutral) across arrays was designed to minimize expectancy effects.

Eye-Tracking Procedure

Testing occurred in a single session at the (University of North Carolina at Chapel Hill). Eye-tracking data were collected using a Tobii T60XL eye tracker, which uses the Pupil Center Correction Reflection method to record eye movements from both eyes at a sampling rate of 60 Hz with spatial accuracy of approximately 0.5°. Children were tested individually, and sat either by themselves on a chair or on a cushion/booster seat to ensure a distance of approximately 60 cm from a 24″ widescreen computer monitor. Raw eye tracking data were aggregated into fixations by Tobii Studio software using a fixation criterion of gaze remaining within a radius of 30 pixels for a minimum of 100 ms, as is consistent with previous research on using visual search arrays (Sasson et al. 2008, 2011). A five-point calibration procedure was completed prior to testing and repeated until quality was high.

Children were simply told that they would see lots of pictures on the screen and could look at them however they wanted. Visual search arrays were displayed one at a time for 10 s each in a random order. Prior to each trial, a crosshair appeared at the center of the screen to reorient attention.

Data Analysis

We analyzed the same dependent variables as Sasson et al. (2008, 2011) to measure visual attention: (a) exploration (the number of unique images viewed) was quantified by tabulating the total number of different images on which the participant recorded at least one fixation; (b) perseveration (how long individual images were explored) was quantified by tabulating the total fixation time per image explored, and (c) detail orientation (the amount of detail each image was inspected) was quantified by tabulating the number of individual discrete fixations per image explored.

Analysis of visual attention between groups and sex was conducted using separate repeated measures ANOVAs on each of the three dependent variables, with image type (male, female or neutral) as the within-subject variable and group (ASD, TD) and sex (male, female) as the between group variables. Effects sizes were calculated using partial eta squared (small = 0.01; medium = 0.09; large = 0.25). All analyses controlled for CA and MA.

Results

Preliminary analysis revealed there was a main effect of diagnosis on the total percentage of time spent attending to the screen ($F = 4.38$, $p = .03$, $\eta^2 = .06$). Children in the ASD group spent less time attending to the screen overall than TD controls (90.49 vs. 95.90%) and there was considerably more variability in total attention percentage (ASD = 36–99%; TD = 74–99%.). There were no effects of sex ($F = .09$, $p = .76$) or a diagnosis × sex interaction ($F = 0.12$, $p = .73$) on total attention to the screen. Total attention to the screen was entered as a covariate for exploration, but not for perseveration or detail orientation. Perseveration controls for attention to the screen by only examining images where a fixation has been registered. Detail orientation is calculated considering total attention.

Exploration

Controlling for MA, CA and total time attending to the screen, there were no main effects of condition (image type), diagnosis or sex on the number of unique images explored (all p's > .05; Fig. 2). Despite no main sex and condition effects, there was a significant condition × sex interaction ($F = 20.41$, $p \leq .001$, $\eta^2 = .21$; Fig. 2). Post hoc analyses revealed that females across diagnoses looked at more *female* images than males ($t = -3.50$, $p \leq .001$).

Perseveration

There were no main effects of condition, diagnosis or sex on perseveration after controlling for CA and MA (all p's > .05; Fig. 3). As with exploration, there was a significant condition × sex interaction with a large effect size ($F = 26.53$, $p \leq .001$, $\eta^2 = .25$). Females perseverated more to *female* images ($t = -5.60$, $p \leq .001$) and males perseverated more to *male* images ($t = 3.65$, $p \leq .001$). There was no difference for perseveration to neutral images ($t = .89$, $p = .38$).

There was also an interaction between condition, diagnosis and sex ($F = 4.70$, $p \leq .01$, $\eta^2 = .05$). The four groups differed in their perseveration to *female* images ($F = 15.51$, $p \leq .001$). ASD females perseverated more to *female* images than both ASD males ($p = .03$) and TD males ($p = .01$), but less than TD females ($p = .008$). TD females also perseverated more to *female* images than both ASD males ($p \leq .001$) and TD males ($p \leq .001$). The groups further differed in their perseveration to *male* images ($F = 4.39$, $p = .007$). ASD males perseverated more to *male* images than ASD females ($p = .05$). TD males also perseverated more to *male* images than ASD females ($p = .04$). There were no differences in perseveration between ASD males and TD males to all image categories.

Fig. 2 Exploration by image type

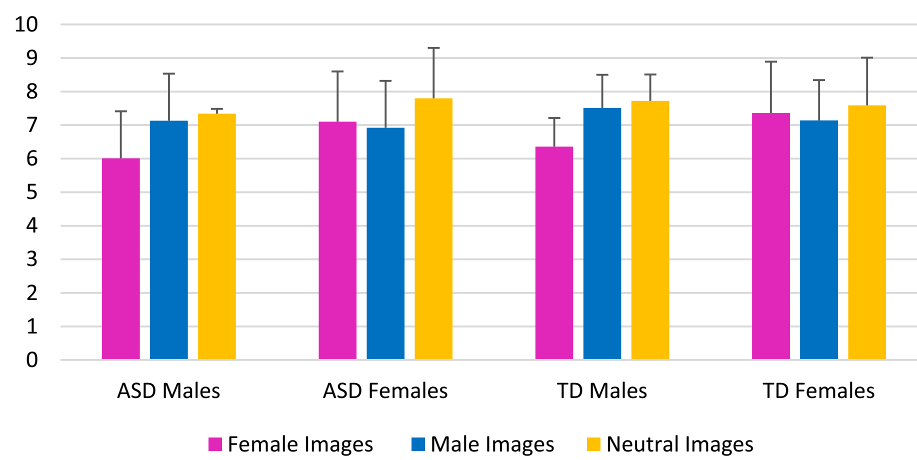
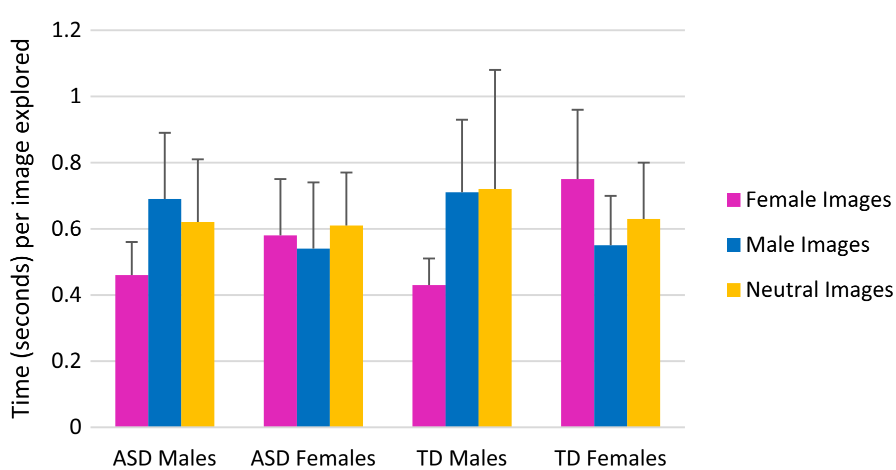


Fig. 3 Preservation by image type



Detail Orientation

There were no main effects for diagnosis for detail orientation ($p > .05$); however, there were trends toward condition ($F = 2.66$, $p = .07$, $\eta^2 = .03$) and sex effects ($F = 3.33$, $p = .07$, $\eta^2 = .04$). Males trended to be more detail oriented than females (Fig. 4) and overall subjects were more detail oriented to both male and neutral images. There was a significant condition × sex interaction with a large effect size ($F = 27.53$, $p \leq .001$, $\eta^2 = .26$). Males were more detail oriented to both *male* ($t = 4.10$, $p \leq .001$) and *neutral* images ($t = 1.97$, $p = .05$) than females.

There was also a condition × diagnosis × sex interaction ($F = 4.66$, $p \leq .01$, $\eta^2 = .06$). Post hoc analyses revealed differences in detail orientation to *male* images ($F = 5.83$, $p \leq .001$) in both the ASD and TD males. ASD males were more detail oriented than both ASD females ($p = .04$) and TD females ($p = .009$) to male images. TD males were also more detail oriented than TD females ($p \leq .01$). There were no differences between ASD and TD males.

Discussion

Previous studies have shown that children with ASD demonstrate restricted visual exploration and perseverative attention while viewing arrays containing images depicting common CI (Sasson et al. 2008, 2011). However, these studies were conducted with predominantly male samples using CI-related images of objects that are more typical of male than female interests (DeLoache et al. 2007). Given the emerging literature suggesting that differences in CI between males and females fall along traditional gender lines (Sutherland et al. 2017), the goal of the current study was to understand whether attention to *gender-typical* images differs between male and female children with and without ASD. Here, for the first time, a large sample of female children with ASD was included in a study of visual attention to CI in ASD. Across both ASD and TD groups, males and females explored a similar number of images overall and spent a similar amount of time fixating individual images. However, a number of condition by sex effects emerged, with females and males of both groups attending to a greater degree to images that corresponded with interests typically associated with their biological sex. The findings from the current study suggest that what captures the attention of ASD males and females differs and more closely aligns with gender differences observed in typical development (Caldera et al. 1989; Cherney and London 2006; DeLoache et al. 2007; Robinson and Morris 1986). Our findings of more typical attention patterns to more *gender-typical* images in ASD females is inconsistent with the EMB theory of ASD, but consistent with recent evidence of sex differences in CI in ASD (Sutherland et al. 2017; Hiller et al. 2016).

Evidence for gender-typical visual interest in ASD males and females was found across each dependent measure. First, individuals with ASD explored more images that aligned with interests common to their biological sex in typical development. Whereas for males this aligns with the EMB predictions of ASD as *male* toys are more typically associated with greater systematizing (a key construct of the EMB theory), for ASD females it suggests a deviation from ASD male peers and more alignment with TD female peers. With greater exploration and time spent attending to *female* images, attention in ASD females mirrored what was observed for TD girls in this study. This confirms the importance of considering biological sex (and gender) when studying ASD females, and calls into question the applicability of EMB theory to explain visual attention to common CI by females on the spectrum. Importantly, these effects did not extend to neutral images. Thus, the eye-tracking evidence presented here converges with findings of *gender typical* preferences observed for

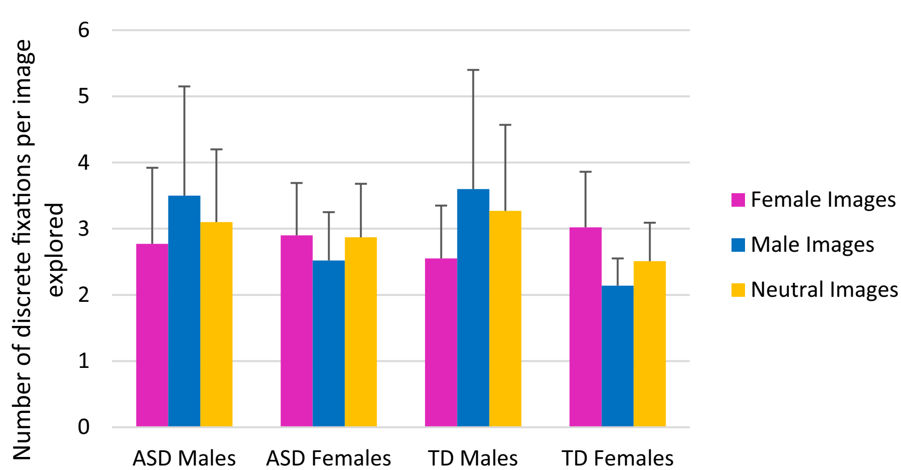


Fig. 4 Detail orientation by image group

ASD observationally (Harrop et al. 2017) and from parent report (Hiller et al. 2016; Knickmeyer et al. 2008; Sutherland et al. 2017).

Sex *typical* effects extended to perseveration, with males maintaining attention to *male* images relative to female images, with female participants demonstrating the opposite patterns. However, descriptively ASD females demonstrated similar *rates* of perseveration across image categories (Fig. 3), suggesting that they potentially did not modulate their attention across image types to the same extent as other groups. This could reflect an underlying cognitive profile in ASD females that merits further study.

While preservation and exploration aligned with images associated with biological sex in typical development, detail orientation appeared to be specific to males in our sample. Males were more detail oriented than females to *male* and *neutral* images. This heightened detail orientation did not extend to *female* images, suggesting that males modulated their detail orientation dependent on the image type and they did not inspect female images with the same level of detail as they did *male* images. This aspect of attention also differentiated ASD males and females, with ASD males demonstrating greater detail orientation on male images than both TD and ASD females. ASD females, however, never demonstrated greater detail orientation than ASD males, even on female images. This finding suggests a greater detail orientation attentional profile in ASD males than females. This is consistent with a tendency to greater systemizing tendencies posited by the EMB theory of ASD, but again this finding only applied to males and not females with ASD.

Collectively, our findings suggest that the content of experimental paradigms (eye-tracking, ERP, behavioral) needs to be considered in ASD and cannot simply assume what has produced large group effects in largely male samples will apply to ASD females. As with reports of play and CI, females with ASD attended to images most aligned with their biological sex, and biological sex interacted with condition (image type) for all indices of attention. Our data also confirm the strong existence of differences in typical development in what captures and maintains the attention of males and females, which in turn has implications for learning practices. Overall, regardless of diagnosis, images that aligned most with biological sex produced the largest differences. This may reflect sexual dimorphism in what captures the attention of males and females (irrespective of diagnosis) or a potential socialization effect.

We did not replicate the diagnostic effects observed in previous studies using a similar paradigm but with different image categories (Sasson et al. 2008, 2011). ASD males in our study were comparable to TD males on indices of attention and to similar image categories (mostly *male* images). This may have occurred for several reasons. First, the *male* images included, while overlapping somewhat with common CI, were different from those in previous studies and may have not been sufficiently salient to drive similar effects. That is, the images captured our ASD males' attention to the same degree as TD males, but the inclusion of *high autism interest* objects may have differentiated our ASD males further, replicating previous findings of circumscribed attention in (mostly male) ASD samples. Second, the power to detect effects between the ASD and TD groups may have been reduced by our inclusion of biological sex as a between-groups variable in addition to clinical diagnosis, as previous studies using a similar paradigm collapsed across sex and only included diagnosis as a between-group variable examined. Finally, differences in sample characteristics and methodology may have affected comparability between studies.

These findings also have implications for the appropriateness of gold-standard diagnostic measures and how we approach interventions with females on the autism spectrum. A number of diagnostic tools and screening instruments utilize items such as dolls and ask questions about engagement with make believe toys. Such questions may mask the appearance of CI in females as they may not align with preconceived assumptions of ASD (Lai et al. 2015) and contribute to the possibility of under diagnosing females with autism (Dean et al. 2017; Dworzynski et al. 2012; Frazier et al. 2014). Further, perseverative play is a diagnostic symptom often observed in ASD and might be less discernable in females during the diagnostic process using toys included within assessments that may more sensitively elicit this behavior in ASD males. Therefore, diagnostic and screening processes that utilize toys within assessments and infer symptoms should consider using sex-neutral, or sex-specific toys to minimize the chances that males and females will perform differently based upon motivational factors related to items used. Further, as CI have been utilized within ASD intervention to encourage motivation and have led to a number of positive outcomes (Koegel et al. 2012; Legoff and Sherman 2006; Vismara and Lyons 2016), CI selected should not be general (e.g. trains and Lego) as the focus of male and female interests may produce differential outcomes within these intervention models.

While our findings suggest greater motivation in ASD females to images aligning with their own gender, a recent study of ASD adults reported elevated affective responses to images of CI by adults with ASD (Sasson et al. 2012). The greatest effects were found for ASD females, despite the more *male* focus of the images. Thus, the content and engagement with CI may change with development in ASD females and may reflect more commonly observed CI with time and experience pointing to the need for longitudinal studies of ASD females.

Overall, our condition × sex effects were stronger for *female* images (and therefore ASD and TD females) than those for male and neutral objects. Females with ASD explored and perseverated more on female images than males with ASD. While the study design ensured that male and female images included the same number of faces/characters to minimize the chances that social content of the images drove these effects, it remains a possibility that female images represented more socially-relevant interests and activities than male images. For instance, although containing no explicit social content, tea sets are typically interacted with socially (with a real or imagined playmate). Thus, greater preference for female images by ASD females may reflect greater social motivation relative to their male counterparts that has been reflected in other studies (Sedgewick et al. 2016) and contribute to greater social camouflage reported in ASD females (Dean et al. 2017; Head et al. 2014).

Limitations

As subjects in our study did not view the original arrays including common CI-related images (Sasson et al. 2008, 2011), we cannot conclude that ASD females would not attend similarly to what has been reported previously for majority ASD male samples (i.e. more focused attention to images such as road signs, trains and electronics). Based on parent report data (Sutherland et al. 2017; Hiller et al. 2016), we designed our paradigm as a test of *typical* sex differences. However, future research should embed CI-related images and personalized images within *gendered* arrays to see whether the effects of CI or gender are stronger and whether previous diagnostic effects emerge particularly for ASD males (Sasson et al. 2008, 2011).

Prior to developing our paradigm, we surveyed parents of TD children to confirm the group membership (male, female or neutral) of a random selection of our images. However, our survey was small and there is potential that some biases could exist. For example, parents from different racial/ethnic, cultural and SES backgrounds may rate images differently. We also did not gather information about the familiarity with toys included in our arrays. Further, there were a number of images that could represent *trends* at the time of data collection, such as Pokemon Go® and Frozen®.

As the eye-tracking task was a brief passive-viewing task, this study required minimal cognitive demands therefore we did not specifically match on MA. This decision was made due to the difficulty in recruiting ASD females and wanting to recruit a larger than typical sample of ASD females. Specifically, males with ASD in our study had a higher MA than females with ASD. This difference was expected given reports of higher-functioning females being diagnosed later and the presence of co-occurring intellectual disability being a factor in ASD diagnoses for females (Dworzynski et al. 2012). While we co-varied MA and CA to control for differences in functioning, a strategy consistent with previous eye-tracking studies of ASD (Chevallier et al. 2015; Fletcher-Watson et al. 2009; Sasson and Touchstone 2014), it is possible that both higher functioning males and females may be more successful and motivated at engaging with more *typical* interests, such as those aligning with their biological sex. These effects may not be observed to the same degree in lower functioning children. Future studies are encouraged to explore whether patterns reported here vary a function of MA in males and females with ASD and more tightly match samples. Finally, although the sample size of females with ASD is a notable strength of our study, our sample of TD controls was relatively small. The control groups were identical in size to one another (N = 16), but smaller than our ASD groups, and this discrepancy may have affected the power to detect effects of clinical status.

Conclusions

Across multiple measures of visual attention, ASD and TD females in this study explored more *female* images and spent more time attending to these, whereas ASD and TD males explored more *male* images, spent more time attending to these and were also more detail oriented to *male* and *neutral* images. Collectively, results suggest sex differences in visual attention in ASD that align with sex-typical patterns. These findings are inconsistent with the EMB theory of autism that would predict a more male visual profile of attention in females with ASD, and highlight the importance of considering what is *typical* when researching, diagnosing, and treating ASD females.

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Compliance with Ethical Standards

Conflict of interest CH has received research grants from North Carolina Translational and Clinical Sciences (NC TraCS) and Autism Science Foundation. BB has received research grants from the Eunice Kennedy Shriver National Institute of Child Health & Human Development. All authors declare no conflicts of interests.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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