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S.I. : LOCAL VS. GLOBAL PROCESSING IN AUTISM SPECTRUM DISORDERS

Local and Global Visual Processing in Autism Spectrum Disorders: Influence of Task and Sample Characteristics and Relation to Symptom Severity

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Abstract Local and global visual processing abilities and processing style were investigated in individuals with autism spectrum disorder (ASD) versus typically developing individuals, children versus adolescents and boys versus girls. Individuals with ASD displayed more attention to detail in daily life, while laboratory tasks showed slightly reduced global processing abilities, intact local processing abilities, and a more locally oriented processing style. However, the presence of these group differences depended on particular task and sample (i.e., age and gender) characteristics. Most measures of local and global processing did not correlate with each other and were not associated with processing style. Significant associations between local–global processing and ASD symptom severity were observed, but the causality of these associations remains unclear.

Keywords Autism spectrum disorders · Visual processing · Local processing · Global processing · Sample characteristics · Symptom severity

Introduction

Autism spectrum disorders (ASD) are characterized by persistent impairments in social communication and social interaction and by restricted, repetitive patterns of behavior, interests or activities (DSM-5; American Psychiatric Association 2013). Besides these core characteristics, atypical visual processing has also been reported in individuals with ASD (for a review, see Simmons et al. 2009) and has been suggested as an underlying factor in some of their symptoms (Happé and Ronald 2008).

Altered visual processing in ASD is primarily addressed by two prominent theories, namely the Weak Central Coherence (WCC) account and the Enhanced Perceptual Functioning (EPF) theory. Central coherence refers to the typical tendency to (automatically) integrate information (Frith 1989). According to the original version of the WCC account, individuals with ASD show a deficit in central coherence or global processing, which is reflected in a relative inability to integrate pieces of information into coherent wholes and a preference for piecemeal or local processing (Frith 1989). In the revised version, the idea of a global processing deficit was attenuated and weak coherence was conceptualized as a processing bias or style in ASD, which can be overcome when explicitly instructed to do so (Happé and Frith 2006). The EPF theory uses a somewhat different framework to conceptualize altered perception in ASD (Mottron et al. 2006). It proposes enhanced feedforward low-level processing in ASD combined with an autonomy of low-level information

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processing for higher-order operations. More specifically, higher-order (more global processing) is proposed to be optional in individuals with ASD, while it is mandatory for typically developing (TD) individuals even when it impedes performance (Mottron et al. 2006). Nevertheless, similar to the revised WCC account, the EPF theory suggests that individuals with ASD show a local bias (when processing hierarchical stimuli), without a global processing deficit (for a more elaborate description, see Mottron et al. 2006).

Numerous studies have investigated local–global processing in ASD but they contain many inconsistencies (for reviews, see Dakin and Frith 2005; Happé and Frith 2006; Simmons et al. 2009; for a meta-analysis, see Van der Hallen et al. 2015). This might in part be due to differences in the tasks used. This, together with difficulties in determining to what extent a task targets local or global processing or whether these abilities are assessed independently or in direct trade-off, blurs the interpretation of research findings (Happé and Booth 2008). In this study we investigated local and global processing abilities and processing style and we will address some of the inconsistencies in the literature. We administered four classical visual processing tasks in children and adolescents with ASD and in matched TD controls. Two of these tasks have traditionally been related to global processing (i.e., coherent motion sensitivity and fragmented object outlines recognition), and one (i.e., the Visual Search task) has traditionally been associated with local processing abilities. However, these tasks actually involve both local and global processes to some extent (see "Discussion"). Nevertheless, in line with a recommendation of Happé and Booth (2008) we tried to reduce the trade-off between increased local and reduced global processing abilities by selecting tasks such that reduced performance in the global processing tasks is not simply due to increased local processing abilities, and increased or faster performance in the local processing tasks is not simply due to reduced global processing abilities. Finally, we included the Rey-Osterrieth Complex Figure task, which was not used to measure processing ability (i.e., how well you can process information in a given way) but processing style (i.e., the natural tendency to process information in a particular way).

In the Coherent Motion task (Milne et al. 2002) a proportion of dots moved coherently in a single direction, creating a fleeting perception of motion, with the remaining dots moving randomly. Participants were requested to indicate the direction of coherent motion. This necessitates global processing, as the global direction of motion can only be inferred by pooling information on individual motion dots, which allows the observer to segregate the signal (coherent motion direction) from the noise (randomly moving dots). In the Fragmented Object Outlines task (Torfs et al. 2010) the outline of an object was gradually built up in ten steps and participants were asked to identify the object as soon as possible. Fragmented object identification requires different types of global processing, since it involves bottom-up grouping of contour fragments (i.e. contour integration) as well as top-down matching of candidate object representations (stored in memory) with perceptual input (Panis and Wagemans 2009). Previous studies have demonstrated that these processes of grouping and matching are influenced by several stimulus attributes, such as object complexity (or homogeneity), object category (natural vs. man-made), global symmetry and fragment curvature (curved vs. straight fragments) (Panis et al. 2008; Panis and Wagemans 2009; Torfs et al. 2010). Manipulating these attributes can therefore help to pinpoint which processes are altered in individuals with ASD.

In the Visual Search task (based on O'Riordan 2004; O'Riordan et al. 2001) participants were instructed to search a pre-specified target embedded within distractors that differed from the target in either color or shape. Several studies have shown that individuals with ASD are faster at detecting the target compared to TD individuals (for a review, see Kaldy et al. 2013), which is supposed to reflect superior local processing abilities, like superior unique item detection and perceptual discrimination. However, O'Riordan (2004) demonstrated that group differences only emerge on difficult search tasks avoiding ceiling effects. To ensure that our task was sensitive enough to detect group differences, we used a similar task to the one developed by O'Riordan (2004), i.e., a conjunction search task in which search difficulty was manipulated by varying the number of distractors and the target-distractor similarity.

To evaluate visual processing style, the Rey-Osterrieth Complex Figure task was used (Tsatsanis et al. 2011). In this open-ended task individuals had to copy a complex multi-part stimulus, without restrictions on how to do so. Afterwards, the degree of continuity or coherence in the drawing process was evaluated, indicating whether participants constructed the figure in a fragmented, piecemeal fashion (reflecting a more local processing style) or whether they continuously drew the configural elements in a coherent fashion (reflecting a more global processing style). The resulting score thus reflects the degree to which a local versus global processing style was employed.

These four local–global visual processing tasks were complemented with a questionnaire measuring attention to detail in daily life. Furthermore, two basic Reaction Time (RT) tasks were included, to allow controlling for potential RT confounds on the Fragmented Object Outlines task and the Visual Search task.

The inconsistencies in studies investigating local–global visual processing in ASD may not only be due to differences in task characteristics, but could also result from differences in sample characteristics, such as gender and age. Thus far, only a few studies have addressed this; the effect of gender in particular has barely been explored. Since ASD is far more common in boys than in girls, many studies only included boys or ensured a group-wise matching for gender ratio. Interestingly, some studies with TD individuals demonstrated gender differences in local–global processing, with the specific effect depending on the task characteristics (Booth 2006; Dukette and Stiles 1996; Kimchi et al. 2009; Kramer et al. 1996; Roalf et al. 2006). Nevertheless, in the general population too, such studies are sparse and most of them investigated differences in local–global processing style, rather than processing abilities. Our study supplements the existing literature by studying gender differences in processing style and processing abilities, and by examining whether group differences between individuals with ASD and TD controls depend on gender. Another factor known to influence local–global processing is age. Studies in TD individuals have shown that, with increasing age, local and global processing abilities improve and there is a shift from a more locally to a more globally oriented processing style (for reviews, see Booth 2006; Happé and Booth 2008). Yet, the size of the age effect and the age of maturation appear to be task and stimulus dependent (Kimchi et al. 2005; Kovács 2000; Quinn and Bhatt 2015; Scherf et al. 2009). So far, less is known about age effects in individuals with ASD and whether differences between TD and ASD individuals are constant throughout development or not. Therefore, we compared the performance of ASD versus TD individuals within two different age groups: children (8–11 years) and adolescents (12–18 years). Furthermore, we investigated the influence of age on task performance and investigated group differences in rates of development. Finally, we explored the association between local–global processing and IQ.

We also explored the mutual associations between the different local–global measures. Currently, it is unclear whether local and global processing abilities are in direct trade-off or whether they are independent abilities. According to the first view, local and global processing abilities constitute two extremes of one dimension, with superior local processing abilities corresponding to reduced global processing abilities and vice versa. In line with this, Frith and Happé (1994) proposed that superior local processing is inherently related to reduced global processing. According to the second view, both types of processing abilities are independent and separate dimensions (Happé and Booth 2008), and performance in one dimension does not predict performance in the other. This second view is supported by studies showing different developmental trajectories for global versus local visual processing (for a review, see Happé and Booth 2008). Interestingly, Booth (2006) demonstrated that both types of processing were positively correlated in TD individuals, while they appeared to be in trade-off in individuals with ASD. Given these findings, we investigated whether the association between the local–global measures depended on group membership (ASD vs. TD).

Finally, we evaluated the association between local–global processing and ASD symptoms. In the revised version of the WCC account, the explanatory scope was limited to the non-social assets and deficits in ASD (restricted and repetitive patterns of behavior and interests, or RRBIs) (Happé and Frith 2006; Happé and Ronald 2008). Nevertheless, Brunsdon and Happé (2014) suggested that altered local–global processing might also be related to ASD impairments in social interaction and communication (see also Noens and van Berckelaer-Onnes 2005, 2008). In general, few studies have examined the relation between local–global processing and ASD symptoms, and conflicting findings have been reported (for a review, see Brunsdon and Happé 2014). Here, we will examine the association between local–global processing and both RRBIs and social ASD symptoms.

Taken together, the current study aimed to investigate altered local and global visual processing abilities and processing style in individuals with ASD compared to TD individuals. We examined whether group differences were robustly found across age groups (children vs. adolescents) and gender, and whether task performance depended on age, gender and IQ. Also the mutual associations between the various local–global tasks were studied, to test whether local and global processing abilities are in trade-off or independent, and how they relate to processing style. Finally, associations between local–global processing performance and ASD symptomatology were addressed.

Methods

Participants

One-hundred and seventeen Dutch speaking children, aged between 8 and 18 years, participated in the study. All had a verbal (VIQ), performance (PIQ), and full-scale IQ (FSIQ) above 70. Fifty-nine participants had a formal diagnosis of ASD, made by a multidisciplinary team according to DSM-IV-TR criteria (American Psychiatric Association 2000). Individuals with a neurologic disorder or severe sensory (including visual) constraints were excluded. Participants had normal or corrected-to-normal vision. Sixteen participants were diagnosed with a co-occurring developmental disorder (seven had an Attention Deficit/Hyperactivity Disorder, one had a tic disorder, four had dyslexia, two had a developmental coordination disorder and two had an anxiety disorder) and six of them took psychoactive medication during the study. Fifty-eight participants were TD children, who were recruited through schools, personal contacts and advertisements. According to parental reports, none of the TD children or any of their first-degree relatives presented a neurological or psychiatric disorder.

A subset of this total sample was included in the group comparisons. For these analyses group membership was more strictly defined, resulting in the exclusion of five individuals with ASD whose diagnosis could not be confirmed with the Developmental, Dimensional and Diagnostic Interview (3di; Skuse et al. 2004) and three TD children who scored 2 *SD* above the mean on the Social Responsiveness Scale (SRS; Constantino and Gruber 2005; Roeyers et al. 2011). Additionally, none of the TD children showed repetitive or stereotyped patterns of behavior as measured with the Repetitive Behavior Scale—Revised (RBS-R; Bodfish et al. 2000). Participants of both groups were group-wise matched for gender, chronological age, PIQ and FSIQ, resulting in two groups comprising 50 children each. Nevertheless, the ASD group had a significantly lower VIQ compared to the TD group. Descriptive statistics for both groups are displayed in Table 1. To allow an unconfounded investigation of the effects of age (children vs. adolescents) and gender (boys vs. girls) on local–global processing in ASD versus TD, each of the subsamples were group-wise matched for all other variables (except for VIQ, see Table 6 in Appendix).

Informed consent was obtained from the participants' parents and from participants aged 16 years or older. The study protocol was approved by the Medical Ethical Committee of the University Hospitals Leuven and the Ethical Committee of the Faculty of Psychology and Educational Sciences of the KU Leuven.

Measures

Intelligence

Intelligence was estimated with an abbreviated version of the Dutch Wechsler Intelligence Scale for Children (WISC-III-NL; Kort et al. 2005) or Wechsler Adult Intelligence Scale (WAIS-III-NL; Wechsler 2005), comprising four subtests: Vocabulary, Similarities, Picture Completion and Block Design (Sattler and Saklofske 2001). The first two subtests provided an estimate of VIQ, while the other subtests provided an estimated PIQ score. Averaging the estimated VIQ and PIQ scores resulted in an estimate of FSIQ.

Coherent Motion Task

The Coherent Motion (CM)task was based on Milne et al. (2002). This task evaluates the ability to detect coherent motion embedded in noise. In each trial, a random dot kinematogram was displayed, comprising a patch (7° × 7° visual angle) of 150 high luminance white dots presented on a black background (similar to Milne et al. 2002; dot size = 1 pixel or 0.08° diameter, angular velocity = 8.8°/s, dot lifetime = 5 frames or 200 ms at a frame rate of 25 frames per second, maximal stimulus presentation = 1 s, dot luminance = 125 cd/m^2, background luminance = 0.39 cd/m^2). A proportion of the dots moved coherently in a single direction (left or right, i.e., signal dots), creating a fleeting perception of motion, with the remaining dots moving randomly in a Brownian manner (noise dots). To increase the global processing demands, a limited dot lifetime was used, preventing the tracking of individual dots and necessitating more global pooling. Participants were asked to indicate the direction of coherent motion by

Table 1 Characteristics of the participants matched for gender, age, PIQ and FSIQ

Characteristics	ASD group (*n* = 50: 30 M, 20F) Mean (*SD*)	TD group (*n* = 50: 30M, 20F) Mean (*SD*)	Test-statistic	*p*
Age (years)	12.21 (2.58)	12.48 (2.72)	$F = -0.25$	.62
VIQ[a]	104.32 (15.86)	111.60 (11.38)	$F = -6.97$	.01
PIQ[a]	104.32 (13.16)	103.84 (13.66)	$F = 0.03$	.86
FSIQ[a]	104.32 (10.83)	107.72 (9.30)	$F = -2.82$	.10
SRS[b,c]				
Total	101.08 (24.24)	20.31 (14.06)	$F = 363.20$	<.001
Social problems	83.38 (20.38)	18.57 (12.59)	$F = 328.09$	<.001
RRBI	17.70 (5.57)	1.74 (1.96)	$F = 356.27$	<.001
RBS-R: total[d]	28.15 (19.86)	0.78 (2.06)	$U = 1544.50$	<.001

[a] Standardized IQ scores; [b] raw scores; [c] data are missing from 8 TD participants; [d] data from 32 participants in each group, matched for age, IQ and gender

pressing the left or right arrow on the keyboard. Responses could be entered as soon as the stimulus appeared on the screen and maximally until 15 s after stimulus presentation. A response terminated the trial and auditory feedback (a tone) was provided after every correct response. CM thresholds were estimated by varying the percentage of coherently moving dots using a two-down, one-up adaptive staircase procedure, targeting the threshold corresponding to 70.7 % correct responses. This threshold reflects the smallest proportion of coherently moving dots that is necessary to reliably perceive the global direction of motion. Percentage coherence started at 100 % and decreased by a factor of 0.14. After four reversals a scale factor of 0.12 was used. A threshold was computed by taking the geometric average of the last 4 of 10 reversals within a given run. Each run was repeated three times and the mean of the resulting three thresholds was calculated as a general index of CM sensitivity. Before data collection, participants were given two short practice blocks to familiarize them with the stimuli and the task. In each block, percentage coherence started at 100 % and decreased by a factor of 0.14. Each practice block was terminated after five correct trials. In the first practice block, a stimulus remained on the screen until a response was given, while in the second practice block, the maximal stimulus presentation was 1 s (as in the experimental trials).

Fragmented Object Outlines Task

We used an adaptation of the Fragmented Object Outlines (*FOO*) *task*, developed by Torfs et al. (2010). In each trial, the outline of an object was gradually built up in ten steps, from the most fragmented image (frame 1, showing 10 % of the contour) to the completely closed contour (frame 10, with 100 % of contour, see Fig. 1a–d). The intermediate built-up steps comprised 10, 12, 16, 21, 27, 35, 46, 59, 77 and 100 % of the contour. Each frame was presented for 1 s. Trials were self-paced and started with a 1 s presentation of a fixation cross. Participants were asked to press a button as soon as they believed they had identified the object. After a button press, an answer box appeared in which the experimenter filled in the verbal response of the participant. This response was then scored by the experimenter (for scoring specifications, see Torfs et al. 2010) and feedback about the correctness was given. When the response was correct, the build-up was terminated and the next trial was initiated. When the response was incorrect, the build-up continued until correct object identification occurred or until the contour was completed. In the last case, participants could give one last answer after which the next trial began. Correct object identification could thus occur on each of the frames (1–10) or after the completed build-up (scored as frame 11). First, six practice trials were administered, followed by 40 experimental trials.

The object outlines were derived from the Snodgrass and Vanderwart (1980) picture set containing 260 line drawings of everyday objects (for more information, see Torfs et al. 2010). To ensure that the task targeted visual integration abilities, we reduced the probability that objects could be identified on the basis of local individual parts, by only showing the contour of the object without information about internal local details. We selected object outlines with high identification rates of the closed contour, as determined in a large adult normative study by Wagemans et al. (2008) and based on a pilot study with 80 object outlines administered to 24 children with ASD and 24 TD children (FSIQ > 70, age: 8–14 years).

In the final stimulus set, containing 40 stimuli, we manipulated global symmetry (20 symmetric vs. 20 non-symmetric objects), object category (20 natural vs. 20 man-made objects), object homogeneity (low vs. high) and fragment curvature (curved vs. straight fragments). Combining the two levels of global symmetry and object category resulted in four categories (with 10 stimuli each) that were matched for mean object homogeneity. Object homogeneity is inversely related to the number of peaks in the contour and thus to object complexity, with more homogeneous objects having fewer peaks and being less complex. It is a continuous measure that was dichotomized in such a manner that an equal number of objects in each category had a low (<12) versus high (>12) homogeneity. Additionally, we applied two types of contour fragmentation. Fragments were placed either around salient points, resulting in curved fragments, or around midpoints, resulting in relatively straight fragments (see Torfs et al. 2010). For each participant, a specific set of 20 objects had curved fragments and another set of 20 objects had straight fragments. However, across participants the fragmentation method applied for both sets of objects was counterbalanced within each participant group (ASD and TD). The presentation order of the objects was individually randomized.

As an index of global processing abilities, we measured when correct object identification occurred, by recording the identification frame (ranging from 1 to 11) and the identification latency (in ms). As control measures, we recorded the proportion of objects that could not be identified, even when the contour was completed (proportion unrecognized objects) and the mean number of attempted answers per trial (number of attempts).

Visual Search Task

In the Visual Search (VS) task (based on O'Riordan 2004; O'Riordan et al. 2001), a stimulus was displayed

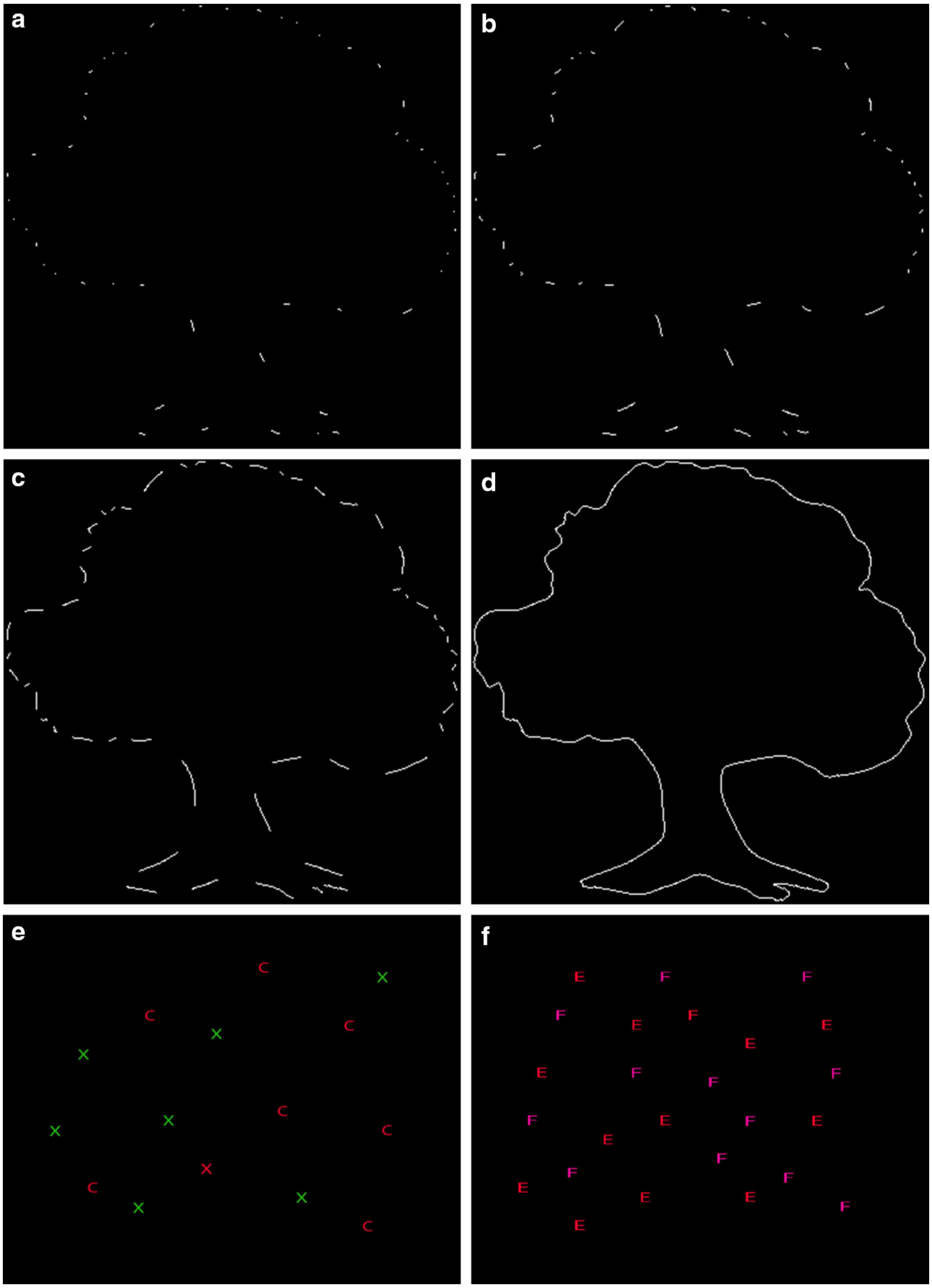

Fig. 1 Stimulus examples from: **a–d** the Fragmented Object Outlines task, respectively showing frame 1, 4, 7 and 10 of the object outline of a tree; **e** the Visual Search task 'low similarity' condition containing 14 distractors; and **f** the Visual Search task 'high similarity' condition containing 24 distractors

containing a pre-specified target hidden among distractors, and participants were instructed to touch the target as soon as possible on the touch screen. Two factors were manipulated within subjects: (1) the number of distractors (14 vs. 24) and (2) the target-distractor similarity. In the 'low similarity' condition, a red X target was hidden among green X and red C distractors. In the 'high similarity' condition, a red F target was embedded between pink F and red E distractors (see Fig. 1e, f). Other stimulus characteristics were the same as described by O'Riordan et al. (2001). Before each trial, participants had to place both hands on the table in front of the touch screen. Then, a fixation cross was presented for 500 ms, followed by the stimulus presentation. The stimulus remained on the screen until the target was touched, or until 10 s elapsed. Afterwards, the experimenter initiated the next trial as soon as the participant placed both hands on the table again. A first practice block with two 'low similarity' trials was followed by a second practice block with two 'high similarity' trials. Afterwards, participants completed 40 experimental trials, divided into two blocks with 10 'low similarity' trials and two blocks with 10 'high similarity' trials. The target remained the same within a block, and participants were instructed what target to search for at the beginning of each block. Within a block, five stimuli with 14 distractors and five stimuli with 24 distractors were randomly presented. The target detection latency (in ms) was registered, which is the time needed to touch the correct target. We additionally calculated the similarity cost, which was defined as the increase in target detection latency in the high similarity compared to the low similarity condition. This individual difference score is thought to reflect the local processing ability to discriminate between different elements or features, with lower values indicating better discrimination. Because hardly any errors were made in this version of the task [M (SD) = 0.12 (0.84)], the number of errors was not informative and was therefore not analyzed.

Rey-Osterrieth Complex Figure Task

In the Rey-Osterrieth Complex Figure (ROCF) task (Rey 1941; Osterrieth 1944), participants had to copy the ROCF according to the procedure applied by Tsatsanis et al. (2011). Afterwards, the style for each drawing was rated, based on the Developmental Scoring System (DSS; Bernstein and Waber 1996) either by one of the authors (LVE or IN) or by two trained research assistants. The research assistants first rated the drawings independently and then met in order to reach consensus. In case of uncertainty, the drawings were additionally scored by one or two of the authors (LVE and/or IN). Based on the ratings, the 'new' style ratio score (developed by Tsatsanis et al. 2011) was calculated, by summing the configural elements from the DSS that were properly aligned and continuously drawn (see Tsatsanis et al. 2011). Compared to the DSS categorical style rating, this score has the advantage that it provides a more continuous measure independent of organization of the figure. Finally, this new style score was reversed, yielding a *fragmentation score* ranging from 0 to 9, with higher scores reflecting a more fragmented or local processing style and thus a less coherent or global processing style.

Control Tasks

Two control tasks were administered. The first is a *Simple Reaction Time* (SRT) *task*, requiring the same motor response as in the FOO task. Participants were instructed to press a button as soon as possible when a square (varying in size and color) appeared on the screen. During each trial a fixation cross was presented centrally for 200 ms, followed by 1000 ms of central stimulus presentation. After each stimulus, feedback was provided for 600 ms. The intertrial interval was 500 ms. First, eight practice trials were completed, followed by 15 experimental trials. The RT (or response latency, in ms) was measured.

The second control task is the *Motor Screening (MOT) test* of the CANTAB (Cambridge Cognition 1996) and mimics the motor response and other basic requirements of the VS task. More specifically, it screens for basic visual, motor and task comprehension difficulties. Participants had to touch a cross, displayed at different locations on a touch screen, as fast as possible, and the mean response latency (in ms) was calculated.

Detail and Flexibility Questionnaire

The *Detail and Flexibility questionnaire* (DFlex) contains 2 subscales: one measuring attention to detail and the other measuring cognitive rigidity (Roberts et al. 2011). Given the focus of this study, we only report the scores on the 'Attention to Detail' scale. The questionnaire was translated into Dutch using the back-translation method.

ASD Symptoms

The *Social Responsiveness Scale* (SRS) for children and adolescents is a normed questionnaire, developed to assess a wide range of behaviors characteristic of ASD (Constantino and Gruber 2005; Roeyers et al. 2011). It consists of five so-called 'treatment scales': social awareness, social cognition, social communication, social motivation and autistic mannerisms. By applying factor-analysis Frazier et al. (2012) demonstrated that a 2-factor model, dividing SRS social and autistic mannerisms scales consistent with DSM-5 'social communication/interaction' and RRBIs domains, best explains the variance in SRS scores. Accordingly, we summed the scores of the 'social' scales to obtain one index of social (communication and interaction) ASD symptoms, while the score on the autistic mannerisms scale was taken as an index of RRBIs.

The *Repetitive Behavior Scale—Revised* (*RBS-R*) assesses the RRBIs observed in individuals with ASD (Bodfish et al. 2000). A distinction is made between 6 different subscales (stereotyped, self-injury, compulsive, ritualistic, sameness and restricted behavior), but we only report the total score. The questionnaire was translated to Dutch using the back-translation method.

Procedure

Participants were tested individually in a quiet room, either at the University Hospital or at school. Besides the tasks described above, additional executive functioning tasks were administered for another study (Van Eylen et al. 2015). The whole testing process took about 4 h, divided into four 1-h sessions. Enough breaks were provided to prevent fatigue. Additionally, computerized tasks were alternated with other task formats to provide enough variation. To prevent order effects, the order of sessions and the order of tasks within a session were counterbalanced. Participants received a small reward for their participation.

Computerized tasks were run on a Dell Latitude E6400 notebook with a refresh rate of 60 Hz. For the FOO task, children were seated 50 cm from the notebook's screen, set to pixel resolution 1024 by 768. For the other computerized tasks, a 17-inch Elo Entuitive touch screen (75 Hz refresh rate) was used at a distance of 57 cm (40 cm for the VS task) and a pixel resolution of 1280 by 1024 (640 by 480 for the CM task). The horizontal angle subtended by the screen at the participant's eye was 90°, ensuring good stimulus visibility.

Questionnaires were completed by the participants' parents.

Data Analyses

Prior to analysis, appropriate transformations (square root or logarithm base 10) were applied if necessary to obtain normally distributed variables. However, in the tables, summary statistics for the raw, non-transformed variables are displayed. For normally distributed local–global and control measures, we investigated the effect of group (ASD vs. TD), age (children vs. adolescents), gender and all two-way interactions. The three-way interaction between group, age and gender was not included in the model, because the number of observations in each cell was too small to produce reliable results. For the VS and the FOO tasks, we also examined the effect of several within-subject factors and their interaction with the between-subject factors. Interactions between within-subject factors were not studied. Since the FOO task also involves verbal processing and both group differs in VIQ, we also included VIQ as a covariate when group differences were found on this task.

An adapted backward model selection procedure was applied to retain the model that provided the best fit. We started from the full model including all effects and eliminated the effects with a p value $\geq .20$. Then, for the remaining effects, all possible combinations were fitted and the best model was selected based on the Akaike and Bayesian Information Criteria (AIC and BIC respectively; Burnham and Anderson 2004). Only this final best model is reported. Since the effect of group was our main interest, it was always included in the model.

For all main local–global measures, Cohen's *d* group effect sizes were calculated by dividing the estimated group difference (Least Square Means) in the final model by the pooled standard deviation ($\sqrt{[(\sigma_1^2 + \sigma_2^2)/2]}$). An effect size ranging from 0.2 to 0.3 is considered small, values around 0.5 are medium and values of 0.8 or above are considered large effects (Cohen 1988).

Repeated-measures mixed model analyses (with Kenward–Roger method to calculate degrees of freedom) were used to analyze repeated measure data. Otherwise, standard ANOVAs were performed for normally distributed variables. For measures that could not be transformed to a normal distribution, non-parametrically Mann–Whitney *U* tests were used to test the effect of group (ASD vs. TD). In the results section we indicate which analysis was performed for each specific variable.

A significance level of $p < .05$ (two-sided) was adopted and post hoc tests were corrected for multiple comparisons using Tukey–Kramer correction. All analyses were performed with and without exclusion of group outliers (>2.5 *SD* of the group mean). If these analyses yielded the same results, only analyses including group outliers are reported. Otherwise, only the results excluding group outliers are mentioned (i.e., for the correct identification frame and latency of the FOO task). For the RT data, also within-subject outliers (>2.5 *SD* of the participant's own mean) were excluded and only correct trials were retained.

To investigate the association among the local–global measures, we calculated zero-order and partial Pearson correlations, the latter controlling for the effect of age and FSIQ. The associations between local–global measures on the one hand and age, FSIQ and ASD symptoms on the other hand, were calculated using Spearman partial correlations, since the assumptions for parametric tests were violated for several variables. Furthermore, generalized linear models were applied to examine group differences in the associations between the local–global measures reciprocally and between these measures and age. These analyses were performed on the matched samples ($N = 100$), to control for possible confounding effects of age, gender and FSIQ. The correlation analyses were performed on the entire sample ($N = 117$).

For some variables there were missing data, mostly limited to one participant per measure. On the RBS-R we have many missing data because it was added to the protocol at a later stage.

Results

Group Comparisons

Table 2 displays descriptive statistics of the final model for the outcome measures. For local–global measures, group effect sizes based on this final model are presented in Fig. 2. For descriptive statistics comparing children and adolescents, see Table 3.

Coherent Motion Task

For the CM task, ANOVA revealed that the *CM threshold* was higher in the ASD compared to the TD group and in children compared to adolescents. However, the effect of group was only significant for the children and the effect of age was only significant for the ASD group [Group × Age interaction: $F(1,\ 96) = 4.60$, $p = .03$; ASD children vs. adolescents: $t(48) = 4.03$, $p < .001$; TD children vs. adolescents: $t(48) = 1$, $p = .75$].

Fragmented Object Outlines Task

For the FOO task, Mann–Whitney U tests showed that the *proportion of unrecognized objects* [ASD: M (SD) = 0.04 (0.04), TD: M (SD) = 0.03 (0.03), $U = 2425$, $p = .48$] and the number of attempts [ASD: M (SD) = 1.11 (0.10), TD: M (SD) = 1.13 (0.08), $U = 2715$, $p = .07$] were comparable between groups. Regarding the *correct identification frame*, repeated-measures mixed models were applied. Although no main effect of group was found, we did observe a group by homogeneity interaction [$F(1,\ 3720) = 10.51$, $p = .001$]. More specifically, individuals with ASD tended to need more frames to correctly identify the contours than TD individuals but only for the high homogeneity condition (see Table 2), and they displayed a larger homogeneity effect [low vs. high homogeneity in the ASD group: $t(3721) = -12.26$, $p < .001$; and in the TD group: $t(3720) = -7.79$, $p < .001$]. Children needed more frames to correctly identify the objects than adolescents (see Table 3), especially for less homogeneous contours (Age × Homogeneity interaction: $F(1,\ 3720) = 17.97$, $p < .001$; age effect for high homogeneity condition: $t(133) = 3.43$, $p = .003$; age effect for low homogeneity condition: $t(134) = 6.55$, $p < .001$), with a larger effect of homogeneity for adolescents [low vs. high homogeneity for children: $t(3720) = -6.92$, $p < .001$; and for adolescents: $t(3720) = -13.25$, $p < .001$]. Overall, the correct identification frame was lower for low (vs. high) homogeneous [$F(1,\ 3720) = 201.39$, $p < .001$] and for symmetrical (vs. non-symmetrical) contours [$F(1,\ 3720) = 22.12$, $p < .001$] and also when the fragments were straight [vs. more curved fragments, $F(1,\ 3720) = 22.37$, $p < .001$]. When including VIQ as a covariate, most effects remained the same, including the non-significant main effect of group [$F(1,\ 100) = 1.08$, $p = .30$] and the significant group by homogeneity interaction [$F(1,\ 3720) = 10.51$, $p = .001$]. However, the effect of group in the high homogeneity condition reduced [$t(132) = 2.14$, $p = .14$].

The results for the *correct identification latency* corresponded to those of the correct identification frame and were therefore not additionally reported here (but see Table 2).

Visual Search Task

For the VS task, the *target detection latency* was analyzed with repeated-measures mixed models and no group differences were found (see Table 2). Overall, individuals with ASD had a slightly higher target detection latency, with a larger (but still non-significant) group difference in the high similarity condition and a larger effect of similarity in the ASD group [Group × Similarity interaction: $F(1,\ 3812) = 8.07$, $p = .005$; low vs. high similarity effect in TD group: $t(3812) = -8.03$, $p < .001$, and in ASD group: $t(3812) = -11.84$, $p < .001$]. Children needed more time to detect the target than adolescents (see Table 3), especially in the high similarity condition (Age × Similarity interaction: $F(1,\ 3812) = 6.98$, $p = .008$; age effect in high similarity condition: $t(124) = 8.53$, $p < .001$; age effect in low similarity condition: $t(124) = 6.75$, $p < .001$), with a larger similarity effect for children [low vs. high similarity effect for children: $t(3812) = -11.70$, $p < .001$; and for adolescents: $t(3812) = -8.10$, $p < .001$]. Overall, the target detection latency was higher in the high similarity (compared to the low similarity) condition [$F(1,\ 3812) = 198.02$, $p < .001$] and with 24 (vs. 14) distractors [$F(1,\ 3812) = 168.71$, $p < .001$].

When analyzing the *similarity cost* using ANOVA, we observed a trend towards a higher similarity cost for individuals with ASD compared to TD individuals and a significantly higher cost for children compared to adolescents (see Tables 2 and 3 respectively).

Rey-Osterrieth Complex Figure Task

For the ROCF task, ANOVA revealed that individuals with ASD had a higher *fragmentation score*, but this group effect was only significant for girls (Group × Gender interaction: $F(2,\ 96) = 7.31$, $p = .001$; see Table 2). Furthermore, in the TD group girls had a lower fragmentation score compared to boys [$t(48) = -3.64$, $p = .003$], while no gender effect was observed in the ASD group

Table 2 Performance on the outcome variables per group per task

Measures per task	ASD ($n = 50$) Mean (*SD*)	TD ($n = 50$) Mean (*SD*)	Group effect *F* value	*p* value	Other significant effects
CM task					
CM threshold[a]	32.10 (17.18)	25.88 (12.02)	4.79	.03	Age***, Group × Age*
Children	39.71 (17.86)	27.23 (11.02)	9.20	.01	
Adolescents	24.49 (12.77)	24.63 (12.97)	0.00	1	
FOO task[c]					
Correct identification frame[a]	5.08 (1.17)	4.85 (1.20)	2.15	.15	Age***, Homogeneity***, Group × Homogeneity*, Age × Homogeneity***, Type***, Symmetry***
Low homogeneity	4.42 (1.27)	4.45 (1.37)	0.03	.99	
High homogeneity	5.73 (1.16)	5.25 (1.13)	6.55	.05	
Correct identification latency (in ms)[a]	4599.07 (1215.61)	4359.93 (1209.26)	1.97	.16	Age***, Homogeneity***, Group × Homogeneity*, Age × Homogeneity***, Type***, Symmetry***
Low homogeneity	3949.22 (1321.75)	3949.74 (1372.19)	0.06	.99	
High homogeneity	5248.16 (1210.57)	4768.47 (1145.65)	5.66	.08	
VS task					
Target detection latency (in ms)[a]	2168.87 (623.48)	2008.75 (428.83)	1.94	.17	Age***, Similarity***, Ndistractors***, Group × Similarity**, Age × Similarity**
Low similarity	1919.3 (541.54)	1858.67 (453.99)	0.13	.98	
High similarity	2417.58 (751.86)	2158.46 (475.61)	5.15	.11	
Similarity cost[a]	568.35 (366.98)	415.74 (221.96)	3.37	.07	Age**
ROCF task					
Fragmentation score	5.04 (2.46)	4.34 (2.75)	4.44	.04	Age***, Group × Gender**
Males	4.67 (2.34)	5.33 (2.60)	1.06	.73	
Females	5.60 (2.58)	2.85 (2.28)	12.64	.003	
DFlex questionnaire[b]					
Attention to detail	51.94 (9.84)	20.31 (8.21)	198.97	<.001	–
SRT task					
Response latency (ms)[a]	301.05 (65.97)	295.78 (47.92)	0.03	.86	Age***
MOT test					
Response latency (in ms)[a]	849.06 (252.72)	866.53 (260.82)	0.15	.70	Age**

p values are displayed for the effect of group or subgroup (the latter only if the effect of group significantly interacts with age, gender and/or task condition; based on contrast analyses with Tukey–Kramer correction). Other significant effects in the final model are also reported

ASD autism spectrum disorders, *TD* typically developing, *CM* coherent motion, *FOO* fragmented object outlines, *VS* visual search, *ROCF* Rey-Osterrieth Complex Figure; *DFlex* detail and flexibility, *SRT* simple reaction time, *MOT* motor screening, *Age* children versus adolescents, *Ndistractor* number of distractors (14 vs. 24)

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

[a] Logarithm base 10 transformation was applied for statistical analysis

[b] Square root transformation was applied for statistical analysis

[c] For the FOO task, results excluding group outliers are reported

[$t(48) = 1.18$, $p = .64$]. Therefore, TD girls also had a lower fragmentation score than boys with ASD ($p = .03$). Finally, children had a higher fragmentation score than adolescents (see Table 3).

Control Tasks

For the *SRT task* and *MOT test*, repeated measures mixed models and ANOVA were applied respectively. They

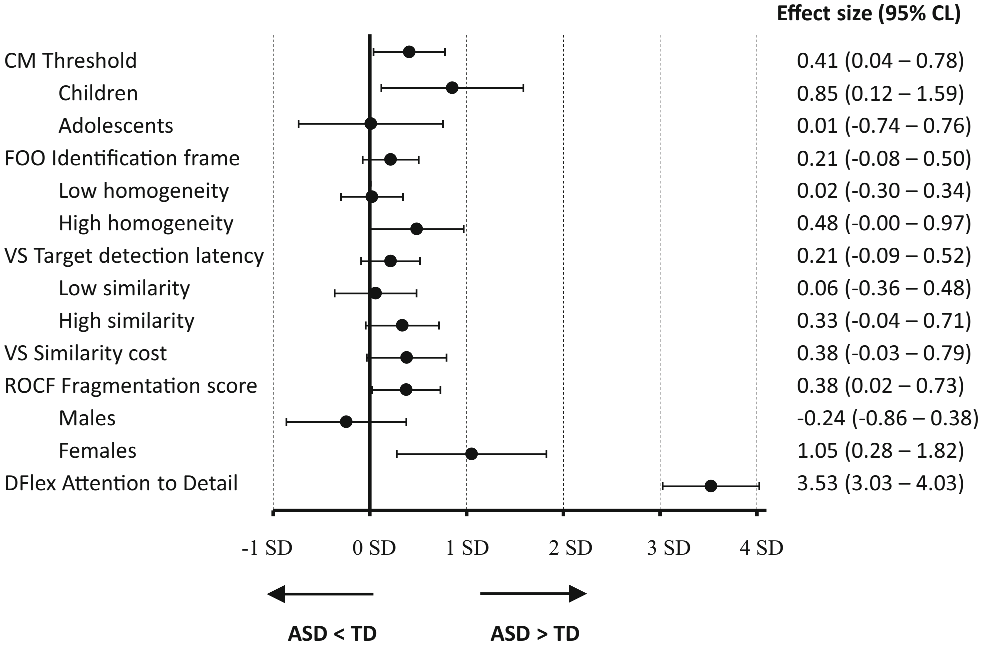

Fig. 2 Effect sizes (expressed as differences in standard deviations) and 95 % confidence limits (CL) for group differences in performance on the local–global processing measures. Positive scores reflect a higher score and negative scores indicate a lower score for ASD compared to TD individuals respectively (ASD > TD vs. ASD < TD). *CM* coherent motion, *ROCF* Rey-Osterrieth Complex Figure, *FOO* fragmented object outlines, *VS* visual search, *DFlex* detail and flexibility questionnaire

Table 3 Comparison of children versus adolescents on the local and global processing measures as well as on the control tasks

Measures per task	Children ($n = 49$)		Adolescents ($n = 51$)	
	Mean (*SD*)	Mean (*SD*)	*F* value	*p*
CM task				
CM threshold[a]	33.60 (16.04)	24.56 (12.74)	12.63	<.001
FOO task[c]				
Correct identification frame[a]	5.54 (1.16)	4.42 (0.92)	28.81	<.001
Correct identification latency (in ms)[a]	5063 (1213)	3919 (918)	27.30	<.001
VS task				
Target detection latency (in ms)[a]	2411 (517.89)	1776 (332.56)	65.74	<.001
Similarity cost (in ms)[a]	603.37 (359.16)	374.44 (194.42)	9.65	.003
ROCF task				
Fragmentation score	5.71 (1.99)	3.71 (2.78)	17.52	<.001
DFlex questionnaire				
Attention to detail[b]	40.06 (22.21)	34.59 (16.55)	–	–
SRT task				
Response latency (in ms)[a]	326.93 (61.52)	271.01 (36.52)	28.04	<.001
MOT test				
Response latency (in ms)[a]	943.19 (307.87)	777.60 (159.61)	11.40	.001

Age (children vs. adolescents) was only included in the final model if it was significant. The reported *F* and *p* values refer to the effect of age in this final model

CM coherent motion, *FOO* fragmented object outlines, *VS* visual search, *ROCF* Rey-Osterrieth Complex Figure, *DFlex* detail and flexibility, *SRT* simple reaction time, *MOT* motor screening

[a] Logarithm base 10 transformation was applied for statistical analysis

[b] Square root transformation was applied for statistical analysis

[c] For the FOO task, results excluding group outliers are reported

Table 4 Spearman correlations between local–global processing measures and age, FSIQ and ASD symptoms for all ASD and TD participants combined

Measures per task	*N*	Age ($N = 117$)	FSIQ ($N = 117$)	Correlations corrected for age and FSIQ: SRS: social problems ($N = 109$)	SRS: RRBIs ($N = 109$)	RBS-R: total ($N = 78$)
CM task						
CM threshold	117	−.41***	−.21*	.21*	.18°	.20°
FOO task						
Object identification latency	117	−.50***	−.35***	.02	.001	−.11
High homogeneity only	117	−.42***	−.31***	.10	.10	−.02
Object identification frame	117	−.51***	−.35***	.01	−.007	−.12
High homogeneity only	117	−.41***	−.31***	.09	.09	−.05
VS task						
Target detection latency	115[a]	−.66***	−.26**	.16°	.23*	.03
High similarity only	115[a]	−.66***	−.22*	.22*	.29**	.03
Similarity cost	115[a]	−.30**	−.13	.24*	.33**	.07
ROCF task						
Fragmentation score	117	−.42***	−.23*	−.0007	.04	.10
DFlex questionnaire						
Attention to detail	78	−.19°	−.38***	.81***	.82***	.84***
SRS						
Social problems	109	−.15	−.31**	–	–	–
RRBIs	109	−.14	−.29**	–	–	.83***
RBS-R						
Total	78	−.24*	−.27*	–	–	–

FSIQ full-scale IQ, *ASD* autism spectrum disorders, *TD* typically developing, *CM* coherent motion, *FOO* fragmented object outlines, *VS* visual search, *ROCF* Rey-Osterrieth Complex Figure, *DFlex* detail and flexibility, *SRS* Social Responsiveness Scale, *RRBIs* restricted and repetitive patterns of behaviour and interests, *RBS-R* Repetitive Behavior Scale—Revised

° $p < .10$; * $p < .05$; ** $p < .01$; *** $p < .001$

[a] Two participants that were colour blind were excluded from the analysis

revealed that both groups performed comparably, but children had a higher response latency than adolescents (see Tables 2 and 3 respectively).

Detail and Flexibility Questionnaire

For the *Attention to Detail* scale of the DFlex questionnaire, ANOVA showed that individuals with ASD scored significantly higher than TD individuals (see Table 2).

Correlations

Correlations with Age and FSIQ

Increasing age and increasing FSIQ were both associated with lower scores and thus better performance on the CM, FOO and VS task (except no correlation was found between FSIQ and the similarity cost of the VS task), a more globally oriented style on the ROCF task and less repetitive behaviors based on the RBS-R. Additionally, increasing FSIQ was associated with less attention to detail based on the DFlex and less social problems and RRBs measured with the SRS. For an overview of these correlations, see Table 4.

Generalized linear models demonstrated that the association between CM sensitivity and age differed between ASD and TD individuals [Group × Age interaction: $F(1, 96) = 6.45$, $p = .01$], with increasing age being associated with increasing sensitivity in the ASD group ($r = -0.58$, $p < .001$) but not in the TD group ($r = -0.18$, $p = .20$). For all other local–global measures, no group by age interaction was found (all $p > .13$).

Correlations Between Local–Global Measures

Table 5 presents the correlations between the local–global measures. Zero-order correlations yielded positive correlations between all measures. After controlling for age and

Table 5 Pearson correlations between local–global processing measures

	N	CM threshold ($N = 117$)	FOO identification frame ($N = 117$)	FOO identification latency ($N = 117$)	VS target detection latency ($N = 115$)	VS similarity cost ($N = 115$)	ROCF fragmentation score ($N = 117$)	DFlex attention to detail ($N = 78$)
CM threshold[a]	117	–	.24**	.23*	.41***	.23*	.21*	.38***
FOO task								
Identification frame[a]	117	−.05	–	–	.49***	.24*	.34***	.17
Identification latency[a]	117	−.06	–	–	.49***	.22*	.34***	.18
VS task								
Target detection latency[a]	115	.19*	.19*[,c]	.19*[,d]	–	–	.35***	.25*
Similarity cost[a]	115	.11	.07	.05	–	–	.16	.22
ROCF fragmentation score	117	−.01	.09	.09	.06	−.02	–	.18
DFlex attention to detail[b]	78	.26*	−.12	−.11	.05	.06	−.002	–

Values above the diagonal represent zero-order correlations, while correlations below the diagonal are partial correlations corrected for age and FSIQ

FSIQ full-scale IQ, *CM* coherent motion, *FOO* fragmented object outlines, *VS* visual search, *ROCF* Rey-Osterrieth Complex Figure, *DFlex* detail and flexibility questionnaire

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

[a] Logarithm base 10 transformation was applied

[b] Square root transformation was applied

[c] After correction for MOT response latency: $r = .10$; $p = .31$

[d] After correction for MOT response latency: $r = .09$; $p = .33$

FSIQ, only the following correlations remained: the target detection latency of the VS task correlated positively with the CM threshold and with both measures of the FOO task (correct identification frame and latency). However, target detection latency of the VS and FOO measures also correlated with MOT latency (VS task: $r = .34$, $p < .001$; both FOO task measures: $r = .29$, $p < .01$). After additionally controlling for this association, the correlation between VS and FOO measures disappeared. Furthermore, the similarity cost of the VS task did not correlate with any of the local–global measures.

We also observed a positive correlation between the CM threshold and the Attention to Detail scale of the DFlex.

Generalized linear models revealed the same associations between the local–global measures (as described above) and indicated that none of these associations differed between the groups (all $p > .10$).

Correlations Between Local–Global Measures and ASD Symptomatology

Some local–global measures correlated positively with ASD symptomatology (see Table 4). More specifically, a higher score on the SRS index of social ASD symptoms was associated with higher CM thresholds, higher scores on the VS task (i.e., the target detection latency on the high similarity condition and the similarity cost), and a higher score on the Attention to Detail scale of the DFlex.

The same local–global measures also correlated positively with the RRBIs score of the SRS, but the correlation with the CM threshold was only marginally significant, while the correlation with the mean target detection latency of the VS task was significant. When RRBIs were measured with the RBS-R, a similar correlation pattern was observed for CM and DFlex, but the correlations with the VS measures were low and insignificant. RRBI scores measured with the SRS versus RBS-R were highly correlated.

Discussion

The present study aimed at investigating local–global visual processing in individuals with ASD compared to TD individuals. In what follows, we first discuss the observed group differences concerning global and local processing abilities and processing style, as well as the influence of task and sample characteristics (such as age and gender) on these group differences. Next, we address the main effect of these sample characteristics and the correlation of age and FSIQ with the local–global processing measures. This is followed by a discussion of the associations between the local–global processing measures and their association with ASD symptomatology. Finally, we summarize the general conclusions and provide directions for further research.

Group Differences in Local–Global Processing

Global Processing Abilities

Global processing abilities were measured with a Coherent Motion and a Fragmented Object Oultines task. Both tasks revealed that individuals with ASD do not present general global processing deficits, but do show subtle reductions in global processing abilities, depending on age and/or stimulus characteristics.

On the *Coherent Motion task*, individuals with ASD had a lower coherent motion sensitivity than TD individuals, which suggests reduced global processing. However, group differences were only significant for children (aged 8–11 years) and not for adolescents (aged 12–18 years). Additionally, only in the ASD group and not in the TD group, an age effect was observed with adolescents outperforming children. Conversely, in a younger sample than ours (5–12 years) Annaz et al. (2010) observed that the performance of TD individuals did improve with age, while this was not the case for individuals with ASD. Taken together, these findings suggest that TD individuals already reach mature coherent motion sensitivity in our task between 8 and 11 years of age, while individuals with ASD show a delayed developmental trajectory. Nonetheless, in adolescence (12–18 years) they attain a similar mature performance level compared to TD individuals. Our findings correspond to the results obtained by Spencer et al. (2000), showing group differences between ASD and TD children aged 7–11 years, with adult-like performance at 11 years only for the TD group. However, their study did not directly compare adolescents with and without ASD, and therefore did not elucidate whether coherent motion sensitivity remains consistently reduced until adulthood or whether it is just developmentally delayed. Our results suggest the latter.

Most previous studies have reported reduced coherent motion sensitivity in ASD, but results are equivocal (for reviews, see Dakin and Frith 2005; Manning et al. 2013; Simmons et al. 2009). Our data indicate that group differences might depend on participants' age. Moreover, several studies revealed that inconsistencies might be due to differences in stimulus parameters. For instance, Robertson et al. (2012) found that adults with ASD differed from TD adults, but only if stimuli were not presented longer than 200 ms. This finding suggests that adults with ASD need more time to globally integrate the visual information, but eventually manage to do so to the same extent as TD individuals. Since our stimuli lasted up to 1 s, this might have led to adequate performance in the ASD adolescents. Likewise, Manning et al. (2013) found reduced coherent motion sensitivity in children with ASD aged 7–14 years, but only if stimulus speed was slow (1.5°/s) and not in the fast speed condition (6°/s). These authors contend that the slow speed condition made it more difficult to perceive the global direction of motion, and therefore made the task more sensitive to reveal group differences. In our paradigm stimulus speed was fast (8.8°/s), possibly precluding subtle group differences in the adolescent group. Taken together, these findings demonstrate that differences in coherent motion sensitivity between ASD and TD individuals are influenced by age and stimulus parameters. More specifically, group differences become more subtle as individuals grow older, and therefore more sensitive tasks, requiring faster and/or more elaborate global processing, are needed to reveal them.

Although reduced coherent motion sensitivity has typically been interpreted as evidence for impaired global processing abilities, alternative explanations have been proposed. Dakin, Mareschal and Bex (2005) indicated that coherent motion sensitivity is limited by both local and global processing. On the one hand, reduced local processing may result in an imprecise estimation of the direction of each individual dot (local motion) and has been associated with high local and internal noise (Dakin et al. 2005; Simmons et al. 2009). On the other hand, global processing deficiencies refer to an inability to globally integrate information across individual dots (which has been related to reduced global pooling or undersampling) and/or an inability to segregate signal from noise dots (Dakin et al. 2005; Manning et al. 2014; Tibber et al. 2014). Decreased motion coherence has also been attributed to a general motion processing deficit due to atypical dorsal stream functioning (Milne et al. 2002; Spencer et al. 2000). While our coherent motion paradigm does not enable us to differentiate between these different accounts of reduced performance, the current literature does provide some directions. For instance, there is evidence that dorsal stream processing and motion perception *per se* are intact in individuals with ASD, rejecting the hypothesis of a general dysfunction of the dorsal visual stream (Bertone et al. 2003; for a review, see Grinter et al. 2010). Moreover, Manning et al. (2014) demonstrated intact processing of local motion, since children with ASD obtained typical direction discrimination thresholds in the absence of noise and presented normal levels of local (internal) noise. These results were obtained with an equivalent-noise paradigm, which disentangles the contribution of local and global factors on motion perception (for more information, see Dakin et al. 2005 and Tibber et al. 2014). Concerning the global factors, Manning et al. (2014) found no evidence for reduced global integration (or pooling) in ASD. In a previous study, Manning et al. (2013) already demonstrated that children with ASD are able to integrate information about individual dots across space and time in the absence of noise, since they showed normal speed discrimination thresholds. However, when signal dots are intermixed with noise dots, like in the coherent motion paradigm, group differences emerge. Together, these findings suggest that children with ASD have no general global information processing deficit, but rather have particular difficulties segregating the signal from the noise. Given the previously mentioned evidence of intact coherent motion sensitivity under certain stimulus conditions, it is clear that even these signal–noise segregation difficulties are quite subtle and only emerge under highly taxing circumstances (for instance, by applying a limited dot lifetime, slow dot speed and/or short stimulus presentations).

On the *Fragmented Object Outlines task*, the effect of group depended on stimulus homogeneity. More specifically, individuals with ASD tended to be impaired in the identification of highly homogeneous fragmented contours, while no group differences were found for low homogeneous contours. Stimulus homogeneity has been shown to affect two types of global processing required in this task: (1) bottom-up grouping via contour integration, and (2) top-down matching of candidate object representations (stored in memory) with the perceptual input (for more information, see Panis and Wagemans 2009, and Torfs et al. 2010). For highly homogeneous contours bottom-up grouping is easier than for low homogeneous contours, but top-down matching is harder because these highly homogeneous contours activate more object representations (Panis and Wagemans 2009; Torfs et al. 2010). Therefore, our findings indicate that individuals with ASD had more difficulty identifying contours that are difficult to match (highly homogeneous), compared to contours that are more difficult to group (low homogeneous contour). This suggests that individuals with ASD have no problems with bottom-up grouping of information or contour integration, but rather have difficulties with more high-level top-down matching, or with the complex interplay between both processes (as argued by Evers et al. 2014). Importantly, group differences on our task could not simply be reduced to group differences in object recognition, in conservativeness to provide answers, or in reaction time since both groups yielded a comparable proportion of unrecognized objects, made an equal number of attempts and had a comparable reaction time (based on the Simple Reaction Time task and the Motor Screening test). Furthermore, group differences in either of these measures would probably result in a main effect of group, but would not provoke the observed group by homogeneity interaction. When controlling for VIQ, we observed the same group by homogeneity interaction. However, the effect of group in the high homogeneity condition reduced. Finally, and in line with previous reports, we observed a main effect of several stimulus characteristics, namely an identification advantage for symmetrical versus non-symmetrical objects, for low versus highly homogeneous contours, and for contours with straight versus curved fragments (Panis et al. 2008; Panis and Wagemans 2009; Torfs et al. 2010). No identification advantage was found for natural versus man-made objects (cf. Evers et al. 2014, but see Panis and Wagemans 2009 and Torfs et al. 2010 for different findings).

Previous studies have also reported intact contour integration in individuals with ASD (Annaz et al. 2010; for a review, see Simmons et al. 2009). In these studies, participants merely had to detect the presence of a fragmented, meaningless contour, whether or not embedded in noise (see Annaz et al. 2010). However, when meaningful fragmented objects are presented and participants have to identify and name them, additional processes are involved (like top-down matching) and group differences have been found. For example, Booth (2006) administered a similar fragmented figures test and found that individuals with ASD needed significantly more time to correctly identify the fragmented objects, although they identified the stimuli in the same frame as TD individuals. However, she also observed a group by IQ interaction and only found group differences in the low IQ subgroup ($M = 58$) and not in the average IQ subsample ($M = 102$). Thus, similar to our findings, individuals with ASD of average intelligence showed no pronounced global processing deficits. Evers et al. (2014) did observe slower fragmented object identification in individuals with ASD of average intelligence using more complex Gaborized object outlines that were embedded in noise. By embedding the contour in a noisy background, additional segregation processes (to segregate the signal from the noise) are required for correct object identification, inducing an even more complex interplay between component processes. Interestingly, Evers et al. (2014) propose that global processing abilities as such are not impaired in ASD, but that the interplay between bottom-up and top-down mechanisms is inefficiently regulated in these individuals.

Taken together, the findings of coherent motion and fragmented object outlines tasks provide a nuanced picture of the visual processing abilities in ASD. Individuals with ASD of average intelligence have no general global processing deficit. Basic integration of motion stimuli and form or contour information per se seems intact. However, group differences do seem to emerge when particular global processes are highly taxed, namely when the signal needs to be segregated from noise and when tasks require a complex interplay between bottom-up and top-down processes.

The observation that reduced global processing abilities are only disclosed if global processes are highly taxed, corresponds to the idea of ASD as a complex information processing disorder (Bertone et al. 2005; Minshew and

Goldstein 1998; Williams et al. 2006). According to that view, individuals with ASD show ‘selective impairments in the neural processing of complex information’, with complexity being defined as the level of demands placed on the brain’s integrative processing capacity (Williams et al. 2006). However, it is still unclear how ‘complex’ these stimuli should be and which advanced global demands are required to yield group differences. Bertone et al. (2005) hypothesized that group differences should emerge as soon as integration of information cannot simply be achieved by V1, but requires activation and coordination between higher-order brain regions. Proceeding from this assumption, individuals with ASD should show deficiencies on both the Coherent Motion and the Fragmented Object Outlines task, since they address brain regions like MT/V5 and prefrontal cortex, respectively (Bar 2003; Braddick et al. 2003). Our findings, however, reveal only subtle impairments on both tasks, depending on age and/or stimulus characteristics. We therefore argue that further research is needed to systematically investigate which factors underlie reduced global processing in ASD.

Local Processing Abilities

Local processing abilities of individuals with ASD were examined using a conjunction Visual Search task, which revealed intact but not enhanced local processing in our ASD group. Consistent with previous reports (O’Riordan 2004), we found that the target detection latency increased with an increasing number of distractors and with a higher target-distractor similarity. However, contrary to our expectations, individuals with ASD were not faster but even slightly slower in target detection (especially in the high similarity condition). This finding could not be due to slower motor responses or difficulties with other basic task requirements in individuals with ASD, since performance on the Motor Screening control test was comparable for both groups. Thus, our results do not corroborate the evidence for superior visual search in ASD (for a review, see Kaldy et al. 2013). Moreover, the search rate of individuals with ASD was more strongly affected by target-distractor similarity compared to TD individuals, with a trend towards a higher similarity cost in the ASD group. These findings conflict with the enhanced discrimination hypothesis as formulated by O’Riordan (2004). O’Riordan (2004) proposed that individuals with ASD present an enhanced discrimination ability, which would be reflected by a reduced influence of target-distractor similarity on target detection latency.

Nevertheless, our observations correspond with those of several other studies. For example, Constable et al. (2012) also reported (insignificantly) slower visual search performance in individuals with ASD and found no group differences in discrimination thresholds. Likewise, Baldassi et al. (2009) administered a different kind of search task and also concluded that enhanced discrimination is not a feature of ASD. Moreover, a recent quantitative meta-analysis comparing visual search performance and discrimination abilities between ASD and TD individuals revealed no group differences (Van der Hallen et al. 2015). Thus, so far, it remains unclear what conditions and stimulus characteristics may induce reduced search rates in individuals with ASD (for some suggestions, see Almeida et al. 2013; Baldassi et al. 2009; Hessels et al. 2014).

At a more general level, there is also debate about the mechanisms driving search task performance (Dakin and Frith 2005; Kaldy et al. 2013; O’Riordan et al. 2001; Wolfe 1998). Although performance on a visual search task is typically interpreted in terms of local processing abilities, it is clear that various types of grouping and integration of information also play a role. Firstly, conjunction visual search requires integration of multiple stimulus dimensions of an object, referred to as feature integration. Secondly, Humphreys et al. (1989) showed that target detection is enhanced under conditions that facilitate grouping of distractors, implying that an increased ability to group distractors (i.e., global processing) would facilitate target detection (see also Duncan and Humphreys 1989; Wolfe 1998). On the other hand, an increased drive to integrate information and to group target *and* distractors might also hinder target-distractor separation and thus visual search performance (Baldassi et al. 2009). This all suggests that the ability to segregate a target from distractors is determined by a subtle balance between local and global processes (for a review of several component processes determining search task performance, see Wolfe 1998). This makes it difficult to interpret the performance of individuals with ASD, since superior performance on particular aspects might be masked by deficiencies in other abilities.

Processing Style

The general processing style was assessed by means of the Rey-Osterrieth Complex Figure task. Here, we found that the ASD group applied a more locally oriented processing style than the TD group, but this group difference was only present in girls and not in boys. Interestingly, this group difference was not due to a more local processing style in girls with ASD, but resulted from a more configural processing style in TD girls compared to any other group (TD boys, ASD boys and ASD girls). In view of a general developmental shift from a more locally oriented to a more globally oriented processing style (Tsatsanis et al. 2011), our findings suggest that TD girls have already completed this shift during childhood (8–11 years), whereas it occurs later in the other groups. So, a relatively delayed or reduced transition from a local to global processing style in girls with ASD compared to TD girls, could bring about the current findings. To further test this hypothesis, additional data from even younger girls are needed. In younger age groups, we would not expect a shifted processing style in TD girls and, accordingly, no group differences between ASD and TD girls. Moreover, additional data from an adult sample could specify whether this shift is simply delayed or also reduced. Pertaining to the lack of group differences in boys, a study of Tsatsanis et al. (2011) indicated that group differences in males only emerged during adulthood. Similar to our study and other reports (e.g., Booth 2006), they found no group differences in children (aged 6–14 years, predominantly consisting of boys) and indicated that this is due to a part-oriented (local) approach in both groups. However, in an older sample (aged 14–42 years) the TD individuals presented a more global processing style than individuals with ASD, as the TD group shifted towards a configural approach, whereas the ASD group remained part-oriented (Tsatsanis et al. 2011). In sum, we only observed a more locally oriented processing style in girls with ASD, but we assume that group differences in males might emerge during adulthood, signifying the importance of investigating different gender and age groups.

Note however that the Rey-Osterrieth Complex Figure task is not a purely perceptual task, since it involves motor action, namely drawing. Accordingly, the findings from this task may not generalize to purely perceptual tasks that do not require any production. Nevertheless, more purely perceptual tasks using Navon-like hierarchical stimuli have also revealed a more locally oriented processing style in ASD (Koldewyn et al. 2013; for a review, see Happé and Frith 2006), but a gender effect has not yet been explored with those tasks.

Attention to Detail in Daily Life

Results from the Detail and Flexibility questionnaire indicated pronounced group differences, with heightened attention to detail in individuals with ASD compared to TD individuals. This provides a strong indication of altered local–global processing in daily life. However, these findings are based on a parent-report questionnaire and might therefore partly reflect reporting biases of the parents. Furthermore, this questionnaire confounds measures of local and global processing, as well as processing style. It is therefore unclear what this score exactly reflects.

Influence of Sample Characteristics on Local–Global Processing

Regarding the influence of sample characteristics on local–global processing, no main effect of gender was observed in any of the administered tasks. However, as mentioned above, a group by gender interaction was found on the Rey-Osterrieth Complex Figure task, with boys demonstrating a more locally oriented processing style than girls, but only for the TD group. These findings are in line with reports of Booth (2006), who showed that TD boys are more part-oriented than girls, although both genders have comparable local and global processing abilities. Only a few studies investigated gender effects in individuals with ASD and they yielded inconsistent findings, probably due to differences in task paradigm and participants' age (Bölte et al. 2011; Lai et al. 2012).

We did observe pronounced age effects on all measures, except the Attention to Detail scale of the Detail and Flexibility questionnaire. These effects were investigated by comparing the performance of children versus adolescents and by investigating the association between the local–global processing measures and age. Both types of analyses revealed that as individuals grow older both their local and global processing abilities improve and they develop a more globally oriented processing style. These findings confirm previous reports (for reviews, see Booth 2006; Happé and Booth 2008). Additionally, we observed a group by age interaction on the Coherent Motion task, with age effects being restricted to the ASD group (see "Global Processing Abilities" section). Furthermore, we found a negative correlation between FSIQ and performance on all local–global processing measures (except the similarity cost of the Visual Search task), indicating that a higher FSIQ is associated with better local and global processing abilities and with a more globally oriented processing style (in line with Booth 2006).

Given the significant effects of both age and FSIQ on local–global processing, it is clear that group differences in these variables are potential confounds that should be controlled for, either by matching the groups or by including age and FSIQ as a covariate (however, see Dennis et al. 2009, for the risks associated with controlling for IQ). Furthermore, since group differences in local–global processing were sometimes restricted to a particular gender (on the Rey-Osterrieth Complex Figure task) or age group (on the Coherent Motion task), it is important to include males and females across a wide age range to obtain a full picture of local–global processing in individuals with ASD.

Correlations Among Local–Global Measures

To examine whether local and global processing abilities are in direct trade-off or constitute independent abilities, we calculated the mutual correlations between the local–global measures. If they are in direct trade-off, a negative correlation was to be expected, whereas no correlation was expected between independent abilities. Zero-order correlations between the local–global measures indicated a strong positive correlation between all measures. However, as mentioned above (see "Influence of Sample Characteristics on Local–Global Processing" section), all local–global measures were also highly correlated with age and FSIQ. After controlling for these potential confounds, most correlations between laboratory measures of local and global processing became non-significant (except for a weak positive correlation between target detection latency on the Visual Search task and the coherent motion threshold). These findings suggest that our laboratory measures of local and global processing ability involve largely different, independent mechanisms (in line with Milne and Szczerbinski 2009). Additionally, we did not find a different correlation pattern for both groups.

Furthermore, no association was found between the different global processing measures (Coherent Motion and Fragmented Object Outlines task). Although both tasks require integration of visual information, the lack of correlation indicates that they mainly rely on different processes. The Coherent Motion task requires integration of motion stimuli in order to segregate the coherently moving dots from the random noise. This relies on dorsal visual stream functioning, critically involving V5/MT (Braddick et al. 2003; Britten et al. 1992). On the contrary, the Fragmented Object Outlines task requires form or contour integration, matching this form percept with object representations stored in memory and semantically labeling them. This mainly relies on ventral visual stream processing and addresses brain regions up to the prefrontal cortex (Bar 2003; Mishkin et al. 1983; but see Braddick et al. 2000). Other studies also found that global processing measures share relatively little variance (Booth 2006; Milne and Szczerbinski 2009), indicating that multiple processes are involved in perceptual integration, and suggesting that different types of global processing co-exist that may be independent of each other. In accordance with Booth (2006), we also found no association between our measures of processing style and local or global processing abilities, implying they also rely on different independent mechanisms.

Finally, increased attention to detail in daily life, as rated by the parents, was associated with reduced coherent motion sensitivity. Daily life situations are typically characterized by many irrelevant sources of information and individuals endogenously have to select and direct attention in order to pick up relevant signals. So, the commonality with the Coherent Motion task may be the requirement to endogenously select attention and integrate information in order to segregate a signal from noise. However, further research is needed to test this assumption.

Overall, we found no evidence for a trade-off between local and global processing abilities. Most tasks did not correlate after correcting for age and IQ, suggesting that they measure different processes (see also Milne and Szczerbinski 2009; Dale and Arnell 2013). The lack of a correlation between global processing measures implies that multiple processes are involved in perceptual integration and suggests that different types of global processing exist that may be independent of each other. It is important to realize this when aiming to chart global processing abilities of particular clinical populations. Other studies indicate that the same applies for different tasks measuring local–global processing style and, although to a lesser extent, tasks measuring local processing abilities (Booth 2006; Dale and Arnell 2013; Milne and Szczerbinski 2009). It is therefore argued that an overall picture of local–global processing requires multiple indices per domain (Milne and Szczerbinski 2009). However, it is currently unclear which different types of local and global processing should be distinguished. This requires a refined understanding of different perceptual organization processes at different levels in the visual system (see Wagemans et al. 2012, for further review and discussion), which will be one of the main challenges of future research in this area.

The Association Between Local–Global Processing and ASD Symptomatology

Finally, we investigated the association between local–global processing and ASD symptom severity, corrected for FSIQ and age. Overall, we observed that poorer performance on some local–global measures was associated with more RRBIs as well as with more social problems, contradicting the view that local–global processing would selectively relate to RRBIs (Happé and Frith 2006; Happé and Ronald 2008).

In general, both symptom domains were associated with reduced coherent motion sensitivity and increased attention to detail in daily life. As indicated above, these local–global measures were mutually related and are hypothesized to reflect the ability to globally integrate information embedded in noise. Accordingly, the positive correlation with ASD symptoms might indicate that a reduced ability to globally integrate information embedded in noise is associated with more ASD symptoms. Note that the association between ASD characteristics and attention to detail in daily life was much stronger than the association with coherent motion sensitivity. This stronger association may be due to a common informant bias for measures that were both based on parental report.

Additionally, slower performance and a higher similarity cost in the Visual Search task were also associated with more social problems and RRBIs, as measured with the Social Responsiveness Scale. However, the wide variety of processes required in the Visual Search task (see "Local Processing Abilities" section) makes it unclear what determines the correlation with the ASD symptom domains. Interestingly, although group differences were found for the Rey-Osterrieth Complex Figure task, individual differences in processing style were not related to individual differences in symptom severity. Possibly, this association may still emerge in older age groups, given that our TD boys still had to make the developmental shift to a more global processing style (see "Processing Style" section).

Overall, these findings suggest that the mixed pattern of results in the literature concerning the association between local–global processing and ASD symptoms might be due to differences in the measures used to tap both local–global processing and ASD symptoms, as well as differences in participants' age (for a review, see Brunsdon and Happé 2014).

Although associations were observed between local–global processing and ASD symptom severity, these associations were small (except between questionnaires) and do not necessarily imply a causal relation. According to some accounts, altered local–global processing is hypothesized to mediate the relation between brain abnormalities and behavior and as such may cause (at least some) ASD symptoms (Brunsdon and Happé 2014; Happé and Ronald 2008). Alternatively, Van de Cruys et al. (2014) propose that a common underlying cause for both the cognitive and the behavioral ASD characteristics might induce a spurious correlation between them. Their basic idea is that ASD results from a specific alteration in predictive coding mechanisms in the brain (i.e., a uniformly high and inflexible precision of prediction errors), pertaining to (meta)learning, attention, perception, social motivation and so forth. Further research is needed to clarify the nature of the association between cognitive and behavioral ASD characteristics, as it has important implications for intervention.

General Conclusions and Future Directions

Although individuals with ASD displayed more attention to detail in daily life than TD individuals, differences in local–global visual processing were far more subtle when measured with laboratory tasks. On these more controlled tasks, no general global processing deficits were found, but individuals with ASD showed slightly reduced global processing abilities. Furthermore, they displayed a more locally oriented processing style and intact, not enhanced, local processing abilities. Additionally, we found that the presence of these group differences depended on particular task and sample (i.e., age and gender) characteristics.

Other studies have also indicated the influence of task characteristics. Concerning global processing abilities, it seems that individuals with ASD only show difficulties when specific global processes (e.g., segregating the signal from noise) are highly taxed. However, further research is needed to elucidate the specific factors underlying altered local–global processing in ASD. Furthermore, since group differences in local–global processing were sometimes restricted to a particular gender or age group, it is important to include males and females across a wide age range to obtain a full picture of local–global processing in individuals with ASD. Our study only included 8–18 year old individuals with a FSIQ above 80. Hence, it remains to be shown whether our findings can be generalized to participants outside this age and IQ range. Moreover, further insight into the maturational trajectories and possible developmental delays of individuals with ASD should be obtained using longitudinal (instead of cross-sectional) designs.

We also found that most measures of local and global processing abilities did not intrinsically correlate and were not associated with processing style. Additionally, although associations were observed between local–global processing and ASD symptom severity, further research is needed to specify the nature of this relationship. Finally, note that local and global processing abilities and processing style are poorly defined constructs. Therefore, more clarity is needed about what they encompass and about the construct validity of specific measures.

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Author contribution LVE conceptualized the study design, programmed the computerized tasks, conducted and supervised the data collection, performed the data-analyses and interpretation, and drafted the manuscript. All other authors made substantial contributions to conception and design. BB provided the script for the Coherent Motion task and helped with adjusting it for the currect study. JW suggested to use the Fragmented Object Outlines task. All authors also critically revised the manuscript, provided feedback and approved the final version of the manuscript.

Compliance with Ethical Standards

Ethical standard The study protocol was approved by the Medical Ethical Committee of the University Hospitals Leuven and the Ethical Committee of the Faculty of Psychology and Educational Sciences of the KU Leuven and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Informed consent Informed consent was obtained from the participants' parents and from participants aged 16 years or older, prior to their inclusion in the study.

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Table 6.

Table 6 Characteristics of all matched subsamples

	n	Age Mean (*SD*)	FSIQ Mean (*SD*)	Gender ratio M:F	Group ratio ASD:TD
ASD	50	12.21 (2.58)	104.32 (10.83)	30:20	–
Children	25	10.13 (1.30)	102.38 (9.40)	14:11	–
Male	14	10.55 (1.20)	103.82 (9.68)	–	–
Female	11	9.58 (1.28)	100.55 (9.16)	–	–
Adolescents	25	14.30 (1.66)	106.26 (11.97)	16:9	–
Male	16	13.89 (1.15)	108.00 (13.96)	–	–
Female	9	15.03 (2.21)	103.17 (6.91)	–	–
Male	30	12.33 (2.05)	106.05 (12.14)	–	–
Female	20	12.04 (3.26)	101.73 (8.13)	–	–
TD	50	12.48 (2.72)	107.72 (9.30)	30:20	–
Children	24	10.25 (1.15)	107.38 (8.28)	15:9	–
Male	15	10.22 (1.12)	107.17 (8.55)	–	–
Female	9	10.28 (1.26)	107.72 (8.32)	–	–
Adolescents	26	14.54 (2.03)	108.04 (10.30)	15:11	–
Male	15	14.03 (1.34)	108.27 (10.02)	–	–
Female	11	15.24 (2.61)	107.73 (11.15)	–	–
Male	30	12.13 (2.28)	107.72 (9.17)	–	–
Female	20	13.01 (3.26)	107.73 (9.73)	–	–
Children	49	10.18 (1.22)	104.83 (9.14)	29:20	25:24
Male	29	10.38 (1.15)	105.55 (9.10)	–	14:15
Female	20	9.90 (1.29)	103.78 (9.31)	–	11:9
Adolescents	51	14.42 (1.84)	107.17 (11.07)	31:20	25:26
Male	31	13.95 (1.22)	108.13 (12.01)	–	16:15
Female	20	15.15 (2.38)	105.68 (9.54)	–	9:11
Male	60	12.23 (2.15)	106.88 (10.70)	–	30:30
Female	40	12.52 (3.26)	104.73 (9.35)	–	20:20

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