2016

Under-reactive but easily distracted: An fMRI investigation of attentional capture in autism spectrum disorder

Brandon Keehn
Purdue University, Speech, Lanuage and Hearing Sciences, bkeehn@purdue.edu

Aarti K N Nair
San Diego State University, Joint Doctoral Program in Clinical Psychology, San Diego, United States

Alan J. Lincoln
Alliant International University, Department of Clinical Psychology, San Diego, United States

Jeanne Townsend
University of California, San Diego, Department of Neuroscience, San Diego, United States

Ralph Axel Müller
San Diego State University, Department of Psychology, San Diego, United States

Recommended Citation

Keehn, B., Nair, A., Lincoln, A.J., Townsend, J., Müller, R.-A. Under-reactive but easily distracted: An fMRI investigation of attentional capture in autism spectrum disorder. Developmental Cognitive Neuroscience Volume 17, 1 February 2016, Pages 46-56 http://dx.doi.org/10.1016/j.dcn.2015.12.002

Developmental Cognitive Neuroscience 17 (2016) 46–56

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: http://www.elsevier.com/locate/dcn

Under-reactive but easily distracted: An fMRI investigation of attentional capture in autism spectrum disorder

Brandon Keehn[a,b,c,d,*], Aarti Nair[c], Alan J. Lincoln[e], Jeanne Townsend[d], Ralph-Axel Müller[c]

[a] Department of Speech, Language, and Hearing Sciences, Purdue University, West Lafayette, IN, USA
[b] Department of Psychological Sciences, Purdue University, West Lafayette, IN, USA
[c] Brain Development Imaging Laboratory, Department of Psychology, San Diego State University, San Diego, CA, USA
[d] Research on Autism and Development Lab, Department of Neurosciences, University of California, San Diego, San Diego, CA, USA
[e] Alliant International University, San Diego, CA, USA

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 2 December 2015
Accepted 2 December 2015
Available online 7 December 2015

Keywords:
Autism
Attention
fMRI

ABSTRACT

For individuals with autism spectrum disorder (ASD), salient behaviorally-relevant information often fails to capture attention, while subtle behaviorally-irrelevant details commonly induce a state of distraction. The present study used functional magnetic resonance imaging (fMRI) to investigate the neurocognitive networks underlying attentional capture in sixteen high-functioning children and adolescents with ASD and twenty-one typically developing (TD) individuals. Participants completed a rapid serial visual presentation paradigm designed to investigate activation of attentional networks to behaviorally-relevant targets and contingent attention capture by task-irrelevant distractors. In individuals with ASD, target stimuli failed to trigger bottom-up activation of the ventral attentional network and the cerebellum. Additionally, the ASD group showed no differences in behavior or occipital activation associated with contingent attentional capture. Rather, results suggest that to-be-ignored distractors that shared either task-relevant or irrelevant features captured attention in ASD. Results indicate that individuals with ASD may be under-reactive to behaviorally-relevant stimuli, unable to filter irrelevant information, and that both top-down and bottom-up attention networks function atypically in ASD. Lastly, deficits in target-related processing were associated with autism symptomatology, providing further support for the hypothesis that non-social attentional processes and their neurofunctional underpinnings may play a significant role in the development of sociocommunicative impairments in ASD.

1. Introduction

Individuals with autism spectrum disorder (ASD) often fail to attend to *salient* behaviorally-relevant information in their environment (e.g., their name being called or a person entering a room), but oddly may appear to be distracted by *subtle* behaviorally-irrelevant details within their surroundings (e.g., light shining through blinds, air flowing through a duct). Various empirical accounts of attention in ASD have described individuals as both over-focused and yet easily distracted. Previous studies have shown increased distractibility and an inability to filter irrelevant information in ASD (Burack, 1994; Murphy et al., 2014), which may be due, in part, to increased perceptual capacity (Ohta et al., 2012; Remington et al., 2009, 2012). On the other hand, prior research has also demonstrated that individuals with ASD are atypically over-focused (Liss et al., 2006; Lovaas et al., 1979), which may be linked to a narrower attentional spotlight (Robertson et al., 2013; Townsend and Courchesne, 1994) and deficits in increasing the breadth of attention (Mann and Walker, 2003; Ronconi et al., 2013). The existence of these two paradoxical states in individuals with ASD – over-focused, yet susceptible to distraction – may be the result of dysfunctional modulation and interaction of attentional networks (Fan et al., 2012).

Attentional selection may be directed based on the desires or goals of the individual (i.e. top-down control) or can be driven by salient information within the environment (i.e. bottom-up modulation). Adaptive allocation of attention rarely consists of exclusively top-down or bottom-up mechanisms; rather,

* Corresponding author at: Department of Speech, Language, and Hearing Sciences, 715 Clinic Drive, Lyles-Porter Hall, West Lafayette, IN 47907, USA. Tel.: +1 765 496 0204.
E-mail address: bkeehn@purdue.edu (B. Keehn).

http://dx.doi.org/10.1016/j.dcn.2015.12.002

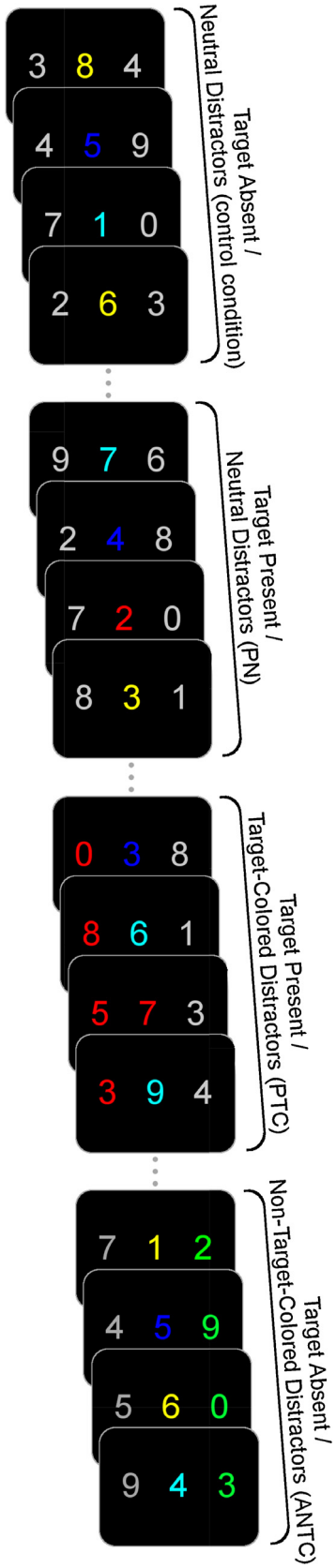

Fig. 1. Example of experimental trials. Each trial lasted 480 ms and consisted of four iterations of simultaneously varying numbers (120 ms per iteration; no ISI between trials). Dots ("...") indicate presentation of control trials that separated target present and absent conditions. The target present non-target colored condition (PNTC) is not displayed, but is identical to target present target-colored condition (PTC) with the exception that peripheral distractors were green. Likewise, the target absent target-colored (ATC) is not displayed, but identical to the target absent non-target-colored condition (ANTC), except that peripheral distractors were red. Note: target and non-target colored distractors appeared equally in either left or right peripheral stream. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

successful attentional selection requires the integration of these two processes. For example, a child's attention may be directed at a person entering a room on the basis of bottom-up modulation of attention; however, the child's attention may be more likely to be captured by the new person if they are expecting guests or it is the time of day when their parents arrive to pick them up from school (i.e., based on the top-down expectations). Contingent attentional capture, as when a stimulus-driven shift of attention is contingent upon on a pre-existing top-down attentional setting, is one such example of a combination of top-down and bottom-up systems (Folk et al., 1992). Thus, this form of attentional orienting may provide insight into top-down and bottom-up processes, as well as the interaction between these neurocognitive networks.

Corbetta and colleagues (2008; 2002) have proposed that two distinct networks underlie top-down and bottom-up modulation of attention; a bilateral dorsal frontal-parietal network, which includes frontal eye fields (FEF) and intraparietal sulci (IPS) and is responsible for voluntary control of attention, and a right-lateralized ventral frontal-parietal network, which includes ventral frontal cortex (VFC)/anterior insula (AI), middle frontal gyrus (MFG), and temporal parietal junction (TPJ) and is responsible for behavioral re-orienting of attention on the basis of bottom-up information. fMRI studies investigating the developmental differences in the activation (Konrad et al., 2005) and connectivity (Farrant and Uddin, 2015a) of these networks in typically developing (TD) children (7–12 years old) and adults have shown that these regions undergo continued maturation into adolescence and adulthood, with patterns of hyper- and hypo-connectivity varying according to age in children and adults with ASD (Farrant and Uddin, 2015b).

Studies examining these networks in adults have demonstrated that behaviorally-relevant stimuli (e.g., a target/deviant in oddball paradigm) result in activation of ventral, and to a lesser extent dorsal, attentional networks (Kim, 2014), reflecting detection of salient, environmental changes. Previous functional magnetic resonance imaging (fMRI) studies have also demonstrated that contingent attentional capture by task-irrelevant stimuli results in increased activation of both networks and, further, results in enhanced activation of visual cortex for irrelevant information that shares task-relevant features (Serences et al., 2005). In their task, Serences et al. (2005) had participants view three streams of continuously changing letters of varied colors and instructed them to attend only to the central stream (see Fig. 1). The task was to respond only to red letters (which appeared infrequently) within the central stream. Letters in the to-be-ignored peripheral distractor streams most frequently appeared in gray; however, occasionally, peripheral distractors were either target-colored (red) or a unique, non-target color (green; a color not included in the central stream). Behavioral and neuroimaging results of their study showed evidence of attentional capture by the target-colored, but not the non-target-colored distractors (i.e., contingent attentional capture), and engagement of both dorsal and ventral attentional networks. Importantly, the task design permitted analysis of peripheral distractors in the absence of any target-related processing (isolated activation due solely to appearance of to-be-ignored information).

In the present study, we employed a modified version of the rapid serial visual presentation (RSVP) paradigm by Serences et al. (2005) to investigate activation of dorsal and ventral attentional

Table 1
Participant characteristics.

	ASD ($n = 16$)	TD ($n = 21$)	t-value	p
Age (years)	14.2 (1); 12–17	14.3 (1); 12–17	−.09	.9
Verbal IQ	112 (17); 83–147	106 (10); 87–126	1.34	.1
Nonverbal IQ	112 (14); 84–140	107 (11); 88–129	1.06	.2
Total motion	.31 (.26); .01–.84	.22 (.18); .01–.64	1.31	.1
Percentage censored	.06 (.08); 0–.22	.05 (.07); 0–.24	−.66	.5
SRS total score	77 (10); 57–94	42 (5); 35–52	14.4	<.001
ADOS				
Communication	3 (1); 0–5	–	–	–
Social interaction	8 (3); 3–13	–	–	–
Repetitive behavior	2 (2); 0–5	–	–	–

IQ determined using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999).

networks and capture-related activity in visual cortex in a group of children and adolescents with ASD. The goal of the current study was three-fold: first, we sought to investigate target-related processing (in the absence of colored distractors) in ASD. Based on previous fMRI and event-related potential (ERP) studies we hypothesized that individuals with ASD would show atypically reduced activation in regions of both dorsal and ventral attentional networks. Our second goal was to investigate attention capture by irrelevant information as a function of whether that information shares characteristics with attentional set. Given evidence of either over-focused or distractible states reviewed above, three potential outcomes were possible: (1) Over-focused attention would result in limited attentional capture by irrelevant distractors regardless of task-relevance (e.g., Liss et al., 2006); (2) alternatively, over-focused attention might engender enhanced capture of distractors that share a target-defining feature (i.e., enhanced top-down processing); (3) conversely, inability to filter irrelevant information could result in capture by irrelevant distractors regardless of task relevance (e.g., Murphy et al., 2014). Lastly, because links between non-social attentional impairments and social deficits in ASD have been reported (Fan et al., 2012; Keehn and Joseph, 2008; Keehn et al., 2010), we investigated the association between ASD symptomatology and behavioral and neural indices of target-related processing and attentional capture to further determine how attentional dysfunction may be linked to sociocommunicative impairments in children and adolescents with ASD.

2. Methods

2.1. Participants

A total of 19 high-functioning children and adolescents with ASD and 23 TD children and adolescents participated in the present study; two children with ASD were excluded due to excessive motion (see below), one due to extreme outlier for error rates (greater than 3 × inter-quartile range), and two TD participants were excluded due to equipment malfunction. Thus, the final sample included sixteen individuals with ASD (two females; one left-handed) and 21 age-, nonverbal IQ-, and motion-matched TD children and adolescents (5 females; 3 left-handed) (see Table 1). Clinical diagnoses were confirmed using the Autism Diagnostic Interview-Revised (ADI-R; Rutter et al., 2003), the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 1999), and expert clinical judgment (AJL) according to DSM-IV criteria. Individuals with ASD-related medical conditions (e.g., Fragile-X syndrome, tuberous sclerosis) were excluded. Participants in the TD group had no reported personal or family history of autism and were confirmed via parent report to be free of ASD-related symptoms or any other neurological or psychiatric conditions. Normal color vision had been confirmed for all participants prior to induction using the Ishihara Tests for Colour Deficiency (Ishihara, 1999). Informed assent and consent was obtained from all participants and their caregivers in accordance with the University of California, San Diego and San Diego State University Institutional Review Boards.

Table 2
Outline of target absent and present conditions for each distractor type.

	Peripheral distractor color		
	Gray (N)	Red (TC)	Green (NTC)
Target absent	Control trials (92%)	Absent target-colored (ATC; 1.6%)	Absent non-target-colored (ANTC; 1.6%)
Target present	Present neutral (PN; 1.6%)	Present target-colored (PTC; 1.6%)	Present non-target-colored (PNTC; 1.6%)

Percentage of trials listed in parentheses.

2.2. Task

The experiment was presented using Presentation software (http://www.neurobs.com). Stimuli were projected onto a screen placed at participants' feet and were viewed using a mirror attached to the head coil. The paradigm was a modified version of a task used by Serences et al., (2005) (see Fig. 1), including numbers instead of letters (to simplify the task for younger participants). Stimuli included three streams of simultaneously varying numbers (0–9). The task was to identify red numbers appearing in a central stream of colored (blue, yellow, teal) numbers. Participants were instructed to look only at the central stream and responded with their dominant-hand, using a two-choice button-box, pressing the left button if the target (red number) was low (0–4) or the right button if the target was high (5–9). Digits presented in the peripheral streams were gray in most trials (see Table 2 for trial type percentages); colored distractors appeared infrequently in either the left or right peripheral streams and were either the same color as the target (TC; red) or a non-target color that never appeared in the center stream (NTC; green). For each trial these three numbers (central and two peripheral distractors) were presented in a series of four unique iterations (480 ms total, 120 ms per iteration; no ISI between trials). On target present trials, a red number occurred in the center stream on the third iteration with or without the appearance of target- and non-target-colored peripheral distractors (which appeared at the onset of the trial). For target absent trials, no red number appeared in the center stream with the appearance of either target- or non-target-colored peripheral distractors. Lastly, control trials consisted of target absent trials in which gray peripheral distractor appeared.

Digits subtended approximately 1° by 1.3° visual angle and peripheral streams were located at 5.1° to the left and right of the central stream. Target present neutral (PN), present target-colored (PTC), and present non-target-colored (PNTC) and target absent target-colored (ATC), absent non-target-colored ANTC) trials were separated by 2.88 to 12 s during which control trials were presented. For behavioral data analysis, only responses occurring between 200 and 2400 ms after target present trials were included. Participants completed four 6-minute runs, each with 12 trials for each condition (PN, PTC, PNTC, ATC, and ANTC; 60 total) and 690 null trials. Within each run, trial types were presented in an optimized pseudorandom sequence created using RSFgen (http://

afni.nimh.nih.gov). Participants were instructed to respond as quickly as possible without making errors.

To ensure that any group differences in accuracy were not due to general impairments in number processing, participants also completed a baseline number task outside the scanner after the scanning session. The task consisted of one block of 60 trials. For each trial, a single gray number (0–9) was displayed in the center of the screen and remained onscreen until the participant responded. Similar to the primary experimental task, participants responded via a dominant-hand, two-choice, button-box response as to whether the number was between 0 and 4 or 5 and 9 (left button ≤4; right button ≥5) and were instructed to respond as quickly as possible without making errors.

2.3. MRI acquisition

Data were acquired using a GE 3Tesla MR750 scanner with an 8-channel head coil. High-resolution anatomical images were acquired using a standard FSPGR T_1-weighted sequence (256 × 256 matrix; 180 slices; 1 mm^3 resolution). Four functional runs each consisting of 180 whole-brain volumes acquired in 42 interleaved slices using a single-shot, gradient-recalled, echo-planar pulse sequence (TR: 2000 ms; TE: 30 ms; flip angle: 90°; 64 × 64 matrix; 3.4 mm slice thickness; in-plane resolution 3.438 mm^2). The field map was acquired using a gradient recalled acquisition in steady state (GRASS) sequence (TE1 = 6.5 ms, TE2 = 8.5 ms) with the same resolution and slice locations as the functional data. Participants' heads were stabilized with foam padding to reduce motion.

2.4. fMRI preprocessing

Data were analyzed using the Analysis of Functional Neuroimages suite (AFNI; Cox, 1996). Visual inspection and quality control (3dToutcount, 3dTqual) of each run were completed. Data were then slice-time corrected, realigned to the middle time point of the first run, and co-registered to the anatomical volume using a single transformation matrix (epi_align_anat.py). To correct distortions due to magnetic field inhomogeneties data were field-map corrected. Data were then smoothed with a Gaussian filter to an effective full-width at half maximum of 6 mm (3dBlurToFWHM), scaled to a mean of 100 (3dcalc), and concatenated (3dTcat) to create a single time-series with 720 vol.

In order to control for head motion, the first temporal derivative for the six motion parameters (3 rotations, 3 translations) was calculated and the magnitude of displacement (D_t) was computed as the root sum of squares for each of the 720 time points (Jones et al., 2010). Time points with excessive head motion ($D_t > 1$; roughly equivalent to 1 mm when rotational displacement is small) as well as the immediately preceding and following time points were censored. Additionally, if fewer than five time points remained between two censored time points, these were excluded as well. Finally, the root mean square of displacement magnitudes across the entire time series was calculated as an estimate of total motion in each participant. Any participant with greater than 25% of their data removed on the basis of the criteria described above was excluded from the present study.

2.5. fMRI analysis

The hemodynamic impulse response function (IRF) for each stimulus type (PN, PTC left, PTC right, PNTC left, PNTC right, ATC left, ATC right, ANTC left, and ANTC right) was estimated using a general linear model. Variable-shape IRFs for each stimulus type were estimated using piecewise linear B-spline (tent) basis functions (Saad et al., 2006). Seven tent functions were used to model the response from the onset of the trial for each stimulus type and at each of the next six time points (0–12 s post stimulus onset). The six motion parameters corresponding to translation and rotation were used as orthogonal regressors. Statistical maps for each stimulus type were computed as the sum of the fit coefficients for three time points occurring within 2–6 s, corresponding to the peak hemodynamic response. Statistical maps were interpolated to 3 mm^3 isotropic voxels and spatially normalized to the structural volume, which had been standardized to the N27 Talairach-Tournoux template using AFNI auto-Talairach procedures.

The current study focused on target-related processing and contingent attentional capture. Activation for the target present neutral (PN) condition was of particular interest as this condition allowed us to examine target-related processes in the absence of colored distractors. Additionally, target absent conditions were used to examine contingent attentional capture in the absence of target- and response-related processes. One-sample *t*-tests (3dttest) were used to assess within-group differences for target present neutral and target absent TC–NTC contrasts. Two-sample independent *t*-tests were used to compare groups. All statistic maps were corrected for multiple comparisons to a cluster corrected threshold of $p < .05$ (voxel-wise uncorrected $p < .01$; 39 contiguous voxels), using Monte Carlo simulation (Forman et al., 1995). In addition to whole-brain analysis, a separate region of interest (ROI) analysis was conducted using previously defined areas of activation from Serences et al. (2005) (see Supplementary Material).

3. Results

3.1. Behavioral

3.1.1. Baseline

Error rates and median RT for correct trials were entered into a 2 (group: ASD, TD) × 2 (number: ≤4, ≥5) mixed-model repeated-measures ANOVA. Four individuals did not complete the baseline task (ASD = 2; TD = 2). For error rate there was no significant main of group (ASD = 5%, TD = 4%), $F(1, 31) = 1.1$, $p > .05$, $\eta_p^2 = .04$, nor a significant number × group interaction, $F(1, 31) = .23$, $p > .05$, $\eta_p^2 = .01$. Likewise for RT, there was no main effect of group (ASD = 629 ms; TD = 586 ms), $F(1, 31) = .96$, $p > .05$, $\eta_p^2 = .04$, nor a significant number × group interaction, $F(1, 31) = .21$, $p > .05$, $\eta_p^2 = .01$, suggesting that there was no group differences in numerical processing.

3.1.2. Error rate

Mean error rates and median response times (RT) for correct target present trials were entered into a 2 (group: ASD, TD) × 3 (distractor type: neutral, TC, NTC) mixed-model repeated measures ANOVA. There was no significant main effect of group, $F(1, 35) = 2.0$, $p > .05$, $\eta_p^2 = .05$, or distractor type, $F(2, 70) = 1.6$, $p > .05$, $\eta_p^2 = .05$, nor was there a significant interaction between group and distractor type, $F(2, 70) = .7$, $p > .05$, $\eta_p^2 = .02$ (see Fig. 2). As our design was not fully factorial (i.e., the neutral condition did not include distractors), we conducted a separate 2 (group: ASD, TD) × 2 (distractor type: TC, NTC) × 2 (distractor location: left, right) mixed-model repeated measures ANOVA. There was a trend toward a significant main effect of distractor type, $F(1, 35) = 3.8$, $p = .06$, $\eta_p^2 = .1$, reflecting increased error rates for the TC compared to the NTC condition across both groups. However, there was no main effect of group, nor were there any significant interactions between group and any other factor (all $p > .1$). In addition, a separate ANCOVA was conducted with IQ as a covariate. Similar to original analysis there was no significant interaction between group and distractor type. However, there was now a significant main effect of group, $F(1, 34) = 7.1$, $p < .05$, $\eta_p^2 = .17$, reflecting increased error rates in individuals with ASD.

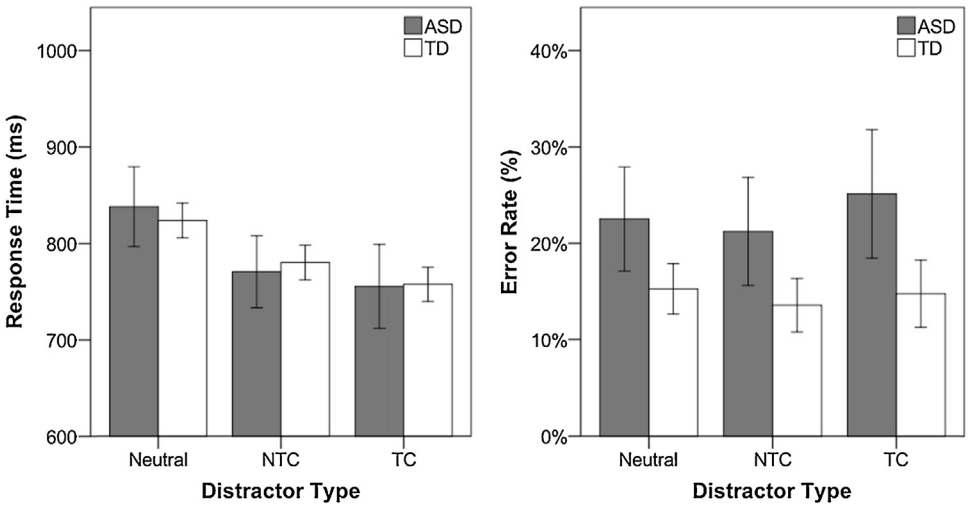

Fig. 2. Mean RT (left graph) and error rate (right graph) for ASD (gray) and TD (white) groups.

3.1.3. Response time

There was no difference in RT between groups, $F(1, 35) = .00$, $p > .05$, $\eta_p^2 = .00$, nor was there a significant interaction between group and distractor type, $F(2, 70) = .9$, $p > .05$, $\eta_p^2 = .03$ (these results remain unchanged when IQ was entered as a covariate). There was a significant main effect of distractor type, $F(2,70) = 35.7$, $p < .001$, $\eta_p^2 = .51$. Post-hoc comparisons for all participants revealed that responses to neutral stimuli were significantly slower than both responses to TC and NTC distractors, and responses to NTC were significantly slower than TC distractors (all $p < .05$). Faster RT for TC and NTC compared to neutral condition and faster TC compared to NTC responses suggests that peripheral distractors captured attention and that TC distractors facilitated responses (i.e., cued participants to potential target appearance) to a greater degree than NTC distractors. Separate exploratory paired *t*-tests for ASD and TD groups showed that TC RT was faster than NTC for the TD group, $t(20) = -2.7$, $p < .05$, $d = .59$, but not the ASD group, $t(15) = -.94$, $p > .05$, $d = .26$. Independent-samples *t*-tests revealed that the groups did not differ in RT for TC, NTC, or the neutral conditions (all $p > .7$).

3.2. fMRI

Analysis of functional imaging data examined target-related processing in the absence of TC and NTC peripheral distractors (i.e., PN versus control condition) and distractor-related processing in the absence of target- and response-related processes (i.e., ATC versus ANTC condition). Of particular interest in the target absent trials was the TC versus NTC comparison, for which greater TC compared to NTC activation is associated with contingent attentional capture.

3.2.1. Target-related activation

As illustrated in Fig. 3, TD participants exhibited activation in both dorsal and ventral networks as well as response-related motor activation, consistent with a pattern previously reported for other

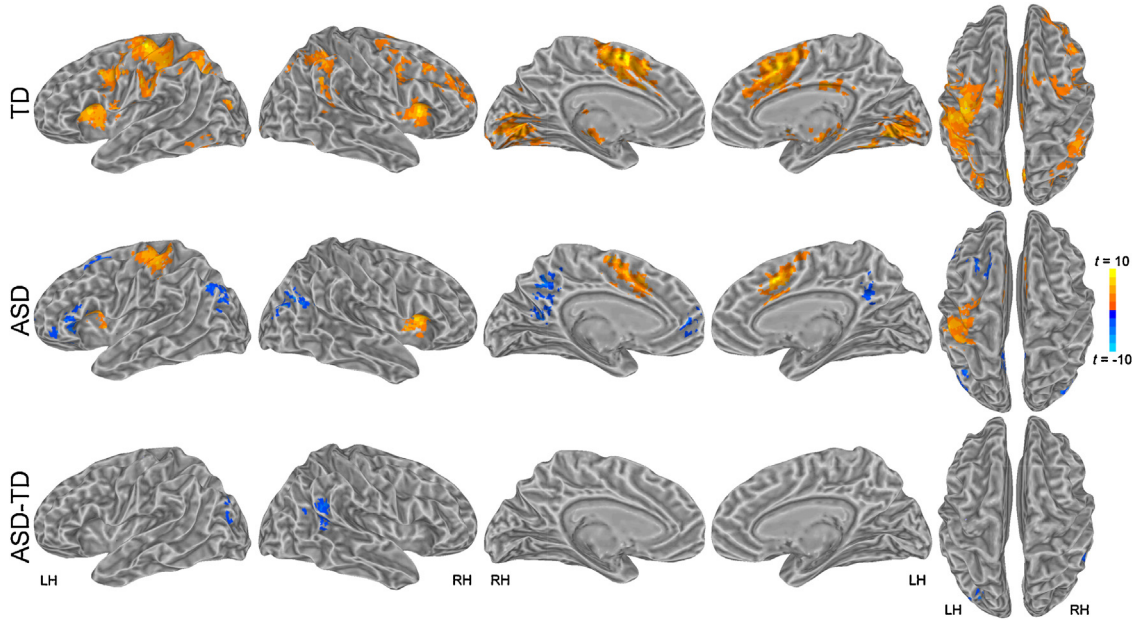

Fig. 3. Activation for the target present neutral condition (PN) for typically developing group (top row), the ASD group (middle row), and the ASD–TD contrast (bottom row; clusters correspond regions of TD > ASD activation).

Table 3
Significant clusters for target present neutral trials for ASD and TD groups.

Group	Peak location	Hemi-sphere	Talairach coordinates			Volume (voxels)	*t*-score
			x	*y*	*z*		
ASD	Postcentral gyrus	L	−47	−26	54	415	7.06
	Middle cingulate gyrus	R	8	11	39	329	9.18
	Precuneus	L	−8	−56	36	194	−5.75
	Insula	R	32	17	12	127	7.60
	Inferior frontal gyrus	L	−41	29	3	89	−5.17
	Middle occipital gyrus	R	41	−71	24	84	−6.83
	Angular gyrus	L	−41	−65	33	81	−5.42
	Superior frontal gyrus	L	−17	11	51	67	−6.56
	Anterior cingulate gyrus	L	−8	50	9	52	−4.21
	Insula	L	−29	8	18	41	5.36
TD	Supplementary motor area	L	−5	2	51	2220	10.31
	Fusiform gyrus	R	26	−53	−16	1636	7.28
	Insula	L	−29	17	12	713	7.08
	Insula	R	32	17	9	390	8.01
	Middle frontal gyrus	R	41	32	36	285	5.89
	Intraparietal sulcus	R	44	−38	42	282	6.15
	Middle frontal gyrus	R	50	8	39	187	5.26
	Parahippocampal gyrus	R	20	−29	−4	55	4.60
	Angular gyrus	R	47	−47	27	50	4.67
	Middle cingulate cortex	R	8	−20	30	42	5.74
ASD < TD	Cerebellar vermis	L	−2	−41	−22	105	−4.41
	Superior temporal gyrus	R	50	−47	21	76	−5.40
	Cerebellum	L	−8	−50	−40	70	−4.70
	Middle occipital gyrus	L	−29	−74	21	47	−4.25

'odd-ball style' tasks (Kim, 2014). These regions included areas of the right-lateralized ventral network (temporal-parietal junction (rTPJ), middle and inferior frontal gyri, insula) and of bilateral dorsal network regions (i.e., frontal eye fields [FEF] and intraparietal sulci [IPS]; see Table 3). Individuals with ASD showed less robust target-related activation compared to TD participants, as well as areas of significant deactivation. Between-group comparison revealed areas of significantly reduced activation in the ASD group in the rTPJ, middle occipital gyrus, and cerebellum.

3.2.2. Contingent attentional capture in target absent trials

For target absent trials, neither TD nor ASD group showed any significant effects for the TC–NTC comparison; however, patterns of activation for both groups combined at uncorrected threshold (Supplementary Fig. 1) were similar to those reported by Serences et al. (2005). Between-group comparison, which reached cluster-correct threshold, revealed significantly greater activation in right inferior frontal gyrus and inferior parietal lobe for the ASD group (Fig. 4, Table 4).

To examine extrastriate activity associated with contingent attentional capture (similar to Serences et al., 2005), ROIs were defined within the visual cortex based on activation for both TC and NTC target absent trials. Two spherical ROIs (6 mm radius) were selected from peaks within significant activation clusters derived from an analysis of combined ASD and TD activation map for target absent condition (Fig. 5a).

Mean fit coefficients within ROIs for target absent trials were entered into a 2 (group: ASD, TD) × 2 (hemisphere: left, right) × 2 (distractor type: TC, NTC) × 2 (distractor location: left, right) mixed-model repeated measures ANOVA. Activation was significantly greater for TC compared to NTC distractors, $F(1, 35) = 4.7$, $p < .05$, $\eta_p^2 = .12$. There was also a significant 2-way hemisphere by distractor location and a 3-way hemisphere by distractor type by distractor location interactions (all $p > .05$). To further examine the significant 3-way interaction, contralateral (e.g., left target, right hemisphere) and ipsilateral (e.g., left target, left hemisphere) variables were created for TC and NTC distractors. Peripheral distractors resulted in increased activation in the contralateral hemisphere for both TC, $t(36) = 8.4$, $p < .001$, $d = 1.4$, and NTC, $t(36) = 4.2$, $p < .001$, $d = .7$, conditions. Importantly, similar to Serences et al. (2005), increased activation for TC compared to NTC distractors for contralateral, $t(36) = 3.9$, $p < .001$, $d = .64$, but not ipsilateral hemisphere, $t(36) = -.1$, $p > .05$, $d = .01$, was found, indicating that TC peripheral distractors captured attention.

Activation in visual ROIs did not differ in ASD and TD groups, $F(1, 35) = 1.3$, $p > .05$, $\eta_p^2 = .04$. However, there was a significant group by hemisphere by distractor location interaction, $F(1, 35) = 6.1$, $p < .05$, $\eta_p^2 = .15$, and marginally significant 4-way interaction between group, hemisphere, and distractor type and location, $F(1, 35) = 3.2$, $p = .08$, $\eta_p^2 = .08$. As illustrated in Fig. 5c, ASD and TD groups both showed contralateral > ipsilateral effects for both TC and NTC conditions (all $p < .052$); however, only the TD group evidenced increased TC compared to NTC activation for contralateral targets, $t(20) = 4.0$, $p < .01$, $d = .88$, whereas the ASD did not, $t(15) = 1.8$, $p > .05$, $d = .44$, suggesting that TC distractors did not uniquely capture attention in children and adolescents with ASD. Further, independent-samples *t*-tests showed no difference in activation for TC ipsilateral, $t(35) = 1.1$, $p > .05$, $d = .35$, NTC contralateral, $t(35) = -1.3$, $p > .05$, $d = .45$, or NTC ipsilateral, $t(35) = -.77$, $p > .05$, $d = .25$, between groups; however activation for TC contralateral was marginally reduced in ASD, $t(35) = -1.8$, $p = .09$, $d = .59$.

3.3. Relationship with ASD symptomatology

The ADOS was used to assess symptom severity in individuals with ASD. The ADOS involves a series of experimenter-administered social occasions and "presses" designed to provide quantitative observational ratings of communicative and social behaviors. Summary scores for the diagnostic algorithm for Communication, Social, and Communication and Social domains were used as ADOS symptom measures; higher ADOS scores reflect increased symptom severity.

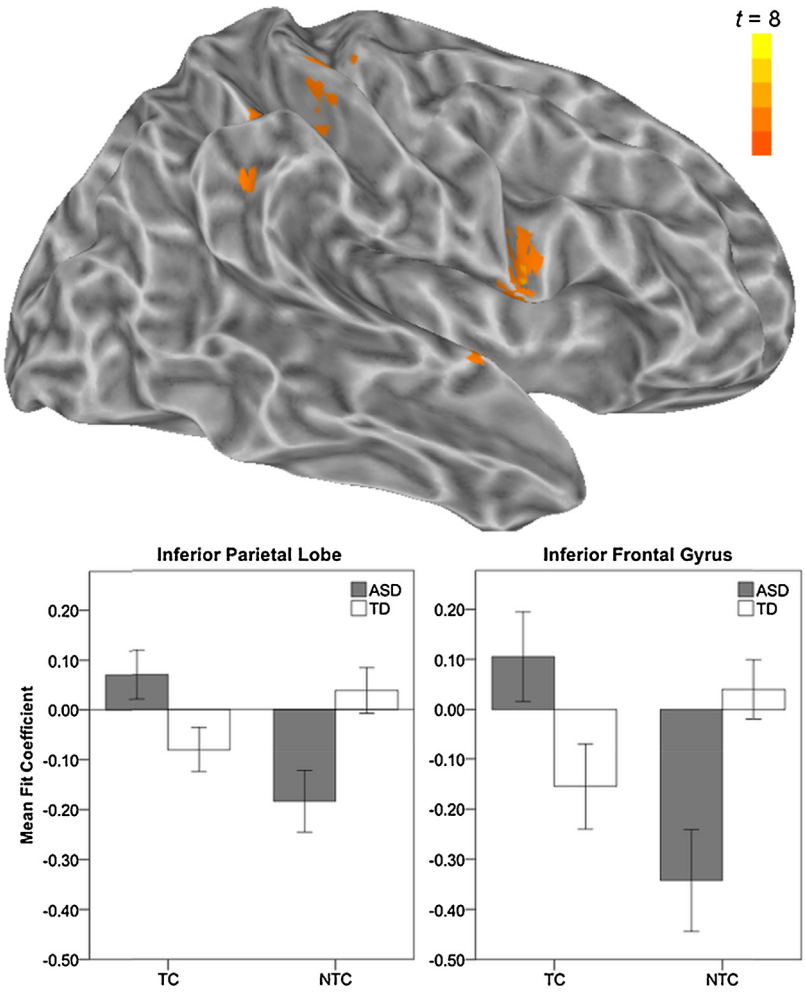

Fig. 4. Clusters of significantly greater activation in the ASD group for the TC-NTC comparison. Graphs depict activation for TC and NTC condition within clusters.

Table 4
Significant clusters for target absent TC compared to NTC distractor types for ASD and TD groups.

Group	Peak location	Hemi-sphere	Talairach coordinates			Volume (voxels)	*t*-score
			x	y	z		
ASD > TD	Inferior parietal lobe	R	44	−38	42	77	4.36
	Inferior frontal gyrus	R	50	2	12	52	4.39

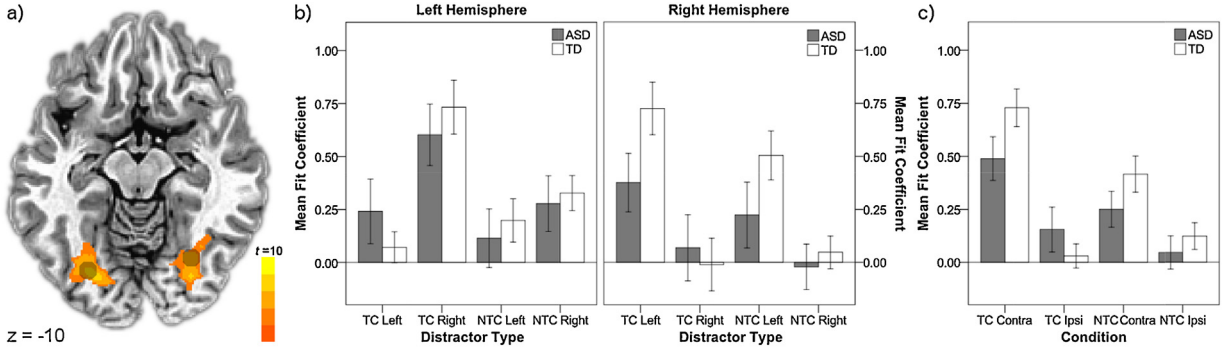

Fig. 5. Activation for target absent conditions (TC and NTC) from combined ASD and TD groups from which occipital regions of interest were selected (a). Two spherical ROIs (depicted as semi-transparent black circles) were selected from peaks within significant activation clusters: left ROI ($x = -25.5$, $y = -70.5$, $z = -12.5$) and right ROI ($x = 28.5$, $y = -64.5$, $z = -12.5$). Activation for each ROI for TC and NTC appearing to the left/right of target for ASD (gray) and TD (white) groups (b). Average activation for contralateral (e.g., left ROI, right distractor) and ipsilateral (e.g., left ROI, left distractor) for TC and NTC conditions for both ASD and TD groups (c). Error bars represent ± 1 SEM.

3.3.1. Target-related processing

To examine whether ASD symptomatology was associated with behavioral and neural indices of target processing correlations were performed between ADOS scores (Social, Communication, Social and Communication, and Restricted and Repetitive Behaviors domains) and RT, error rate, and target-related activation (a total of 12 correlations). We focused on regions of interest associated with ASD-TD target present neutral contrast; however, given issues of non-independence (Poldrack and Mumford, 2009; Vul et al., 2009) we used activation measures from ROIs derived from Serences et al., 2005 (see Supplementary Materials for details). For the ASD group, there was a significant correlation between PN error rate and ADOS Communication and Social score, $r(15) = .53$, $p < .05$, with increasing error rates associated with increasing ASD symptomatology. This association remained in partial correlations controlling for age and verbal and nonverbal IQ. For the ROI analysis, target present activation of rTPJ ROI was associated with PN error rate, $r(15) = .55$, $p < .05$, ADOS Social, $r(15) = -.48$, $p = .06$, and ADOS Communication and Social, $r(15) = -.45$, $p = .08$, scores. No other significant correlations between behavioral or neural measures and ADOS scores were found.

3.3.2. Contingent attentional capture

A difference score was created that reflected increased activation to TC compared to NTC distractors in the contralateral hemisphere (e.g., contralateral TC peripheral distractors—activation to contralateral NTC distractors). The index reflects activation within visual ROIs associated with attentional capture. Regions of interest were used for these correlations were study-specific as activation in occipital cortex corresponded to retinotopic location of peripheral distractors (which varied slightly from Serences et al., 2005). However, there were no significant correlations with ADOS scores (all $p > .8$). Correlations were not corrected for multiple comparisons.

4. Discussion

The current study examined how relevant and irrelevant information captures attention in individuals with ASD. Reduced target-related brain activation in children and adolescents with ASD suggests that they were less responsive to behaviorally-relevant information compared to their TD peers. Both behavioral and brain results for TD individuals indicate that to-be-ignored, irrelevant information captures attention when it shares a feature with the target; however, for individuals with ASD distractors similar to the target did not uniquely capture attention. Insensitivity to appearance of the target and reduced activation of the rTPJ – a region associated with re-orienting attention to behaviorally-relevant information – was related to increased ASD sociocommunicative symptoms. Each of the following results will be discussed in turn.

4.1. Target-related processing

Similar to previous fMRI and ERP studies that investigated attention to behaviorally-relevant targets we found differences in brain activation between ASD and TD groups (e.g., Belmonte and Yurgelun-Todd, 2003b; Clery et al., 2013; Courchesne et al., 1989). In particular, individuals with ASD showed reduced activation of the rTPJ and cerebellum. Furthermore, reduced activation of the rTPJ was also associated with increased error rates, indicating that failure to activate this region is associated with poorer target-related processing. Decreased activation in rTPJ and cerebellum have previously been reported in children with ASD for an auditory oddball paradigm (Gomot et al., 2006). The rTPJ may act as a 'circuit breaker' (Corbetta and Shulman, 2002), modulating activity of the dorsal attentional network. In agreement with this, our ROI analysis (see Supplementary Results) showed reduced activation in the dorsal network ROIs in individuals with ASD, which is also consistent with previous visual oddball studies (Belmonte and Yurgelun-Todd, 2003a; Clery et al., 2013).

These findings are also in accord with electrophysiological studies, which have shown reduced amplitude of the P3b component in individuals with ASD (see Jeste and Nelson, 2009, for review). The TPJ is a potential generator of the P3b component, which is associated with response to task-relevant stimuli and context updating (Polich, 2007). In addition, damage to the cerebellum has also been linked to reduced P3 amplitudes, indicating that the cerebellum may also maintain a temporal structure of events and respond to target-related perceptual deviance (Kotz et al., 2014). Consistent with previous oddball tasks (Gomot et al., 2006), results of the current study show significantly reduced target-related cerebellar activation in the ASD group. Although not considered in Corbetta and colleagues (2008; 2002) model of attentional networks (or other neurocognitive models of attention, e.g., Petersen and Posner, 2012), the cerebellum may play an important role in attentional processes (Akshoomoff et al., 1997; Townsend et al., 1999) and has been implicated in the neuropathology of ASD (Fatemi et al., 2012). Together, results from the target present neutral condition are indicative of atypical cortical and subcortical responsivity to behaviorally-relevant information in ASD, and are consistent with prior electrophysiological findings of an atypical cortical-cerebellar network in ASD that is associated with impaired attention orienting (Townsend et al., 2001).

More speculatively, activity of ventral attentional network and rTPJ have been linked to the locus coeruleus and norepinephrine system (Corbetta et al., 2008), which has been implicated in atypical orienting processes in ASD (Kaldy et al., 2013; Keehn et al., 2013). The LC-NE system has efferent projections to both cerebellum (mainly in Purkinje cells) and throughout the cerebral cortex (see Amaral and Sinnamon, 1977, for review). Activity of the LC-NE system has been associated with the P3 component (Nieuwenhuis et al., 2005), and, more generally with attentional function (Aston-Jones and Cohen, 2005). Future research should continue to examine the relationship between subcortical (cerebellum, LC-NE) and cortical networks and their role in attentional dysfunction in ASD. Elucidating network-specific impairments in attention (e.g. LC-NE system) may assist in directing pharmacological treatments and provide an outcome measure for their impact.

4.2. Contingent attentional capture

We failed to replicate the behavioral findings of increased errors to TC compared to the neutral target condition by Serences et al. (2005), but did detect accuracy differences between TC and NTC distractors. Our study differed in that our sample included children and adolescents rather than adults and our paradigm used numbers (rather than letters) to reduce task difficulty for our younger sample, which may have resulted in simpler target discrimination and fewer errors (despite attentional capture). While the absence of robust differences in error rates between TC and neutral conditions may suggest that attention was not displaced from the central stream, accelerated RT to TC compared to NTC condition indicated increased capture and RT facilitation for TD participants (RT was not reported by Serences et al., 2005). Functional imaging results were partially in agreement. Similar to Serences et al. (2005), TD participants showed hemisphere-specific increases to TC compared to NTC distractors in visual cortex. Activation of ventral and dorsal attentional networks was detected, but did not survive cluster-correction (see Supplementary Results). Subthreshold activation in the present study may have resulted from use of 4 rather than 9 runs of experimental paradigm as in the original study.

Similar to TD participants, individuals with ASD showed faster RT to target present TC and NTC trials compared to neutral trials, suggesting that colored distractors captured attention and accelerated RT. However, in contrast to TD participants, individuals with ASD evidenced no facilitation in RT for TC versus NTC distractors. Similarly they failed to show increased activation to TC relative to NTC in visual ROIs, but did show increased activation to contralateral TC and NTC distractors. These results suggest that both task-relevant and task-irrelevant information captured attention in ASD, but that task-relevant information was not enhanced in ASD. The findings are consistent with a recent report by Murphy et al. (2014), who showed reduced suppression of task-irrelevant information in ASD and dysfunction of top-down selective attention. Three potential hypotheses were outlined in the introduction regarding attention to irrelevant distractors: over-focused attention would result in limited capture by irrelevant distractors regardless of task-relevance, or, potentially, enhanced capture of distractors that share a target-defining feature (i.e., enhanced top-down processing). Alternatively, inability to filter irrelevant information could result in capture by irrelevant distractors regardless of task relevance. Both behavioral and neuroimaging results suggest that rather than being over-focused, children and adolescents with ASD were unable to filter distractors, adding support to the theory that individuals with ASD have difficulties filtering distracting information.

Prior studies have demonstrated that individuals with ASD have increased perceptual capacity (Remington et al., 2009, 2012), which may be associated with greater attention to task-irrelevant information (Lavie, 2005). Ohta et al. (2012) demonstrated that increased perceptual load was associated with reduced activation of visual cortex to irrelevant background stimuli for both TD and ASD groups, but that modulation was significantly reduced in ASD. Although the current study did not manipulate load, increased capture by irrelevant stimuli that did not share a task-relevant feature may be due to increased perceptual capacity in ASD.

Given evidence of equivalent capture by TC and NTC distractors in ASD participants, why would they show increased TC versus NTC activation in nodes of attentional networks? One possibility is that activation of right IFG reflects inhibition of response-related processes that were cued by the onset of the distractors (Shulman et al., 2009). Although, equivalent RT for TC and NTC (as observed in the ASD group) suggests that both distractor types captured attention, perhaps TC distractors required a greater inhibitory response. Alternatively, faster RT for TC and NTC compared to neutral trials suggests that colored distractors may have cued participants to potential target appearance. A second possible explanation for increased TC compared to NTC activation in attention networks, indicative of attentional capture, and the absence of behavioral effects is that individuals with ASD fail to use the implicit rule present in the task (i.e., that when a to-be-ignored distractors appear, a target is likely to follow). Using an implicit learning (paired association) task, we have previously shown that while individuals with ASD do not demonstrate behavioral facilitation, they show electrophysiological response similar to TD individuals (i.e., P3 component to "violations" of rule) (Townsend et al., 2012). Similarly, in the present study there appears to be a separation between overt behavior (i.e., absent of RT differences between TC and NTC conditions) and bottom-up modulation of attention in individuals with ASD, as evidenced by greater TC activation of ventral frontal-parietal regions.

4.3. Association between target- and distractor-related processes and ASD symptoms

Lastly, we sought to map differences in behavioral and neurofunctional indices of attentional capture to heterogeneous phenotypic differences in sociocommunicative deficits across the autism spectrum. Impairments in target detection and atypical target-related activation, specifically in rTPJ, were associated with increased ASD symptomatology. This is in agreement with previous reports that have shown that reduced bottom-up modulation of attention to dynamic onset stimuli (Keehn and Joseph, 2008) and reduced efficiency of the Posner's alerting network (which overlaps with the ventral attentional network, i.e., rTPJ) is associated with increased sociocommunicative impairment in individuals with ASD (Keehn et al., 2010).

Why might activation of rTPJ during a non-social attentional task be associated with sociocommunicative function in children with ASD? It has been proposed that attentional re-orienting to behaviorally-relevant information and higher-order social-cognitive processes may share a common neural substrate, namely, the rTPJ (Corbetta et al., 2008). A previous meta-analysis has shown substantial overlap between activation associated with theory of mind and attentional re-orienting, and suggests higher-level social processes may rely on lower-level computational mechanisms (Decety and Lamm, 2007). However, the degree to which these neurocognitive functions overlap remains disputed (e.g., Kubit and Jack, 2013; Scholz et al., 2009).

Nevertheless, reduced activation of ventral attentional network, specifically the rTPJ, may be associated with impairments in orienting to both social and non-social stimuli seen in children with ASD (Baranek et al., 2013; Dawson et al., 1998; Dawson et al., 2004). A failure to engage the ventral attentional network may also be associated with hypo-responsiveness, reduced alerting efficiency, and poor bottom-up modulation of attention to dynamic stimuli. These domain-general abnormalities in attentional modulation may interfere with the development of higher-level social-information processing skills in children with ASD. For example, early joint attention responses depend on the attention-capturing characteristics of environmental stimuli (Butterworth and Grover, 1990), and may rely on more basic attentional mechanisms. Failure to respond to salient, behaviorally-relevant information in one's environment may result in reduced joint attention, which could delay language acquisition and affect the development of understanding others' intentions (see Keehn et al., 2013, for review). Such developmental trajectories may result in reduced differentiation and specialization of these cortical networks (Shih et al., 2011), and may be important in the development of social and communication deficits that are defining of ASD (Pelphrey et al., 2005).

4.4. Limitations

Although our paradigm elicited faster response times to peripheral distractors, accuracy findings did not reveal decreased performance for TC compared to both NTC and neutral conditions consistent with prior reports of contingent attentional capture. This may partially explain why we did not find significant differences between TC and NTC conditions at cluster-corrected levels. However, it is unclear whether these differences are due to the younger age of our sample, differences in stimuli (numbers compared to letters), or length of experiment (4 versus 9 runs). Despite these differences, we did replicate previous occipital ROI findings of attentional capture in our TD group. These results along with evidence of RT facilitation and reduced accuracy for TC compared to NTC distractors suggest that we did find evidence of attentional capture in our TD sample. Lastly, our correlations should be viewed as exploratory as our sample size was limited ($n = 16$) and correlations were not corrected for multiple comparisons.

4.5. Conclusion

Children with ASD often fail to attend to behaviorally-relevant information, but oddly may appear to be distracted by irrelevant

details in their environment. Our findings shed light on both aspects of attentional capture in ASD: Behaviorally-relevant target stimuli failed to trigger activation of the rTPJ in ASD, indicating that under-responsivity and impairments in orienting salient events within their environment may be due to deficits in engaging ventral attentional network. Additionally, we found inconsistent evidence of contingent attentional capture in ASD; behavioral and occipital activation findings suggest that task-irrelevant information was equally as likely to capture attention regardless of whether it shared a task-relevant feature or not, whereas increased activation of ventral frontal-parietal regions to target-colored distractors does indicate that task-relevant features uniquely capture attention in ASD. These findings further support the idea that children and adolescents with ASD are susceptible to distraction, and may suggest that impaired capture reflects a disconnection between bottom-up modulation of attention (as evidenced by increased activation to TC compared to NTC distractors) and behavioral responses in ASD. Finally, behavioral and neural indices of target-related processing were associated with sociocommunicative impairments, providing further support for the notion that non-social attentional processes and their neurofunctional underpinnings may play a significant role in the emergence of the heterogeneous ASD phenotype.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dcn.2015.12.002.

References

Akshoomoff, N., Courchesne, E., Townsend, J., 1997. Attention coordination and anticipatory control. Int. Rev. Neurobiol. 41, 575–598.

Amaral, D.G., Sinnamon, H.M., 1977. The locus coeruleus: neurobiology of a central noradrenergic nucleus. Prog. Neurobiol. 9 (3), 147–196.

Aston-Jones, G., Cohen, J.D., 2005. An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. Annu. Rev. Neurosci. 28, 403–450.

Baranek, G.T., Watson, L.R., Boyd, B.A., Poe, M.D., David, F.J., McGuire, L., 2013. Hyporesponsiveness to social and nonsocial sensory stimuli in children with autism, children with developmental delays, and typically developing children. Dev. Psychopathol. 25 (2), 307–320.

Belmonte, M.K., Yurgelun-Todd, D.A., 2003a. Functional anatomy of impaired selective attention and compensatory processing in autism. Cogn. Brain Res. 17 (3), 651–664.

Belmonte, M.K., Yurgelun-Todd, D.A., 2003b. Functional anatomy of impaired selective attention and compensatory processing in autism. Brain Res. Cogn. Brain Res. 17 (3), 651–664.

Burack, J.A., 1994. Selective attention deficits in persons with autism: preliminary evidence of an inefficient attentional lens. J. Abnorm. Psychol. 103 (3), 535–543.

Butterworth, G., Grover, L., 1990. Joint visual-attention manual pointing, and preverbal communication in human infancy. Attention Perform. 8 (Xiii), 605–624.

Clery, H., Andersson, F., Bonnet-Brilhault, F., Philippe, A., Wicker, B., Gomot, M., 2013. fMRI investigation of visual change detection in adults with autism. Neuroimage Clin. 2, 303–312.

Corbetta, M., Patel, G., Shulman, G.L., 2008. The reorienting system of the human brain: From environment to theory of mind. Neuron 58 (3), 306–324.

Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. Nat. Rev. Neurosci. 3 (3), 201–215.

Courchesne, E., Lincoln, A.J., Yeung-Courchesne, R., Elmasian, R., Grillon, C., 1989. Pathophysiologic findings in nonretarded autism and receptive developmental language disorder. J. Autism. Dev. Disord. 19 (1), 1–17.

Cox, R.W., 1996. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. Comput. Biomed. Res. 29 (3), 162–173.

Dawson, G., Meltzoff, A.N., Osterling, J., Rinaldi, J., Brown, E., 1998. Children with autism fail to orient to naturally occurring social stimuli. J. Autism. Dev. Disord. 28 (6), 479–485.

Dawson, G., Toth, K., Abbott, R., Osterling, J., Munson, J., Estes, A., Liaw, J., 2004. Early social attention impairments in autism: Social orienting, joint attention, and attention to distress. Dev. Psychol. 40 (2), 271–283.

Decety, J., Lamm, C., 2007. The role of the right temporoparietal junction in social interaction: how low-level computational processes contribute to meta-cognition. Neuroscientist 13 (6), 580–593.

Fan, J., Bernardi, S., Van Dam, N.T., Anagnostou, E., Gu, X., Martin, L., Hof, P.R., 2012. Functional deficits of the attentional networks in autism. Brain Behav. 2 (5), 647–660.

Farrant, K., Uddin, L.Q., 2015a. Asymmetric development of dorsal and ventral attention networks in the human brain. Dev. Cogn. Neurosci. 12, 165–174.

Farrant, K., Uddin, L.Q., 2015b. Atypical developmental of dorsal and ventral attention networks in autism. Dev. Sci., http://dx.doi.org/10.1111/desc.12359.

Fatemi, S.H., Aldinger, K.A., Ashwood, P., Bauman, M.L., Blaha, C.D., Blatt, G.J., Welsh, J.P., 2012. Consensus paper: pathological role of the cerebellum in autism. Cerebellum 11 (3), 777–807.

Folk, C.L., Remington, R.W., Johnston, J.C., 1992. Involuntary covert orienting is contingent on attentional control settings. J. Exp. Psychol.: Hum. Percept. 18 (4), 1030–1044.

Forman, S.D., Cohen, J.D., Fitzgerald, M., Eddy, W.F., Mintun, M.A., Noll, D.C., 1995. Improved assessment of significant activation in functional magnetic resonance imaging (fMRI): use of a cluster-size threshold. Magn. Reson. Med. 33 (5), 636–647.

Gomot, M., Bernard, F.A., Davis, M.H., Belmonte, M.K., Ashwin, C., Bullmore, E.T., Baron-Cohen, S., 2006. Change detection in children with autism: an auditory event-related fMRI study. Neuroimage 29 (2), 475–484.

Ishihara, S., 1999. Ishihara's Tests for Colour Deficiency: 38 Plates Edition. Kanehara and Co. Ltd, Tokyo, Japan.

Jeste, S.S., Nelson 3rd., C.A., 2009. Event related potentials in the understanding of autism spectrum disorders: an analytical review. J. Autism Dev. Disord. 39 (3), 495–510.

Kaldy, Z., Giserman, I., Carter, A.S., Blaser, E., 2013. The mechanisms underlying the ASD advantage in visual search. J. Autism Dev. Disord., http://dx.doi.org/10.1007/s10803-013-1957-x.

Keehn, B., Joseph, R.M., 2008. Impaired prioritization of novel onset stimuli in autism spectrum disorder. J. Child Psychol. Psychiatry 49 (12), 1296–1303.

Keehn, B., Lincoln, A.J., Muller, R.A., Townsend, J., 2010. Attentional networks in children and adolescents with autism spectrum disorder. J. Child Psychol. Psychiatry.

Keehn, B., Muller, R.A., Townsend, J., 2013. Atypical attentional networks and the emergence of autism. Neurosci. Biobehav. Rev. 37 (2), 164–183.

Kim, H., 2014. Involvement of the dorsal and ventral attention networks in oddball stimulus processing: a meta-analysis. Hum. Brain Mapp. 35 (5), 2265–2284.

Konrad, K., Neufang, S., Thiel, C.M., Specht, K., Hanisch, C., Fan, J., Fink, G.R., 2005. Development of attentional networks: An fMRI study with children and adults. Neuroimage 28 (2), 429–439.

Kotz, S.A., Stockert, A., Schwartze, M., 2014. Cerebellum, temporal predictability and the updating of a mental model. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 369 (1658.).

Kubit, B., Jack, A.I., 2013. Rethinking the role of the rTPJ in attention and social cognition in light of the opposing domains hypothesis: findings from an ALE-based meta-analysis and resting-state functional connectivity. Front. Hum. Neurosci. 7, 323.

Lavie, N., 2005. Distracted and confused? Selective attention under load. Trends Cogn. Sci. 9 (2), 75–82.

Liss, M., Saulnier, C., Fein, D., Kinsbourne, M., 2006. Sensory and attention abnormalities in autistic spectrum disorders. Autism 10 (2), 155–172.

Lord, C., Rutter, M., DiLavore, P.C., Risi, S., 1999. Autism Diagnostic Observation Schedule—WPS (ADOS-WPS). Western Psychological Services, Los Angeles, CA.

Lovaas, O.I., Koegel, R.L., Schreibman, L., 1979. Stimulus overselectivity in autism: a review of research. Psychol. Bull. 86 (6), 1236–1254.

Mann, T.A., Walker, P., 2003. Autism and a deficit in broadening the spread of visual attention. J. Child Psychol. Psychiatry 44 (2), 274–284.

Murphy, J.W., Foxe, J.J., Peters, J.B., Molholm, S., 2014. Susceptibility to distraction in autism spectrum disorder: probing the integrity of oscillatory alpha-band suppression mechanisms. Autism Res. 7 (4), 442–458.

Nieuwenhuis, S., Aston-Jones, G., Cohen, J.D., 2005. Decision making, the P3, and the locus coeruleus-norepinephrine system. Psychol. Bull. 131 (4), 510–532.

Ohta, H., Yamada, T., Watanabe, H., Kanai, C., Tanaka, E., Ohno, T., Hashimoto, R., 2012. An fMRI study of reduced perceptual load-dependent modulation of task-irrelevant activity in adults with autism spectrum conditions. Neuroimage 61 (4), 1176–1187.

Pelphrey, K.A., Morris, J.P., McCarthy, G., 2005. Neural basis of eye gaze processing deficits in autism. Brain 128 (Pt 5), 1038–1048.

Petersen, S.E., Posner, M.I., 2012. The attention system of the human brain: 20 years after. Annu. Rev. Neurosci. 35, 73–89.

Poldrack, R.A., Mumford, J.A., 2009. Independence in ROI analysis: where is the voodoo? Soc. Cogn. Affect Neurosci. 4 (2), 208–213.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118 (10), 2128–2148.

Remington, A., Swettenham, J., Campbell, R., Coleman, M., 2009. Selective attention and perceptual load in autism spectrum disorder. Psychol. Sci. 20 (11), 1388–1393.

Remington, A., Swettenham, J.G., Lavie, N., 2012. Lightening the load: perceptual load impairs visual detection in typical adults but not in autism. J. Abnorm. Psychol. 121 (2), 544–551.

Robertson, C.E., Kravitz, D.J., Freyberg, J., Baron-Cohen, S., Baker, C.I., 2013. Tunnel vision: sharper gradient of spatial attention in autism. J. Neurosci. 33 (16), 6776–6781.

Ronconi, L., Gori, S., Ruffino, M., Molteni, M., Facoetti, A., 2013. Zoom-out attentional impairment in children with autism spectrum disorder. Cortex 49 (4), 1025–1033.

Rutter, M., Le Couteur, A., Lord, C., 2003. Autism Diagnostic Interview-Revised. Western Psychological Services, Los Angeles, CA.

Saad, Z.S., Chen, G., Reynolds, R.C., Christidis, P.P., Hammett, K.R., Bellgowan, P.S., Cox, R.W., 2006. Functional imaging analysis contest (FIAC) analysis according to AFNI and SUMA. Hum. Brain Mapp. 27 (5), 417–424.

Scholz, J., Triantafyllou, C., Whitfield-Gabrieli, S., Brown, E.N., Saxe, R., 2009. Distinct regions of right temporo-parietal junction are selective for theory of mind and exogenous attention. PLoS ONE 4 (3), e4869.

Serences, J.T., Shomstein, S., Leber, A.B., Golay, X., Egeth, H.E., Yantis, S., 2005. Coordination of voluntary and stimulus-driven attentional control in human cortex. Psychol. Sci. 16 (2), 114–122.

Shih, P., Keehn, B., Oram, J.K., Leyden, K.M., Keown, C.L., Muller, R.A., 2011. Functional differentiation of posterior superior temporal sulcus in autism: a functional connectivity magnetic resonance imaging study. Biol. Psychiatry 70 (3), 270–277.

Shulman, G.L., Astafiev, S.V., Franke, D., Pope, D.L., Snyder, A.Z., McAvoy, M.P., Corbetta, M., 2009. Interaction of stimulus-driven reorienting and expectation in ventral and dorsal frontoparietal and basal ganglia-cortical networks. J. Neurosci. 29 (14), 4392–4407.

Townsend, J., Courchesne, E., 1994. Parietal damage and narrow "spotlight" spatial attention. J. Cogn. Neurosci. 6 (3), 220–232.

Townsend, J., Courchesne, E., Covington, J., Westerfield, M., Harris, N.S., Lyden, P., Press, G.A., 1999. Spatial attention deficits in patients with acquired or developmental cerebellar abnormality. J. Neurosci. 19 (13), 5632–5643.

Townsend, J., Keehn, B., Westerfield, M., 2012. Abstraction of mind": attention in autism. In: Posner, M. (Ed.), Cognitive Neuroscience of Attention, Vol. 2. Guilford Publications, Inc, New York, NY, pp. 357–373.

Townsend, J., Westerfield, M., Leaver, E., Makeig, S., Jung, T., Pierce, K., Courchesne, E., 2001. Event-related brain response abnormalities in autism: evidence for impaired cerebello-frontal spatial attention networks. Cogn. Brain Res. 11 (1), 127–145.

Vul, E., Harris, C., Winkielman, P., Pashler, H., 2009. Puzzlingly high correlations in fMRI studies of emotion, personality, and social cognition. Perspect. Psychol. Sci. 4 (3), 274–290.

Wechsler, D., 1999. Wechsler's Abbreviated Scale of Intelligence. The Psychological Corporation, San Antonio, TX.