RESEARCH ARTICLE

Global and Local Visual Processing in Autism: An Objective Assessment Approach

Kritika Nayar, Angela C. Voyles, Lynne Kiorpes, and Adriana Di Martino

We examined global and local visual processing in autism spectrum disorder (ASD) via a match-to-sample task using Kanizsa illusory contours (KIC). School-aged children with ASD ($n = 28$) and age-matched typically developing controls ($n = 22$; 7–13 years) performed a sequential match-to-sample between a solid shape (sample) and two illusory alternatives. We tracked eye gaze and behavioral performance in two task conditions: one with and one without local interference from background noise elements. While analyses revealed lower accuracy and longer reaction time in ASD in the condition with local interference only, eye tracking robustly captured ASD-related global atypicalities across both conditions. Specifically, relative to controls, children with ASD showed decreased fixations to KIC centers, indicating reduced global perception. Notably, they did not differ from controls in regard to fixations to local elements or touch response location. These results indicate impaired global perception in the absence of heightened local processing in ASD. They also underscore the utility of eye-tracking measures as objective indices of global/local visual processing strategies in ASD. ***Autism Res*** *2017, 10: 1392–1404*. © 2017 International Society for Autism Research, Wiley Periodicals, Inc.

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Perceiving the structure of the visual environment involves two core elements: local and global form processing. Global visual processing is typically rapid and automatic [see review Colombo, Mitchell, Coldren, & Freeseman, 1991; Freeseman, Colombo, & Coldren, 1993; Poirel, Pineau, & Mellet, 2008]; it involves establishing spatial relationships and linking local features of a scene together to form a coherent whole [Kimchi, 1992; Navon, 1977]. Local processing, on the other hand, involves selective attention to individual elements of a scene [e.g., Happe & Frith, 2006; Kovacs, 1996; Navon, 1983], it is slower and more cognitively taxing [Freeseman et al., 1993; Navon, 1977; Poirel et al., 2008]. Typically by age five, global perception of a visual scene precedes local level processing [Kimchi, 1992; Navon, 1977; Nayar, Franchak, Adolph, & Kiorpes, 2015], but integrating both levels of information contributes to our complete representation of the visual world [Kimchi, 1992]. The organization of these critical visual processes has been increasingly examined in individuals with autism spectrum disorder (ASD) [Happe & Frith, 2006; Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015] where sensory abnormalities are prevalent [American Psychiatric Association, 2013; Marco, Hinkley, Hill, & Nagarajan, 2011; Rogers & Ozonoff, 2005] and may affect their understanding of the social world.

Investigations of local and global visual processes in ASD have employed a variety of behavioral paradigms and measures of what participants perceived [e.g., see Happe & Frith, 2006, for review; Van der Hallen et al., 2015]. Although these studies have reported mixed results, a detail-oriented processing style in ASD has emerged as a common theme across different approaches and theoretical models [e.g., Behrmann, Thomas, & Humphreys, 2006; Frith, 1989; Happe, 1996; Happe & Frith, 1996, 2006; Mottron, Burack, Stauder, & Robaey, 1999; Plaisted, Swettenham, & Rees, 1999; Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2000; Ropar & Mitchell, 1999, 2001; Van der Hallen et al., 2015; Wang, Mottron, Peng, Berthiaume, & Dawson, 2007]. However, the extent to which this detail-oriented processing style stems solely from a bias

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toward local processing or also includes weaknesses in global processing has been debated, and still remains unclear. Specifically, many studies using hierarchical figures, such as Navon stimuli [e.g., Koldewyn, Jiang, Weigelt, & Kanwisher, 2013; Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Navon, 1977, 1983; Plaisted et al., 1999; Rinehart et al., 2000; Wang et al., 2007], or the embedded figures tests [e.g., Jolliffe & Baron-Cohen, 1997; Ropar & Mitchell, 2001; Shah & Frith, 1983] indicate an ASD-related preference for the local constituents of an image in the absence of weaknesses in global processing [Deruelle, Rondan, Gepner, & Tardif, 2004; Koldewyn et al., 2013; Mottron et al., 2003; Plaisted, Saksida, Alcantara, & Weisblatt, 2003; Plaisted et al., 1999; Rinehart et al., 2000; Tantam, Monaghan, Nicholson, & Stirling, 1989]. Others have found poor global form processing, with or without evidence of a local bias, depending on the stimuli and tasks utilized [Behrmann et al., 2006; Falkmer et al., 2014; Van der Hallen et al., 2015].

Several factors may contribute to these inconsistencies [Van der Hallen et al., 2015]. In part, they emerge from variation in stimuli utilized [Milne, Scope, Pascalis, Buckley, & Makeig, 2009], ranging from hierarchical shapes, embedded figures, block design, visual illusions, and faces. Face perception represents a specific level of expertise [Happe & Frith, 2006] and may not be generalizable to perception of other objects. Other stimuli, like the Navon and embedded figures inherently imply competition between local and global processing [Happe & Frith, 2006]. Block design, in addition to relying on visuospatial skills, also requires the ability to manually manipulate materials. The required integration of fine motor skills and visual perception to complete block design tasks therefore does not isolate perceptual abilities like the use of object and face stimuli do.

Kanizsa illusory contours (KICs) [Kanizsa, 1976] provide an alternative objective approach to assess global/local visual perception. KICs induce the perception of an illusory shape from strategically placed "pacman" elements in the absence of physical boundaries [Nieder, 2002; Ringach & Shapley, 1996]. Although KICs can also be observed as unassociated pacman elements without the induction of the illusory percept, global processing is needed to induce the illusory form [Guttman & Kellman, 2004; Ringach & Shapley, 1996]. Thus, KICs allow the assessment of both global and local perceptual processing [Gregory, 1968], without interference between these levels. This is particularly relevant for ASD studies as a recent meta-analysis showed that diminished accuracy in ASD is only evident in global processing tasks that include a task-irrelevant interfering local component [Van der Hallen et al., 2015]. Additionally, it has been shown that children with ASD can use global strategies when instructed to do so, even if they are more inclined toward local processing [Koldewyn et al., 2013; Plaisted et al., 1999; Wang et al., 2007]. KIC perception can be easily quantifiable as it affords a correct response, and does not require explicit instructions unlike many other types of stimuli.

To date, only two studies have examined performance of KIC perception in children with ASD; their results are contradictory [Happe, 1996; Milne & Scope, 2008]. One study showed that children and adolescents with ASD detected the induced shapes with lower accuracy than did age-matched children with other learning difficulties and younger typically developing controls [Happe, 1996]. In contrast, the other study did not find ASD-related differences in illusory contour perception [Milne & Scope, 2008]. Specifically, by manipulating the angles of the pacman elements to induce a "fat" or "thin" KIC, the authors examined illusory contour perception in children with ASD, age-matched children with special needs without ASD, and typically developing children (TDC). These inconsistent results may be related to differences in approach. For example, Milne and Scope [2008] provided exposure to KICs during practice trials, including guided and explicit instructions as to whether the shapes were fat or thin, and provided feedback for correct responses during testing, which may have facilitated children's abilities to learn to solve the task. In contrast, in Happé's [1996] study, the results were based on subjective report in response to an open-ended question: "how many triangles can you see."

With these considerations in mind, we aimed to assess local and global form processing in children with ASD relative to age-matched controls using an objective approach. We employed a simple match-to-sample paradigm using KICs. In order to quantify performance, we used a touch-sensitive screen to record responses (i.e., reaction time and accuracy). Most importantly, given the inconsistency in prior behavioral findings [Van der Hallen et al., 2015], we employed simultaneous eye tracking to further evaluate the role of local and global strategies. While eye tracking has been used extensively to capture face or social scene perception in ASD [see reviews Boraston & Blakemore, 2007; also see Dalton et al., 2005; Guillon, Hadjikhani, Baduel, & Roge, 2014; Jones & Klin, 2013; Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Pelphrey et al., 2002], no prior studies have utilized simultaneous eye tracking to investigate local and global visual processing in ASD employing KICs [see review, Van der Hallen et al., 2015].

Several authors have highlighted an ASD-related bias toward local visual preference only when tasks required dividing attention between global and local levels but not when tasks are designed to encourage selective attention to global features [Happe & Frith, 2006;

Koldewyn et al., 2013; Plaisted et al., 1999]. As such, we included two KIC perception conditions: one with and one without randomly arrayed background "noise" elements (individual "pacman" elements). The condition without "noise" allowed us to test whether individuals with ASD have a preferential bias for processing at a local level when given the opportunity to use either local or global processing to recognize KICs. The condition with "noise," where the local information might interfere with global perceptual abilities, allowed us to further test the automaticity of global processing [Van der Hallen et al., 2015].

Based on the predominant evidence of a local bias in ASD, we hypothesized that, relative to TDC, children with ASD will show a "local processing" pattern, performing less accurately and with longer reaction times on both testing conditions (main effect of diagnostic group) but with relatively poorer performance in the condition with background noise (diagnosis by condition interaction). Furthermore, we predicted that in their eye tracking and touching behavior(s), children with ASD will look and touch less at the centers of the KIC stimuli (poorer global strategy) and more on the individual pacman elements (stronger local strategy).

Methods

Participants

We included data from 50 children (28 with ASD and 22 TDC; age 7–13 years, Table 1) who completed the KIC task after a successful practice demonstrating mastery of the match-to-sample concept with real forms. Recruitment of individuals with ASD was based on flyers, word of mouth, referrals from parent support groups, the NYU Child Study Center clinic, as well as prior research contacts. Recruitment of TDC was based on flyers in the community, word of mouth, advertisements, and contacts from prior studies.

Clinician's Diagnostic and Statistical Manual of Mental Disorders (DSM)-IV-Text Revision (TR)-based diagnosis of autistic disorder, Asperger's disorder, or pervasive developmental disorder not-otherwise-specified ($n = 21$, $n = 2$, and $n = 6$, respectively) was required for ASD inclusion. The clinicians' diagnosis was aided by research reliable administration and scoring of the autism diagnostic observation schedule-general (ADOS-G; and scored based on the newly revised algorithm) [Gotham, Risi, Pickles, & Lord, 2007; Gotham, Pickles, & Lord, 2009; Lord et al., 2000] and of the autism diagnostic interview-revised (ADI-R) [Lord, Rutter, & Le Couteur, 1994; Lord et al., 1997]. To assess for Axis-I psychiatric comorbidity, we interviewed parent(s)/caregiver(s) with the schedule for affective disorders and schizophrenia for school-age children-present and lifetime version (K-SADS-PL) [Kaufman et al., 1997]. Of the 28 children with ASD, 19 (68%) presented with comorbidity, mostly attention-deficit/hyperactivity disorder (ADHD) alone or combined with other Axis-I disorders (Table 1). Diagnoses were based on review of available records and discussion at case conferences that included a child psychiatrist and/or a clinical psychologist, a social worker, pre-doctoral fellows, and medical students. Inclusion as TDC required absence of any DSM-IV-TR Axis I diagnosis confirmed by the K-SADS-PL, administered to at least one parent for all participants, as well as to the child for all but one who received a brief unstructured interview. Diagnostic assessments were completed at the time of KIC collection for 13 children with ASD and 9 TDC. The remaining 15 with ASD and 13 TDC received diagnostic assessments 26 ± 12 months before KIC data collection (no group differences were found on average time interval). For all participants, inclusion also required performance intelligence quotient (PIQ) above 80. All completed the Wechsler abbreviated scale of intelligence [Wechsler, 1999], but one TDC who completed the Kaufman brief intelligence test before the study [Kaufman & Kaufman, 1990].

To further characterize both groups, parents were asked to complete the child behavior checklist (CBCL) [Achenbach, 1991], Conners' parent rating scales-revised: long form (CPRS-R) [Conners, Sitarenios, Parker, & Epstein, 1998], and social responsiveness scale (SRS) [Constantino & Gruber, 2005]. Current (within a month from KIC testing) and past history of psychotropic medication use was also collected. Finally, parents provided demographic information including ethnicity/race and socioeconomic status. Each family received approximately $60 for participation. The study procedures were approved by NYU School of Medicine's Institutional Review Board and written informed consent/assent from parents and children, respectively, were obtained. 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 was obtained from all individual participants included in the study.

As shown in Table 1, although the two groups differ for Verbal IQ (VIQ) and Total IQ, as expected by study design, they did not differ in PIQ. VIQ or Total IQ were not included as covariates as they were not significantly correlated with outcome variables. Parent CBCL, CPRS-R, and SRS ratings indicated greater externalizing and internalizing problems and social impairments in ASD versus TDC. The two groups did not differ in any demographics except for sex distribution, as all ASD participants were males in contrast with 77% of TDC. All TDC

Table 1. Characteristics of the Sample

	TDC ($n = 22$)			ASD ($n = 28$)			Group comparisons		
	Range	Mean	SD	Range	Mean	SD	*t*	*df*	*P*
Age (years)	7.7–12.8	10.2	1.5	7.2–13.0	9.8	2.0	0.66	48	0.51
Full IQ[a]	96–132	120	9	74–139	111	18	2.11	48	**0.04**
Verbal IQ	95–142	119	12	72–135	108	17	2.55	48	**0.01**
Performance IQ	93–129	115	9	81–147	113	19	0.70	48	0.49
CPRS-R:L T scores									
ADHD Index	40–67	48	8	42–84	64	12	−5.42	43	**<0.0001**
DSM-IV total	40–60	48	6	41–86	64	11	−6.01	43	**<0.0001**
CBCL T scores[b]									
Internalizing problems	34–61	48	8	41–81	64	9	−6.12	41	**<0.0001**
Externalizing problems	33–61	44	9	33–73	58	10	−5.00	41	**<0.0001**
Total problems	24–59	44	10	36–79	64	10	−6.47	41	**<0.0001**
SRS-P T score[c]	34–65	44	7	48–107	77	16	−9.43	47	**<0.0001**
ADOS module 3									
Total				4–21	10	4			
Social affect total				2–15	7	3			
Restricted repetitive behaviors total				0–8	3	2			
Scaled social affect total				2–10	6	2			
Scaled restricted repetitive behaviors total				0–10	7	3			
Scaled severity score total				2–10	6	2			
VABS-II ABC standard score[d]	90-131	113	11	58–99	81	11	9.77	47	**<0.0001**
	n (%)			*n* (%)			x^2	*df*	*P*
Males	17 (77)			28 (100)			7.07	1	**0.01**
Social economic status (SES) (Class 4 or 5;)[e]	17 (85)			17 (71)			1.25	1	0.26
Ethnicity (Hispanic)	2 (10)			5 (19)			0.77	1	0.38
Race							1.00	2	0.61
Caucasian	12 (57)			19 (68)					
African American	1 (5)			2 (7)					
Other	8 (38)			7 (25)					
Medication status									
Medication naïve	22 (100)			18 (64)			10.69	1	**0.001**
Not naïve but off medication				5 (18)					
Current stimulant treatmentf				2 (1)					
Current nonstimulant treatment				3 (11)					
Comorbidity[f]				19 (66)					
ADHD only				8 (42)					
ADHD + ODD or DBD NOS				4 (21)					
ADHD + Anxiety Disorders[g]				3 (16)					
ADHD + ODD + Anxiety Diosrder[h]				2 (11)					
ADHD + Tic Disorder NOS				2 (11)					

Note. Bold values indicate $P < .05$.

ADHD, attention-deficit/hyperactivity disorder; ADOS, autism diagnostic observation schedule; ASD, autism spectrum disorders; DSM-IV, Diagnostic and Statistical Manual of Mental Disorders IV; IQ, intelligence quotient; NOS, not otherwise specified; ODD, oppositional defiant disorder; TDC, typically developing children.

[a] All completed the Wechsler abbreviated scale of intelligence except for one TDC who completed the Kaufman Brief Intelligence Test.

[b] Four parents of TDC and three parents of children with ASD did not complete the CBCL, Child Behavior Checklist.

[c] One parent of a child with ASD did not complete the SRS parent form.

[d] One parent of a TDC did not complete the VABS-II, Vineland Adaptive Behavioral Scale-second edition.

[e] We did not have complete SES information for two TDC and children with ASD.

[f] Comorbidity was assessed at time of KIC administration for $n = 13$ children with ASD (comorbidity for remainder $n = 15$ obtained 8.6–46.5 months prior to task administration).

[g] Treatment with one or more psycho-stimulants. Notably, in these cases, children withheld stimulant medications 24 hr prior to completing KIC.

[h] Anxiety disorders included specific phobia ($n = 1$) and generalized anxiety disorder ($n = 1$).

and 64% of the children with ASD were med-naïve. Finally, given the recent publication of the DSM-5 [American Psychiatric Association, 2013], to facilitate comparison with future studies, we retrospectively established DSM-5 diagnosis based on ADI-R and/or ADOS results using an approach similar to [Huerta, Bishop, Duncan, Hus, & Lord, 2012]. All but five children met retrospective DSM-5 ASD criteria ($n = 7$ based

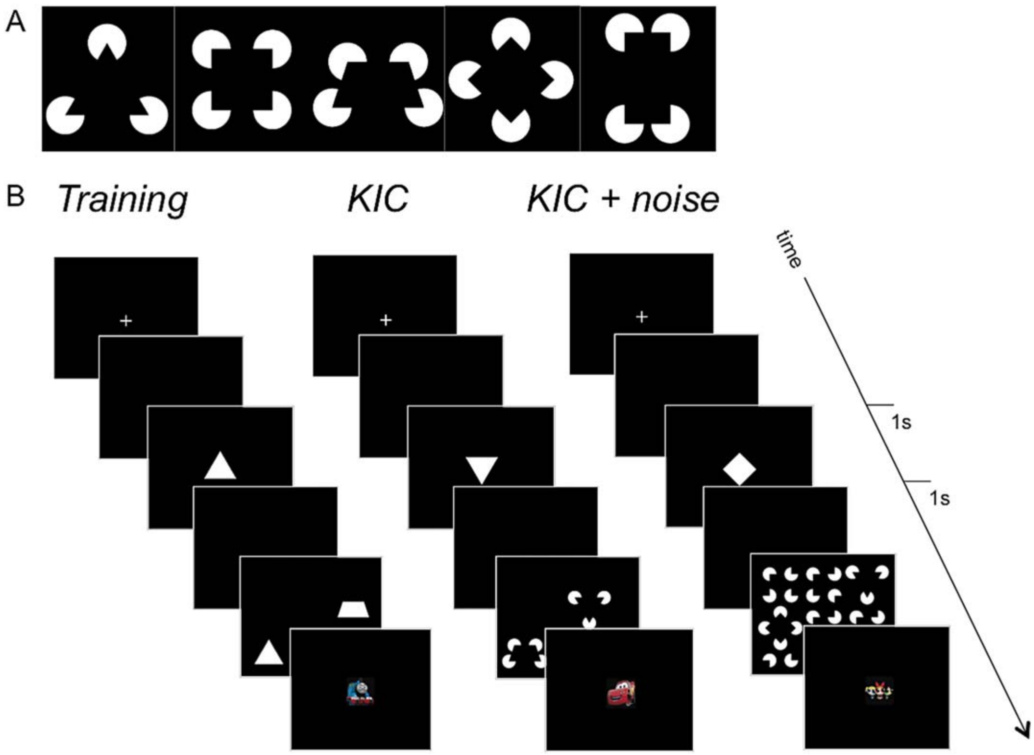

Figure 1. Paradigm and Stimulus. (A) Five illusory shapes used during test phases. Each stimulus (except for the square and diamond) is also presented in its opposite orientation. (B) Experimental paradigm displaying the training and two test conditions (KIC and KIC with background noise). While in this illustration the stimuli location on the screen are identical, during the tasks, stimuli location was randomized and varied between the top and bottom and right and left halves of the screen.

on both ADOS and ADI-R, $n = 4$ on ADOS only, and $n = 12$ on ADI-R only). Repeating task analyses without those five children yielded highly similar patterns of results (data not shown).

KIC Task and Eye Tracking

We administered a two-alternative forced choice match-to-sample paradigm using a touch sensitive monitor (Planar capacitive 27-cm-high × 33.5-cm-wide LCD touch screen, model number PT1701MX-BK) while monitoring eye movements with a Tobii X60 eye tracker. The touch-sensitive monitor allowed us to capture accurate response location and timing information from participants' active decision to touch a certain part of the stimuli. Participants were required to select KICs that matched a previously presented real (nonillusory) sample shape. KICs are comprised of strategically placed "pacman" elements that induce the perception of a shape or contours in the absence of physical boundaries (Fig. 1A) [Kanizsa, 1976]. On each trial, one of five sample real shapes (square, diamond, rectangle, triangle, or trapezoid) appeared for 1 sec at the center of the screen, followed by a black screen for 1 sec, and then two simultaneously presented KIC figures of the same size; one induced the appearance of the sample form, which we refer to as the target KIC (correct match), the other was a distractor KIC. The support ratio for all of the KICs (the relative length of the inducing/induced contour) [Otsuka, Kanazawa, & Yamaguchi, 2004; Rubin, Nakayama, & Shapley, 1997; Shipley & Kellman, 1992] was set at 60% [Nayar et al., 2015]. The size of the KIC figures was also fixed, such that at a distance of 60 cm, the pacman elements' radius was 1.5° and the illusory edge of the square, specifically, was 5°, yielding a total virtual edge length of 8° (1 cm = 1° of visual angle). Average luminance for each solid shape was 180 cd/m^2 and the background luminance averaged 35 cd/m^2; all figures were white on a black background.

The experimental paradigm consisted of two conditions presented in a fixed order: the first assessed basic KIC recognition; the second assessed KIC recognition in the presence of "noise," which consisted of randomly arrayed pacman elements, thus creating local interference (Fig. 1B). This second condition allowed us to explore how task-irrelevant information (i.e., the pacman noise) interfered with global processing [Van der Hallen et al., 2015], in the context of a visual search paradigm. Each condition included 40 trials. The target KICs were presented in randomized order. We also randomized the location of the KIC stimuli (target and distractor) on the screen across four potential loci: upper-lower halves, and left-right halves. To avoid position biases, the target KIC stimuli were not presented on the same side for more than four consecutive trials. A cartoon picture (e.g., Thomas the Tank Engine and Powerpuff Girls) was displayed after every response, regardless of accuracy. To ensure that participants responded, the examiner presented the next trial only after the participant faced the screen. Children were asked to respond as quickly and accurately as possible; periodically they were verbally encouraged to keep going. At the beginning of each testing condition, participants were reminded about matching one of the two test forms to the sample, with the same instructions for match-to-sample practice and the KIC conditions, never mentioning illusory forms.

Participants completed the KIC tests only after achieving at least 80% accuracy during a match-to-sample training condition consisting of 24 trials (administered up to three times). To prevent potential training effects on the illusory stimuli, samples were *real* (nonillusory) shapes (Fig. 1B). For this training phase, a cartoon picture was displayed only after *correct* responses. All TDC participants passed the training condition, two children (out of 30; 7%) with ASD failed after three attempts, and therefore testing was discontinued. Due to technical data collection glitches, eye-tracking data were not available for four individuals (two with ASD and two TDC).

For all conditions, participants sat on an adjustable chair in front of the screen, located arm's distance away (~60 cm). The Tobii eye tracker rested below the touch screen monitor to simultaneously record participants' gaze patterns at a rate of 60 Hz during task administration. Participants' eye gaze was calibrated at the beginning of the experiment using a standard 5-point calibration procedure established by the Tobii Software. If suboptimal (gaze located outside the circumference of the five calibration-check points), calibration was repeated.

Data Analyses

Behavioral responses. For each condition, we measured *accuracy and reaction time*. We indexed accuracy as the total number of correct responses (i.e., touching the target stimulus) divided by 40 trials. Reaction time was computed as the time between the appearance of the illusory stimuli on the screen and the instant the participant touched the screen. Given that correct and incorrect responses present distinct properties [Luce, 1986; Yordanova, Albrecht, et al., 2011; Yordanova, Kolev, et al., 2011], and that the number of errors across subjects and conditions was small (~10%), subsequent analyses were conducted only on correct trials.

Global and local strategy in touching and looking. Based on accepted conventions defining local and global processing strategies [Guttman & Kellman, 2004; Kimchi, 1992; Ringach & Shapley, 1996], we operationally defined attention to the centers of the illusory forms as indicative of "global processing" and attention to any of their pacman inducer elements as reflecting "local processing" strategies. Accordingly, for each condition, to determine whether participants were attending to the constituent elements of the KIC or the holistic forms, we identified two main areas of interest (AOI): the centers of KICs and their pacman elements. Touching/looking at the pacman elements of the KICs indicated a local processing strategy, while touching/looking at the centers indicated rapid perception of the global form. Pacman AOIs were defined as the circle area covered by the physical pacman element plus the empty "pie" of the KICs. KIC center AOIs were defined as the space induced by the pacman elements within their boundaries (not including the "pie"). We calculated touch behaviors at each AOI as percentages (i.e., total AOI touches divided by the total number of trials $\times$ 100). For any given trial, only the initial touch was registered, the stimulus was discontinued followed by a black screen with a cartoon. Looking behavior was calculated as an average of fixation duration to an AOI type over the testing condition. Fixations were defined as gazes greater than 100 ms; for any given trial, we summed the duration of each fixation in an AOI and divided it by the total fixation duration of that trial. The average across trials indexed the AOI fixation for each subject.

To quantify if individuals with ASD may present with an imbalance between local and global processing, we indexed the relative contribution of one strategy versus the other as the difference between global processing (% touches/looks to the center AOI of KICs) and LP (% touches/looks to the pacman AOIs of KICs)—that is, global processing-LP. Positive global processing-LP differences would indicate a greater contribution of global processing over LP of KICs, in contrast with negative differences indicating the opposite pattern; a global processing-LP difference centered around zero would indicate lack of a specific bias for one strategy versus the other.

Finally, TDC and children with ASD did not differ on the average number of total fixations (i.e., regardless of fixation location) per trial (5.7 ± 1.8 and 5.2 ± 1.8 for basic condition, respectively and 7.0 ± 2.4 and 6.7 ± 2.7 for noise condition, respectively), suggesting similar data quality between groups. Additionally, if the child looked off the screen, tracking would terminate and that trial would not have been included in analyses.

Statistical Analyses

Group differences in participants' demographics and clinical characteristics were tested with analysis of

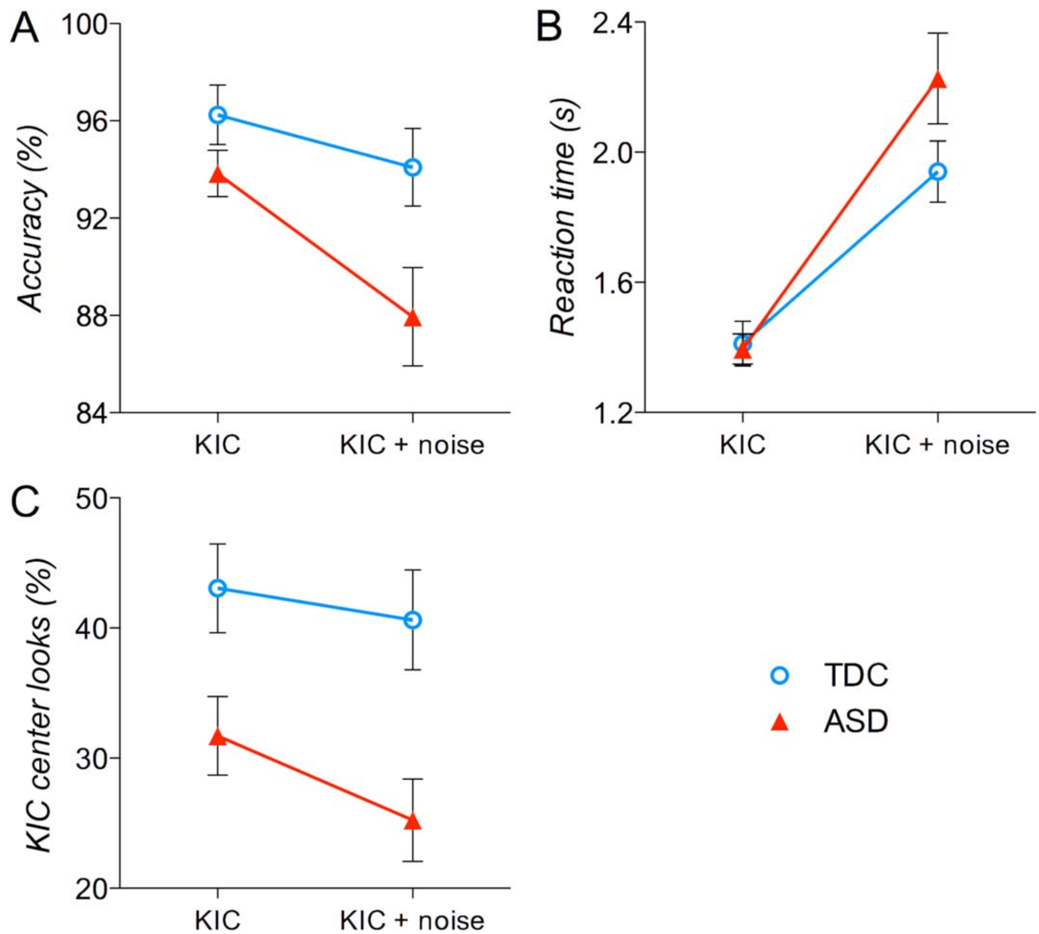

Figure 2. Results of task performance and gaze. (A and B) Main effect of condition on accuracy and reaction time for individuals with ASD and TDC. (C) Main effect of group for percentage of KIC center looks.

variance (ANOVA) and chi squared tests for continuous and categorical variables, respectively. For each behavioral and looking variable, we assessed group differences using a 2 × 2 (group × condition) repeated measures ANOVA. We assessed the main effect of condition (KIC and KIC with background noise), condition by diagnostic group interaction, and the main effect of diagnostic group. Significance level was set at $P < 0.006$ (i.e., 0.05/8) to address potential confounds of multiple tests. Effect size was computed as η^2 (with medium and large effects set at 0.06 and 0.14, respectively).

Results

Accuracy

We first compared the basic KIC condition against the one with background noise for response accuracy across the two groups (Fig. 2A, Table 2). There was a significant effect of condition, indicating that regardless of diagnosis, children committed significantly more errors during the background noise condition. With regard to group comparisons, children with ASD made more errors than TDC, particularly during the condition with background noise resulting in a group by condition interaction with medium effect size. However, neither of these latter comparisons reached our strict statistical threshold.

Reaction Time

Similar to accuracy, there was a significant effect of condition for latency to respond (Fig. 2B, Table 2); regardless of diagnosis, all children were slower in the presence of background noise. Again, the effect of group by condition was medium as children with ASD were slower than TDC in the KIC condition with background noise; this effect did not meet our statistical threshold. These measures reveal that children with ASD were unimpaired at solving the KIC task, relative to TDC. However, examination of the strategy employed gives us insight into the application of local versus global processing in ASD.

Touching and Looking Behaviors

Attention to the center of the KIC versus the individual pacman elements is a signature for global processing

Table 2. Summary of Results

	TDC				ASD				Main effect of groups				Main effect of condition				Group × condition interaction			
	KIC		KIC + noise		KIC		KIC + noise													
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	F	df	P	η^2	F	df	P	η^2	F	df	P	η^2
Behavioral responses																				
Accuracy (%)	96	6	94	7	94	5	88	11	5.27	1, 48	0.03*	0.10	19.82	1, 48	**<0.0001**	0.29	4.69	1, 48	0.04*	0.09
Reaction Time (s)	1.41	0.32	1.94	0.44	1.39	0.24	2.23	0.74	1.25	1, 48	0.27	0.03	101.50	1, 48	**<0.0001**	0.07	5.01	1, 48	0.03*	0.10
Pacman touch (%)	13	20	8	15	10	19	10	16	0.00	1, 48	0.99	<0.001	3.92	1, 48	0.05	0.08	1.76	1, 48	0.19	0.04
center touch (%)	85	20	91	16	88	20	87	17	0.04	1, 48	0.84	0.001	2.55	1, 48	0.12	0.05	3.74	1, 48	0.06	0.07
Global processing-LP touch (%)	72	40	84	32	77	39	77	33	0.01	1, 48	0.92	0.001	3.17	1, 48	0.08	0.06	2.71	1, 48	0.11	0.05
Eye tracking																				
Pacman look (%)	23	8	22	8	23	10	21	12	0.04	1, 44	0.84	0.001	1.04	1, 44	0.31	0.02	0.24	1, 44	0.63	0.01
KIC center look (%)	43	15	41	17	31	16	25	16	10.05	1, 44	**0.003**	0.19	4.19	1, 44	**<0.05***	0.09	0.70	1, 44	0.41	0.02
Global processing-LP look (%)	20	16	18	15	8	14	4	10	13.02	1, 44	**0.001**	0.23	2.08	1, 44	0.16	0.05	0.32	1, 44	0.58	0.01

Note. Bold values indicate $P < 0.006$.
*P-values are not significant based on bonferroni corrections.

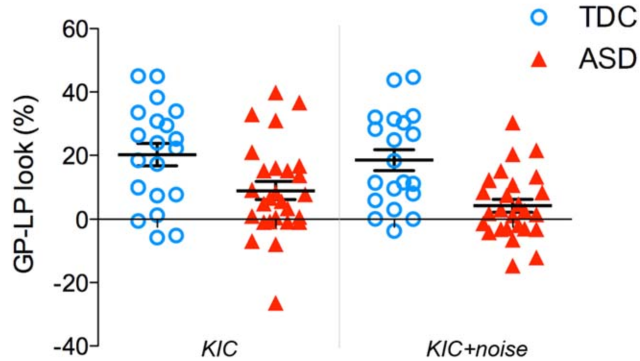

Figure 3. Distributions of global processing-LP looks. Individual global processing-LP% of looks and group mean. ASD centered closer to zero, indicative of neither a local nor a global processing preference.

(Fig. 2C, Table 2). The eye-tracking data revealed a significant medium to large main effect of diagnostic group such that individuals with ASD looked at KIC centers significantly less frequently than TDC regardless of condition (Bonferroni-adjusted post hoc group comparisons within basic KIC and KIC + noise conditions: $F_{(1,44)} = 6.85$, $P = 0.01$ and $F_{(1,44)} = 9.73$, $P = 0.003$, respectively). There were no group, condition, or interaction effects for pacman looks. Finally, we found no significant group differences on touch location, nor were there significant effects of condition or a diagnosis by condition interaction for touch behavior.

Global Processing-LP Difference

Across both conditions, there was a significant large main effect of group for looking behaviors such that global processing-LP difference was smaller for individuals with ASD compared to TDC (post hoc group comparisons within basic KIC and KIC + noise conditions separately: $F_{(1,44)} = 7.36$, $P = 0.01$; $F_{(1,44)} = 14.59$, $P < 0.001$, respectively; Fig. 3, Table 2). On average both groups had positive global processing-LP differences, but TDC had larger positive global processing-LP values than ASD, whose global processing-LP differences were shifted toward zero. Had the global processing-LP difference been negative for ASD participants, this would have been evidence for enhanced local processing. Regarding touch global processing-LP behaviors, neither group nor condition, nor their interaction reached our significance threshold (results remained consistent after removing two outliers; data not shown).

Follow-up Analyses

Background looks and touches. Secondary analyses examined looks and touches toward the background (i.e., any area other than KICs), across conditions (supporting information Table S1). At our statistical threshold, there were no significant effects of condition, group nor their interactions for these variables.

Relationship with ASD symptom severity. We explored the relationship between KIC gaze and performance patterns with ASD symptoms severity indexed by the ADOS and SRS total T scores within groups. No gaze or performance measures were significantly correlated with any of these measures within groups.

Discussion

Using KIC, we assessed local and global visual strategies indexed by objective behavioral performance and eye gaze in school-age children with ASD and TDC. Measures of looking behavior strongly differentiated groups with a large effect size. Specifically, children with ASD showed a lower percentage of looks at the KIC centers indicating reduced preference for global strategies. This was true across two conditions. One basic condition assessed KIC perception when the illusory forms were presented on an otherwise blank background; the other introduced local interference by including randomly arrayed pacman elements along with the KIC choices. In contrast to the findings with eye tracking, behavioral task measures (i.e., accuracy and reaction time) revealed nonstatistically significant effects of group, condition, and their interaction. These results show that eye tracking is a sensitive assay to capture ASD-related abnormalities in visual perception.

Although not statistically significant, we note that a medium to large effect size for slower reaction time in ASD participants in the local interference condition is in line with results of a recent large meta-analysis [Van der Hallen et al., 2015]. This meta-analysis showed that slower reaction time was not necessarily accompanied by inaccuracies in global processing, concluding that individuals with ASD have a local processing bias in the absence of impaired global processing. On the contrary, our findings of medium to large effect size of accuracy in the local interference condition do suggest weaknesses in the strength of global processing. This is consistent with a recent study that highlights the impact of task-related factors in the relationship between local and global processing [Van Eylen, Boets, Steyaert, Wagemans, & Noens, in press]. In our study, adding local distractors made the task more complex, as it required both segregation (extraction of the relevant pacman elements) and integration (creation of the gestalt illusory forms). An alternative interpretation of the present behavioral findings is that weak global processing (suggested by lower accuracy) is also accompanied by local preference (suggested by slower reaction time) in ASD. Our eye-tracking results paint a more complete picture of the organization of visual perceptual levels in ASD, providing a means to discriminate these conflicting perspectives.

Extending our investigation beyond the behavioral performance domain, eye tracking revealed a reduced bias in global processing that otherwise would have been missed, particularly in the condition without local interference. In the basic condition, both local and global visual information were equally relevant (i.e., the pacman elements are necessary to induce the global illusory effect). This allowed us to directly and quantitatively assess both perceptual levels without any interference or a "trade off" between each other. Underscoring this point, the global processing-LP difference in fixations evident in both conditions speaks to the relative strengths of one visual strategy versus the other. Specifically, evidence of lower, but still positive, differences between local and global gaze in children with ASD suggested that weaker global processing was not accompanied by heightened preference for the local aspects of the stimuli in the present paradigm. While TDC focused their attention to the center more than to the local elements of the KIC, children with ASD appeared to be neither strong "global processors," nor preferentially "local processors." One might imagine that the KIC + noise condition has a component of visual search. We did not explicitly rule this out. Prior studies have found that individuals with ASD have superior visual search performance in both conjunctive and feature search tasks and not a deficit [see Brenner, Turner, & Muller 2007, for review]. However, it is conceivable that superior visual search could interact with our task by masking a local processing weakness or otherwise shifting the global-local balance of the task. Future studies could investigate this possibility.

In the context of current theories of visual perception in ASD, our findings do not support models of a detail-focused processing style in ASD with or without concurrent deficits in global processing as purported by the weak central coherence theory [Happe, 1996, 1999; Happe & Frith, 2006] and by the enhanced perceptual functioning theory [Happe & Booth, 2008; Koldewyn et al., 2013; Mottron et al., 1999, 2003; Mottron, Dawson, Soulieres, Hubert, & Burack, 2006], respectively. However, consistent with more recent models of visual processing in ASD [Behrmann et al., 2006; Happe & Booth, 2008], evidence of weak global processing in ASD highlights the need for further objective investigations of both perceptual levels using tasks that do not require their trade off [Happe & Booth, 2008; Van Eylen et al., in press]. Such studies are needed to identify the mechanisms underlying these processes, which have been suggested to be independent [Happe & Booth, 2008].

For example, single unit recordings in animal studies and functional brain imaging in humans [e.g., see Seghier & Vuilleumier, 2006, for review] have shown distinct associations for these perceptual levels within the occipital visual network. Specifically, early visual areas, such as V1 and V2, are involved in extracting local visual information [Lee & Nguyen, 2001; Maertens & Pollmann, 2005; Wu et al., 2012], while higher order visual areas, such as the lateral occipital cortex, appear to serve global processing, for example, integrating the local pacman elements to create a coherent whole [Harris, Schwarzkopf, Song, Bahrami, & Rees, 2011; Ringach & Shapley, 1996; Stanley & Rubin, 2003; Wu et al., 2012]. Growing evidence has shown that visual perception, particularly for illusory contours, involves large-scale networks encompassing multiple brain areas beyond occipital cortex, including parietal and frontal cortex [Seghier & Vuilleumier, 2006]. This is relevant for ASD, which is increasingly recognized as a "dysconnection syndrome" where brain network development is disrupted [e.g., Di Martino et al., 2014; Minshew & Williams, 2007]. Greater insights into the role of local and global processing may provide clues as to what goes awry in the development of brain connectivity in ASD.

In this context, our group differences in global processing in the absence of a local bias suggest a delayed developmental trajectory in visual processing. A recent study of typical children (3–10 years old) completing a similar KIC eye-tracking paradigm, reported a developmental shift from a primarily local to largely global visual preference by seven years of age [Nayar et al., 2015]. Consistent with these findings, our school-age TDC show greater reliance on global strategies. Findings of positive—albeit weaker global processing-LP differences—in ASD are instead consistent with an immature developmental stage. This supports a recent meta-analysis suggesting that performance differences in global processing are only evident in studies of younger children with ASD but not in those with adults [Van der Hallen et al., 2015]. Prior studies using different stimuli explored age-related effects on local/global processing [Van Eylen et al., in press]. However, to date, no studies have directly tested age-related differences using eye tracking or illusory contours in visual processing in ASD versus TDC. As the current study focused on a relatively narrow age-range, future research spanning broader age ranges and employing sensitive eye-tracking approaches are warranted.

The results of this study should be interpreted in light of several limitations. The ASD sample included only males thus limiting our ability to generalize to females with ASD. As sex differences in visual strategies have been reported [Van Eylen et al., in press], future studies including both sexes are warranted. Sixty-six percent of our sample with ASD had comorbid ADHD. Given that initial studies have suggested atypical visual exploration in children with ADHD [Booth, Charlton, Hughes, & Happe, 2003; Song & Hakoda, 2012, 2015], a sample with a greater proportion of ASD children with and without ADHD comorbidity would clarify the diagnostic specificity of visual atypicalities. While the Tobii eye tracker is robust to flexible movements, and examiners confirmed that children did not have gross movements during testing, future studies may consider including video recordings to capture differential movement patterns between groups.

In conclusion, we showed that atypical global visual integration, assayed with eye tracking, characterized school-age children with ASD relative to controls. While eye tracking has previously been used in studies of ASD primarily to capture face or social scene perception [see reviews, e.g., Guillon et al., 2014; Klin et al., 2002; Papagiannopoulou, Chitty, Hermens, Hickie, & Lagopoulos, 2014; Pelphrey et al., 2002], our studies underscore the utility of eye tracking for investigations of the perception of nonsocial stimuli.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.