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Spatial Cognition in Autism Spectrum Disorders: Superior, Impaired, or Just Intact?

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The profile of spatial ability is of interest across autism spectrum disorders (ASD) because of reported spatial strengths in ASD and due to the recent association of Asperger's syndrome with Nonverbal Learning Disability. Spatial functions were examined in relation to two cognitive theories in autism: the central coherence and executive function (EF) theories. Performance on spatial tasks, EFs, and global/local processing was compared in children with ASD and controls. While the ASD group had faster reaction times on the Embedded Figures task, spatial performance was intact, but not superior, on other tasks. There was no evidence for impairments in EF or in processing global/local information, therefore contradicting these two theories. The implications of these results for these two theories are discussed.

KEY WORDS: Autism; Asperger's syndrome; spatial cognition; executive function; central coherence.

INTRODUCTION

Current research on autism and disorders within the autism spectrum (i.e., Asperger's syndrome, PDD, PDDNOS) is often aimed at understanding how the autistic triad of symptoms may develop. This triad includes deficits in social interaction, communication, and a restricted range of behavior, interests, and activities. Disorders across this spectrum share aspects of this triad of symptoms, but may differ in the severity of symptoms and may be less noticeably impaired in certain aspects of the triad (i.e., better communication skills in Asperger's syndrome versus autism).

Previous research has focused on finding a "core deficit" underlying the triad of symptoms in these disorders. For a core deficit to be a satisfying explanation for the symptoms of autism the deficit must be (1) present early on in development (before the onset of the disorder), (2) be pervasive among individuals with the disorder, and (3) be specific to autism (Pennington, 2002). In addition, this deficit must account for the uneven profile of cognitive abilities in autism. One such division in the cognitive profile of autism that has been proposed is relatively intact, or superior, spatial function in comparison to weaker language and communication skills. In the present research we have attempted to take an integrated look at two theories of primary cognitive deficits in autism (executive function theory (Ozonoff, Pennington, & Rogers, 1991; Russell, 1997) and central coherence theory (Happe, 1999; Frith, 1989; Frith & Happe, 1994) in relation to the profile of spatial cognition in children diagnosed with autism and Asperger's syndrome (or what we will refer to here as autism spectrum disorders, or "ASD").

The profile of spatial ability is of interest across the autism spectrum because of reported spatial strengths in ASD and due to the recent association of Asperger's syndrome with Nonverbal Learning Disability (NLD) (Klin, Volkmar, Sparrow, & Cicchetti, 1995). Klin *et al.* have suggested that Asperger's syndrome and NLD have an associated cognitive profile, including deficits in spatial and executive functions.

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While the association between Asperger's syndrome and NLD predicts spatial deficits in the autism spectrum, anecdotal and research evidence suggests that spatial cognition may be a strength in some individuals with autism. For instance, accounts of autistic artists (Mottron & Belleville, 1993, 1995; Selfe, 1983) are frequent, and it is claimed that those with autism may think in visual-spatial ways in order to compensate for their language deficits (Grandin in Schopler & Mesibov, 1995). Several studies have shown that individuals with autism have intact and sometimes superior performance on spatial tasks that require breaking the whole of a pattern into its component parts (i.e., the WISC Block Design (BD) task, Children's Embedded Figures task (EFT)) (Joliffe & Baron-Cohen, 1997; Morgan, Mayberry, & Durkin, 2003; Shah & Frith, 1983, 1993). Individuals with autism have also been found to have intact abilities in mental rotation (Shah, 1988), the WISC Object Assembly task (see Sigman *et al.* in Cohen, 1987 for a review), and superior performance in map learning (Caron, Mottron, Rainville, & Chouinard, 2004).

Therefore, there seems to be a contradiction between research evidence of a spatial strength in autism and the linking of the cognitive profiles in Asperger's syndrome and NLD. In this study we attempted to broaden what is known about spatial cognition across the autism spectrum by testing spatial functions in children diagnosed with both autism and Asperger's syndrome.

In addition to the inconsistency between the proposed cognitive profiles of Asperger's syndrome and autism, certain inconsistencies are apparent between intact spatial function in ASD and current cognitive theories of these disorders (i.e., executive function (EF) theory and central coherence (CC) theory).

Spatial Cognition and EF Theory

There is an inconsistency between findings of EF deficits in autism and findings that individuals with autism may have strong performance on spatial tasks requiring elements of executive function (i.e., WISC Block Design and drawing). Previous studies have shown EF deficits on tasks such as the Wisconsin Card Sorting Task, Tower of Hanoi, and ID/ED (for a review see Hughes, Russell, & Robbins, 1994; Pennington & Ozonoff, 1996). Deficits in verbal working memory (WM) have also been documented (Bennetto, Pennington, & Rogers, 1996) (See Table I for a list of past studies documenting EF deficits in ASD, including the ages studied and the tasks administered). The Wisconsin Card Sorting task and the Tower tasks have been found to be impaired in a number of studies, with performance on the Tower of Hanoi correctly classifying up to 80% of individuals with autism in some samples (Ozonoff, Pennington, & Rogers, 1991).

The findings that drawing ability, BD, and mental rotation are strong in those with autism are puzzling because these tasks require the coordination of the executive and spatial systems. For example, Carroll (1993) isolated a spatial executive factor in a wide-scale factor analysis of spatial tasks. This factor included tasks such as BD, mental rotation, and spatial construction tasks.

Three possibilities exist that could explain the discrepancy between impaired EF and intact or superior spatial function. First, there may be no Spatial WM deficit, but only a Verbal WM deficit. Intact spatial WM would allow those with autism to maintain, update, and manipulate spatial elements but not verbal elements, thus allowing for intact performance on these spatial tasks. Behavioral and brain imaging evidence suggests that there is a separate pool of resources involved in spatial WM tasks and verbal WM tasks (Baddeley, 1986; Shah & Miyake, 1996). It is then possible that those with autism may show impairments in one system and not in the other system. While some studies have found deficits in spatial working memory (i.e. oculomotor delayed-response task and the antisaccade task: Koczat, Rogers, Pennington, & Ross, 2002; Minshew, Luna, & Sweeney, 1999) in individuals with autism and their families, other studies (Griffith, Pennington, Wehner, & Rogers, 1999; Ozonoff & Strayer, 2001) found this function may be intact. Therefore, there is a question regarding the profile of spatial working memory in autism.

Another possibility is that individuals with autism have learned to compensate for their EF deficits on spatial tasks through very extensive practice. For example, it is possible that some individuals with autism develop a rote memory system for drawing that allows them to access patterns from long-term memory. Reliance on learned patterns would require less processing than is required for the creation of unique drawings. A study (Ring *et al.*, 1999) examining EFT performance found that individuals with ASD showed less prefrontal activation during this task, suggesting that they may have developed strategies that are less reliant on executive function.

Table I. Studies of Executive Functions in Autism Spectrum Disorders

Study	Number of Samples[1], Age[2]	Matched	Measures	Effect sizes *d*
Rumsey (1985)	9 ASD	Age, Sex, Education, PIQ	WCST Perseverative Errors*	1.04
	10 Normal			
	Ages 18–39			
Schneider and Asarnow (1987)	15 ASD	Age, SES, IQ (with schizophrenics)	WCST Perseverative Errors	.48
	11 Schizophrenic			
	28 Normal			
	M age: 11			
Rumsey and Hamburger (1988)	10 ASD	Age, Sex, Education, Handedness	WCST Categories**	1.58
	10 Normal		Trails B**	1.03
	Ages 18–39			
Prior and Hoffman (1990)	12 ASD	Sex, Age, IQ	Mazes (time)**	1.24
	12 Mentally Retarded		WCST Perseverative Errors*	.84
	12 Normal			
	Ages 10–17			
Ozonoff *et al.* (1991)	23ASD	Age, IQ, Sex, SES	WCST Perseverative Errors*	1.18
	20 LD		Tower of Hanoi**	1.91
	Ages 8–20			
Minshew *et al.* (1992)	15 ASD	Age, IQ, Sex, Ethnicity	WCST Perseverative Errors	
	15 Normal		Category Test	.38
	Ages 15–40		Trials B (time)	.03
			Goldstein-Scheerer Sorting Test*	.2
				.91
McEvoy *et al.* (1993)	17 ASD	Age, Verbal & Nonverbal MA, Sex, SES	A-not-B task	.47
	13 Mentally Retarded		Delayed Response task	.02
	16 Normal		Spatial Reversal Task*	.81
	Ages 3–7		Alternation	.54
Ozonoff and McEvoy (1994)	17 ASD	Age, IQ, Sex, SES	WCST Perseverative Errors**	1.17
	17 LD		Tower of Hanoi**	1.83
	Ages 11–23			
Hughes *et al.* (1994)	35 ASD	Age, Verbal & Nonverbal MA	ID/ED Task**	No SDs
	38 Moderate Learning Difficulties		Tower of London**	No SDs
	47 Normal			
	Ages 5–18			
Bennetto *et al.* (1996)	19 ASD	Age, IQ, Sex, SES	WCST Perseverative Errors**	
	19 LD		Tower of Hanoi**	1.19
	Ages 11–24		Wechsler Memory Scale	2.47
			(Sentence Span)**	1.3
			Wechsler Memory Scale	.91
			(Counting Span)**	.81
			TempOrder (words)*	.76
			TempOrder (pictures)*	
Russell, Jarrold, and Henry (1996)	22 ASD	Verbal MA	Dice Counting	.34
	22 LD		Odd Man Out	.05

Table I. Continued.

Study	Number of Samples[1], Age[2]	Matched	Measures	Effect sizes *d*
	22 Normal		Sums Span Task	.11
	M age = 12.5			
Griffith *et al.* (1999)	18 ASD	Age, Nonverbal and Verbal MA, SES	A-not-B	.28
	17 Developmentally Delayed		A-not-B Invisible Displacement	.44
	Ages 3–5		Spatial Reversal	.07
			3 Boxes Stationary	.27
			3 Boxes Scrambled	.42
			6 Boxes Stationary	.28
			6 Boxes Scrambled	.06
Ozonoff and Strayer (2001)	25 ASD	Age, Verbal IQ, Performance IQ	Spatial N Back	No SDs
	15 Tourette syndrome		Box Search	No SDs
	15 Normal		Spatial Location Span	No SDs
	M age = 12.94			

$* p < .05$, $** p < .01$.

The final possibility is that the extent to which EF is the core deficit in ASD has been overestimated in the past. More subtle EF deficits would allow for intact spatial processing. While there has been convincing evidence for deficits in set-shifting and planning in the past literature (see Table I), working memory deficits have been less consistent (Griffith *et al.*, 1999; Ozonoff & Strayer, 2001; Russell, Jarrold, & Henry, 1996). In order to better understand the relationship between potential executive deficits in ASD and the spatial cognitive profile, the present study tested spatial working memory and the most reliably impaired facet of executive function in ASD, set-shifting skill.

Spatial Cognition and CC Theory

There is also an inconsistency between relatively spared function in the spatial cognitive domain and central coherence (CC) theory. CC theory (Frith, 1989; Frith and Happe, 1994; Happe, 1999) posits that those with autism may have difficulty attending to the whole or "gestalt" of spatial configurations and will focus more on local features (i.e., they are said to have "weak central coherence"). Weak central coherence has been put forth as an explanation for good performance on the WISC BD and Embedded Figures tasks. CC theory has also been suggested as an explanation for why individuals with autism may not succumb to perceptual illusions (Happe, 1996).

Although CC theory is a satisfying explanation for EFT performance, the theory does not explain how individuals with autism can have generally intact performance across other areas of the spatial domain. In order to have intact mental rotation, WISC Object Assembly performance, and drawing skill, individuals with autism would have to have the ability to access, utilize, and produce both the local and global levels of spatial configurations. Spared performance on Object Assembly is a particularly salient contradiction with CC theory because this task requires constructing pictures of whole objects (e.g., a horse) out of pieces that do not always have local elements.

In addition to the inconsistency between CC theory and the profile of spatial functions in ASD, the evidence for impairments in global and local spatial processing has been mixed with some studies finding impairments in global processing (Plaisted, Swettenham, & Rees, 1999, Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2000) while others have found no perceptual processing impairments (Brian & Byson, 1996; Jolliffe & Baron-Cohen, 1997;

Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Mottron, Burack, Stauder, & Robaey, 1999; Ozonoff, Strayer, McMahon, & Filoux, 1994). Recent studies of perceptual functioning in ASD have claimed that local processing may be enhanced, but that global processing may remain intact in the face of this perceptual difference (Mottron *et al.*, 2003; Mottron, Peretz, & Menard, 2000). Therefore, we expect that tests of perceptual processing in ASD should reveal normal processing at the global and local levels, thus relating to relatively intact spatial function.

Therefore, one goal of this study was to reconcile the inconsistencies between the spatial cognitive profile in ASD and these two core cognitive theories of this syndrome. In addition, we aimed to better define the spatial-cognitive profile across the autism spectrum. In order to replicate a well-documented area of spatial strength, we administered the Children's Embedded Figures task (CEFT). In addition, to better define the performance of groups with ASD in broader areas of spatial cognition, we tested the learning and memory of spatial locations.

Finally, past research indicating that individuals with autism may have intact or superior abilities in spatial cognition raises questions about how these abilities may develop and how the strategies to complete these tasks may differ in this group. It is possible that individuals with ASD may develop enhanced spatial skills with extensive practice. Because of language and social impairments, children with ASD spend less time engaged in social interactions than typically developing children and thus have more time to practice skills of particular interest. If extensive practice increases the performance of individuals with ASD over time, we would expect to see greater increases in ability with age than seen in typical peers.

Therefore, the specific aims of this study are as follows:

1. To better understand the profile of spatial cognitive function across autism spectrum disorders. Are these functions impaired, superior, or just intact?
2. To examine if the ASD group may have better spatial skills at older ages because of extensive practice, we will determine the contribution of age to performance on spatial tasks.
3. To better understand how functions proposed to be the primary deficit in ASD may relate to the spatial cognitive profile. Therefore, we will compare performance on measures of EF and global and local spatial processing in the samples and determine how these functions may relate to performance on spatial tasks.
4. Finally, because there is controversy regarding the profile of these functions in Asperger's syndrome and autism, we will analyze how these functions may differ in these groups separately.

METHOD

Participants

Children with high functioning autism and Asperger's syndrome ($N = 24$) were recruited through local mental health professionals and several had participated in previous studies at the University of Denver. The typically developing control children ($N = 34$) were recruited through the subject pool at the University of Denver and through local church youth groups. None of the control children had a history of a diagnosis of any developmental disability.

All children in the clinical group had been diagnosed with autism or Asperger's syndrome by experienced clinicians independent of this study. This diagnosis was verified by the Autism Diagnostic Interview-Revised (ADI-R) (Lord, Rutter & Le Couteur, 1994), administered by a trained clinician with .90 reliability with the scales' trainers. See Table 2 for sample characteristics.

Measures

Background Measures

The Block Design (BD) subtest of the WISC-III was utilized as a measure of Performance IQ because of the robustness of this task as a measurement of g (general intelligence). BD is more highly correlated with Full Scale IQ than any other performance measure and is often reliably used in conjunction with the WISC-III Vocabulary subtest as a short form of the WISC-III (Sattler, 2001).

We administered the Peabody Picture Vocabulary Test-Third Edition (PPVT-III) as a measurement of language ability. Correlations between the PPVT-III and standardized tests of cognitive abilities are high (median $r = .85$; Sattler, 2001). While the PPVT-III correlates highly with other measures of language ability, it may not be entirely representative of other language skills in autism, such as expressive language.

In addition to the assessment of behavioral functioning provided by the ADI-R, parents completed the Scales of Independent Behavior-Revised (SIB-R) (Bruininks, Woodcock, Weatherman, & Hill, 1996), a checklist-style rating scale designed to assess adaptive behavior. The SIB-R measures Motor, Social and Communication, Personal Living, and Community Living Skills, and also produces a Broad Independence score. Children with autism have been found to have specific deficits on the social and communication scales of similar measures (Stone, Ousley, Hepburn, Hogan, & Brown, 1999; Freeman *et al.*, 1988).

Handedness was assessed with a modified Edinburgh Handedness Inventory (Oldfield, 1971). In this inventory we recorded which hand or foot the child used on 12 tasks. Handedness was assessed because of previous reports of handedness differences in autism. In addition, we felt the need to control for handedness because some studies have suggested that differences in handedness may be related to differences in global and local spatial processing.

Measures of General Spatial Skill

Children's Embedded Figures Test

The CEFT (Witkin, Oltman, Raskin, and Karp, 1971) was administered to replicate the finding of superior performance on this task in ASD. In this task the child searched a visual display for a figure embedded within the display. For example, one display shows a "tent" shape embedded within the form of a baby carriage. The child's task is to use a cardboard cut-out to show the location of the target figure. Accuracy and total search time was recorded on all trials.

Computerized Morris Water Maze

The ability to remember and learn spatial locations was assessed using a computer-generated virtual Morris water maze task adapted from the water maze task used in animal models (Thomas, Hsu, Laurance, Nadel, & Jacobs, 2001). In the computerized version of the Morris Water Maze, the child uses a joystick to navigate in a computer-simulated arena. In this arena there are markers on the walls that help the child develop a spatial map the room. A blue "rug" is visible on the floor of the arena. The child is instructed to move to the blue rug. After several of these practice trials, the child is told that the rug will now be "invisible", and he or she must search the arena to find it. When the child comes in contact with the target in the invisible trials, the target becomes visible, confirming its location. There are 5 trials in which the child must remember the location of the hidden target. The variable of interest is the mean amount of time that the child spends looking for the target in the correct quadrant of the arena (i.e., the north east (NE) quadrant) across the 5 trials. If the participant has successfully learned the location of the target, then he or she should spend more time searching in the correct quadrant.

EF Measures

CANTAB Spatial WM

The CANTAB Spatial Working Memory test is analogous to the self-ordered pointing task developed by Petrides and Milner (1982). For full description of this task and its use in the study of children's development see Luciana and Nelson (1998). This task requires participants to find targets hidden in an array of boxes on a computer screen by using a touch-screen to search the boxes. The task increases in difficulty from three to eight targets. The boxes are baited one at a time and each box is baited only once. Therefore, to complete the task successfully, the participant must remember the spatial locations where the target has been found previously, update this information as new targets are found, and inhibit incorrect responses (i.e., looking under boxes where a target has already been found). These processes are believed to be central to working memory abilities (Pennington, Bennetto, McAleer & Roberts, 1996), and this task has been found to activate the dorsal and ventral regions of the prefrontal cortex (Owen, Doyon, Petrides & Evans, 1996). Performance on this task is assessed by recording the number of times a participant returns to a box in which he or she has already found a target ("between errors") and by a strategy score measuring the efficiency of the search pattern (i.e., starting in a similar place on each search).

CANTAB ID/ED

The CANTAB ID/ED task was used in order to replicate previous findings of a set-shifting deficit in ASD (Hughes *et al.*, 1994). Very similar to the WCST, the ID/ED task measures discrimination and reversal learning whereby the subject is required to shift their responses based on rules that classify figures as "correct" or "incorrect" responses. In the first stages the child must learn to respond to rules that require shifting their responses within one category of features in the display (the intra-dimensional shift (ID)) from a previously reinforced lined-figure to another lined figure). The last two stages (the extra-dimensional shift (ED)) require shifting responses between categories (i.e., the child must now respond to colored shapes instead of lined figures). The ED shift proves to be difficult due to the reinforcement on the first dimension and has been found to be the most difficult for individuals with autism.

Performance on this task was assessed by measurements of the highest stage that the child completed successfully, the number of errors made at the extradimensional shift, and the trials taken to reach criterion at stages 6 and 8 (the intradimensional and extradimensional shifts). A participant failed to reach criterion and the task was terminated at any stage in which the child completed 50 trials without making six consecutive correct responses. Lowe and Rabbit (1998) assessed the test-retest reliability of this task and found that errors to the ID shift had a reliability of .09, while errors to the ED shift had a reliability of .70. Another study (CeNeS, 1999) found that the reliability of the stages completed was .75.

Global and Local Spatial Processing Measures

Banks and Prinzmetal task

The first measure used to assess global-local spatial processing was a visual search paradigm developed by Banks and Prinzmetal (1976). This task requires the child to find a "T" or "F" that is interspersed with other forms that have features that are halfway between a T or an F. The child's task was to choose, as rapidly as possible by responding to labeled mouse button, whether a "T" or an "F" was present in the display. The experimenter advanced the program between each trial in order to ensure that the child was attending before the stimuli appeared.

Banks and Prinzmetal (1976) found that performance in normal adults was strongly influenced by the gestalt grouping of the elements in the display (See Fig. 1 for the visual grouping conditions on the task). In normal perceptual processing on condition 1, the participant's attention is captured by the global form of the X making it more difficult to search for the target despite the few local elements in the display. On condition 2 the target is grouped separately from the distracters. This global grouping will facilitate processing; reaction times should be fastest on condition 2. On condition 5 the target is deeply embedded within the distracters and reaction times are slowest in this condition. Conditions 3 and 4 (not shown) are conditions in which the target is embedded within distracters, but not as deeply embedded as in Condition 5.

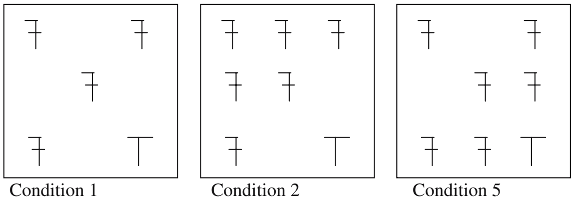

Fig. 1. Conditions of the Banks and Prinzmetal (1976) task.

A measurement of global focus on this paradigm can be derived from the following ratio (Pani, Mervis, & Klein, 1999): (mean condition 1−mean condition 2)/(mean condition 5−mean condition 2). This ratio tells us if the reaction time for condition 1 is closer to condition 2 (the fastest condition) or closer to condition 5 (the slowest condition). Ratios close to one indicate a strong bias from global features, while ratios near zero indicate no bias.

If children with ASD are biased toward the local features of the display, they should show a very different pattern of results across the conditions, and they would be likely to have a lower score for the global pull ratio. Their reaction times would be shorter in condition 1 because of the few local elements; they would show less global pull by the X form. They would also have less advantage from the global grouping in condition 2 because they would be processing the visual information with no reference to the global configuration of the display. Thus, opposite to the pattern seen in normal perceptual processing, their reaction time on condition 1 would be shorter than their reaction time on condition 2. Therefore, a locally focused child's scores on this ratio would be very close to zero and possible negative.

Huttenlocher task

In addition to the Banks and Prinzmetal task, the present study tested perceptual processing by using a spatial coding paradigm developed by Huttenlocher, Hedges, and Duncan (1991). Huttenlocher *et al.* found that people code spatial information in a hierarchical way, by using both the global and local features of a display. They found that when participants were asked to remember the spatial location of a point in a circle, they were using both global and local levels of information to estimate the location, and this strategy could be seen in the nature of their errors. Their errors were biased toward the center of the quadrants in the circle. Those who only use fine-grained or local information without utilizing the global features in their strategies will have responses that are randomly distributed around the target location. Those who utilize only the global features in remembering the location will have errors that are randomly distributed around the categorical prototypes (i.e., around the center of the quadrants).

In the current administration of this task, participants were shown locations in a circle and asked to estimate the location on a touch-screen monitor. After they viewed the location, either on the screen during the practice trials or from a book during tests trials, they estimated the location by touching the corresponding spot on the touch-screen. There was a practice session of five trials in which the child saw two circles concurrently on the screen, one that included a dot. The child practiced copying the dot on the screen in the empty circle during these trials. Proceeded by these initial practice trials were another five practice trials and forty-four test trials in which the child viewed the location in a circle presented in stimulus booklet and touched a blank circle on the screen to indicate the location. Each stimulus was shown very briefly (approximately 1 sec).

If children with ASD code spatial locations in a manner analogous to typically developing children, their estimations should be similarly biased toward the categorical prototype responses (i.e., the center of the quadrants), reflecting their ability to use global information in their estimations. Bias toward categorical information on this task is determined by the difference in an estimate from the prototype. In a particular quadrant, this categorical response rests at 45° and a distance from the diameter of .7 (if the diameter is 1). When the location shown to the individual is closer to the origin than the .7 location, errors are positive (errors toward the .7 location). When the location is closer to the edge than .7 errors should be negative. Thus, if the groups are biased by the categorical representation of the location, examination of the group data should show a negative trend in errors as distance from the origin increases. The bias is also evident for the angle of the response. Locations below 45° in a quadrant cause positive bias (i.e., positive errors) and locations above 45° should cause negative errors. Thus, if a group is biased by the category, a negative trend in errors should be seen as the angle of a location in a quadrant increases. If individuals with ASD have a deficit in global processing, they will have less categorical bias in their answers as compared to typically developing controls. Instead of a negative trend in their errors as the angle in the quadrant or the distance from the radius increases, they will have little or no trend in their errors. Their responses will be close to the actual target with no bias toward the category prototype or the center of the quadrant.

RESULTS

The results will be presented in six sections. The first section details characteristics of the ASD and control samples on the background measures (Table II). The next three sections examine differences between the entire ASD sample and controls on measures of spatial functions, executive functions, and global and local functions. These analyses use linear regression with the sample characteristics, age, and an age by group interaction term as covariates in order to determine the relationship between the background measures and measures of general functioning to task performance. The age by group interaction term was added to determine developmental differences between the samples (Table III).

Next, we detail how the measures of executive functions and global and local spatial processing may relate to performance on the spatial tasks. In the final section we examine the differences between the group with high functioning autism, Asperger's, and the control group on the above mentioned measures (Table IV).

To ensure that the current study had adequate power, throughout the results section we will evaluate the power of the tests to detect group differences.

Background Measures

In order to retain power for detailed analyses of task performance, we will first examine differences in entire ASD sample as compared to controls. This sample included 24 children, aged 7.58 years to 16.75 years ($M = 11.43$ years). The ASD group was compared to 34 control children without developmental disabilities ($M = 11.46$ years, range 7.75–17 years). There were no significant differences between the two groups in chronological age ($p < .40$), in PPVT-III age equivalents or standard scores ($p < .35$) (Dunn & Dunn, 1997), or in Block Design scaled scores ($p < .85$).

Table II. Background Measures in the ASD and Control Samples

Measure	*ASD* (*N* = 24)	*Control* (*N* = 34)[a]	t/χ^2	*P*
M (SD) Chronological age (years)	11.46 (2.32)	12.04 (2.52)	.92	<.40
M (SD) PPVT-III age equivalent (years)	12.85 (4.60)	13.95 (3.62)	.25	<.35
M (SD) PPVT-III standard score	104.40 (20.24)	108.72 (13.04)	.98	<.35
M (SD) WISC Block Design scaled score	12.08 (4.29)	12.32 (4.06)	.20	<.85
% Male	47	84	8.41	<.01
M (SD) Laterality score	.82 (.28)	.87 (.27)	.61	<.55
M (SD) ADI-R reciprocal social interaction[b]	23.18 (3.19)	–	–	–
M (SD) ADI –R communication and language[b]	18.55 (4.17)	–	–	–
M (SD) ADI-R restricted, repetitive behavior and interests[b]	7.50 (2.46)	–	–	–

[a] Control *n* differs between tasks. Sub-samples of children for individual tasks had similar group characteristics to the entire sample.
[b] Means were similar to the mean ADI-R ratings found in Lord, Rutter, and Le Couteur (1994). From Lord *et al.*: *M* ADI-R reciprocal social interaction = 19.00, SD = 3.76; *M* ADI-R communication and language = 16.33, SD = 2.96; *M* ADI-R restricted, repetitive behavior and interests = 4.92, SD = 1.80.

There was also no difference in laterality between the groups ($p < .55$). Similar to the population at large, the ASD group consisted of more males than females. Thus, the groups differed significantly in their gender distributions ($p < .01$). Gender was used as a covariate throughout all of the analyses due to this difference between the groups.

While the groups did not differ on most background measures, children were not specifically selected for the sample based on these characteristics, with the exception of age. Due to time restrictions, some tasks were administered to a sub-sample of control children (Table III lists the tasks that were administered to a smaller sample). The groups did not differ in background measures other than gender in the large sample or the smaller sub-samples. In order to have the best estimate concerning how areas of general ability may relate to performance on measures of spatial ability, EFs, and global and local spatial processing, we included the standard scores on these measures as covariates in the analyses of group performance.

The results of the ADI-R and SIB-R show that the participants tested in the present study could be considered representative of the ASD population at large. This group had scores on the ADI-R similar to the expected range found in Lord *et al.*, (1994) and showed a deficit in social interactions on the social composite score of the SIB-R. The mean chronological age in the ASD group was 11.46 years, but the group's mean social composite age equivalency score on the SIB-R was 8.9 years (*M* social interaction age

Table III. Group Differences in the ASD and Control Groups Covarying Background Characteristics and Age Effects

Measure	ASD *M* (SD)	Control *M* (SD)	*p*	Covariates	Model r^2
Spatial cognition					
CEFT total correct[a]	20.33 (3.77)	20.96 (2.41)	< .40	2***, 3*, 5***	.53
CEFT reaction time[a]	13.89 (5.94)	20.64 (11.05)	< .01	2*, 3*, 5***	.56
% time in target quadrant on Morris Maze	39 (10.7)	43 (12.5)	< .25	3**	.18
Executive function[b]					
CANTAB Spatial WM between errors	41.54 (18.86)	42.95 (15.88)	< .95	2**, 5**	.37
CANTAB Spatial WM strategy score	35.83 (4.46)	36.57 (1.96)	< .55	2**, 5**	.39
CANTAB IDED stages completed	8.21 (.93)	8.09 (1.00)	< .80	2*, 5*	.22
CANTAB IDED stage 6 trials – ID shift	6.88 (1.51)	6.95 (1.74)	< .65	1†	.15
CANTAB IDED stage 8 trials – ED shift	20.26 (15.20)	29.84 (17.81)	< .35	1*, 2†	.34
CANTAB IDED errors at ED shift	12.71 (11.46)	17.67 (9.58)	< .35	1†,2*, 5*	.30
Global and local perceptual processing[c]					
Banks and Prinzmetal global pull ratio	.15 (.92)	.28 (.54)	< .50	None	–
Huttenlocher angular error bias	−.58 (.09)	−.58 (.07)	< .30	1*, 5*	.28
Huttenlocher distance error bias	−.57 (.14)	−.56 (.12)	< .65	5*	.20

covariates: [1]gender, [2]age, [3]age X group, [4]PPVT-III, [5]Block Design, * $p < .05$, ** $p < .01$, *** $p < .001$, † trend, $p < .10$. [a]Control $n = 25$, [b]Control $n = 21$, [c]Control $n = 23$.

Table IV. Mean task scores in the Asperger's Syndrome (AS), High Functioning Autism (HFA), and control groups

Measure	AS $N = 9$		HFA $N = 15$		Control $N = 34$				
	M	SD	*M*	SD	*M*	SD	*F*	*p*	
Background									
Chronological age (years)	11.34	2.52	11.68	2.27	12.04	2.5	.34	<75	
PPVT-III (standard score)	116.33	20.25	98.33	17.83	108.72	13.04	4.08	<.05	*HFA < AS & CONTROL
WISC Block Design (scaled score)	13.33	4.33	11.2	4.33	12.32	4.06	.77	<.50	
Spatial cognition									
CEFT (reaction time)	14.16	6.95	13.74	5.50	20.64	11.05	3.43	<.05	*HFA & AS < CONTROL
% time in target quadrant on Morris Maze	40	7	38	12.4	43	12.5	.69	<.55	
Executive function									
CANTAB Spatial WM (between errors)	34.78	19.41	45.60	17.94	42.95	15.88	1.14	<.35	
CANTAB IDED (stages completed)	8.56	.88	8.00	.93	8.09	.99	1.04	<.40	
Global and local perceptual processing									
Global pull ratio	.00	1.11	.24	.82	.28	.54	.45	<.65	
Angular error bias	−.59	.10	−.57	.09	−.58	.07	.19	<.85	
Distance error bias	−.56	.19	−.58	.10	−.56	.12	.15	<.90	

equivalency = 6.8 years, *M* language comprehension age equivalency = 8.9 years, and *M* language expression age equivalency = 10.9 years).

Tests of General Spatial Skill

Children's Embedded Figures Test

Table 3 details performance on the spatial, executive function, and global and local processing measures. Publications using the EFT in ASD have found effect sizes of 1.32 (Morgan *et al.*, 2003), .82 (Joliffe & Cohen, 1997), and 1.29 (Shah & Frith, 1983), all considered large effects (Cohen, 1992). The sample tested on the CEFT consisted of 24 children with ASD and 25 typically developing controls, or a total of 49 children. Cohen (1992) suggests that power to detect large effect sizes with multiple regression is .80 when the sample has a total of 45 cases and 6 independent variables. Therefore, this study's power to detect differences on the CEFT task was greater than .80.

While the number of targets found on the CEFT did not differ ($p < .40$), the mean reaction time to find the target was significantly different between the groups ($p < .01$). Both variables of performance were related to chronological age ($p < .05$) and Block Design standard score ($p < .001$), and there was a significant interaction of group and age for each variable (See Fig. 2 for a plot of age and reaction time between the two groups). The plot shows that the change in reaction times with age was different in the two samples. The ASD group is significantly better at younger ages, but the performance is more equivalent between the groups at older ages. Therefore, the control group demonstrates more change across age, and "catches up" to the performance in the ASD group. These results replicate a strength in disembedding in ASD, but suggest that the group with autism is not gaining better skills with practice during this period of development. Later analyses will test the processes contributing to performance on this task.

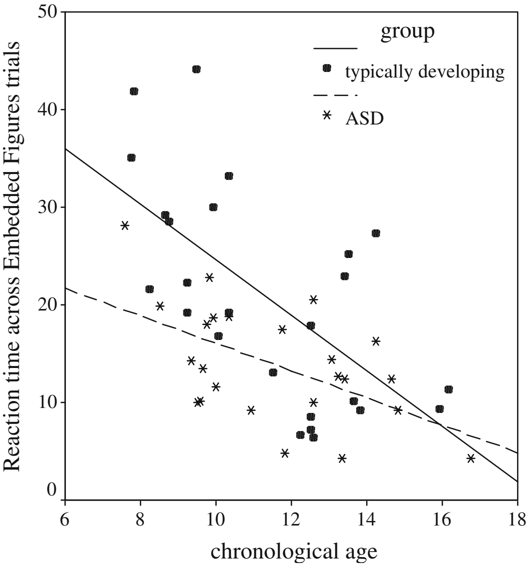

Fig. 2. Mean reaction time of Embedded Figures trials across age in ASD and control groups.

Computerized Morris Water Maze

Task performance was determined by the mean percentage of time the child spent searching for the target in the target quadrant across trials. Both groups spent greater than chance (i.e., 25%) time in the NE quadrant during the learning trials (ASD $M = 39\%$; control $M = 43\%$), suggesting that spatial learning had taken place. The analysis of group performance on this measure showed no difference between the groups ($p < .25$). Suggesting differences with age between the groups, we found a significant interaction of age and group ($p < .01$, See Fig. 3), but no relationship to other background measures. Fig. 3 shows that the typically developing sample is spending more time in the correct quadrant at older ages, but individuals in the ASD group spend roughly the same amount of time in the target quadrant regardless of age. Thus, we found that spatial performance was intact, but not superior, on this task and no increases in performance with age were evident in the ASD sample.

EF Measures

CANTAB Spatial WM

Since other studies have failed to find group differences on Spatial WM tasks (See Table I), we did not calculate power for this task, but we note that our sample (ASD $n = 24$, Control $n = 21$) is as large or larger than the other studies testing this function. Similar to the other studies testing Spatial WM in ASD, we found no differences between the groups on the between errors or strategy score ($p > .55$ for both). Both variables were significantly related to chronological age ($p < .001$ for both) and Block Design standard score ($p < .001$ for both). There was no evidence for differential change with age between the groups or any differences related to gender.

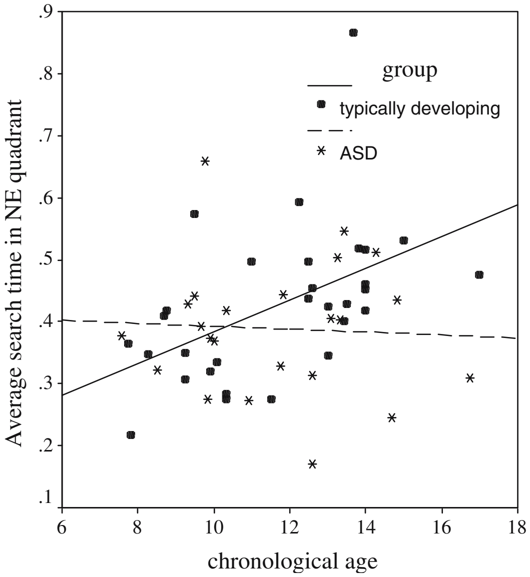

Fig. 3. Mean search time in the target quadrant across age in ASD and control groups.

CANTAB ID/ED

Performance on the ID/ED set-shifting task was also assessed to replicate a deficit in set-shifting. For the analyses of power for this task we used the mean effect size for set-shifting tasks presented in Table I (M effect size = 1.07, large effect). The sample tested on the ID/ED task consisted of 24 children with ASD and 21 typically developing controls, or a total of 45 children. Cohen (1992) suggests that power to detect large effect sizes with multiple regression is .80 when the sample has a total of 45 cases and 6 independent variables. Therefore, we had adequate power to detect group differences on the ID/ED task.

We examined four variables on the task: stages completed, trials to criterion at the intradimensional shift (stage 6), trials to criterion at the extradimensional (ED) shift (stage 8), and errors at the ED shift. Contrary to previous findings in other ASD samples, we found no groups differences that would suggest deficits in set-sifting ($p > .35$ for all variables). Stages completed and errors at the ED shift were both related to chronological age and Block Design standard score ($p < .05$ for both). There were trends for gender to be related to stage 6 trials and errors at the ED shift and for age to be related to stage 8 trials. No other background measures were significantly related. Therefore, contrary to previous studies, we have found no set-shifting difficulties on a computerized version of the ID/ED task.

Global and Local Spatial Processing Measures

Other studies have found mixed results on tests of perceptual function in ASD. In Happe (1996), the effect size for the difference in performance on two-dimensional perceptual illusions was 1.79, but there was no effect for three-dimensional illusions. Our sample size (ASD $n = 24$, Control $n = 23$) is similar to the other studies that have tested these functions, and would allow for adequate power to detect large effect sizes.

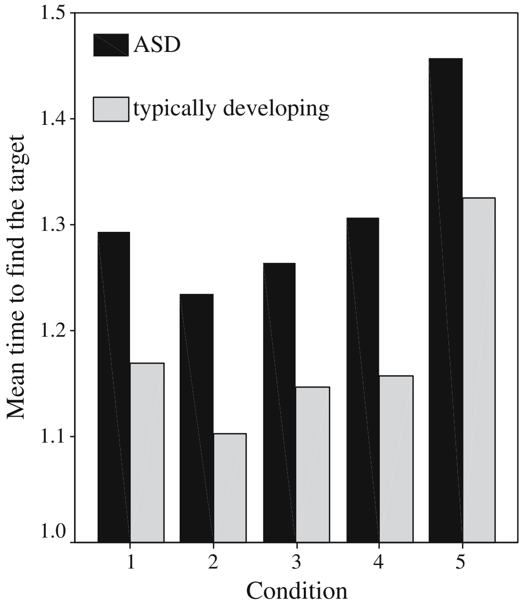

Fig. 4. Reaction times on the Banks and Prinzmetal task in ASD and control groups.

Banks and Prinzmetal task

The accuracy rates of finding the "T" or the "F" in the display were high in both the groups (*M* ASD = 97.6% and *M* control = 98.7%), suggesting that the task administration was valid. Overall, both groups showed the expected pattern of results on this task. Condition 1 was slower than condition 2 on average (t (46) = 3.55, $p < .01$) and condition 5 was the slowest of all of the conditions (t (46) > 7.183 for all, $p < .001$; See Fig. 4 for a display of all five conditions in both groups). We found no differences in the measurement of global pull ($p < .50$). Unlike the other measurements obtained here, no background measures were significantly related to this measure. The ratio of global pull was similar in both groups, suggesting that the ASD and control groups had similar perceptual bias on this task.

Huttenlocher task

The Huttenlocher task measured the extent to which a participant is biased by the global features of a display (the extent that responses to a location in a circle are biased toward a prototypical place in a quadrant—the center of the quadrant). We measured this bias in both radial and angular errors in the children's responses to locations within the quadrant. Consistent with the previous findings in typical populations, we found a significant negative correlation between actual angle, actual radial distance and errors on these dimensions in both groups.

Consistent with the results on the Banks and Prinzmetal task, we found no differences between the groups in the bias on either angular or distance errors ($p < .30$ for angular errors and $p < .65$ for distance errors). Therefore, we did find the perceptual bias that has been found in typical populations, and the bias toward the center of the quadrants did not differ between the groups.

The bias in angular error was related to gender ($p < .01$) and Block Design standard score ($p < .05$), and distance error bias was related to Block Design standard score ($p < .05$). No other background measures were significantly related. These findings are convergent with the findings of the Banks and Prinzmetal task and suggest no perceptual processing deficits on these tasks.

Analyses of Component Processes on the Spatial Tasks

In order to determine how perceptual processing and executive functions may relate to performance on spatial tasks, we examined the contributions of these functions and the interactions between group and these functions to task performance on the CEFT and Block Design tasks. Significant interactions between these functions and group membership would reveal differences in the reliance on each process between the groups.

In this study we have replicated a strength on the CEFT, but that strength is still lacking an explanation. While CC theory has claimed perceptual processes are related to performance on this task, others have claimed that differences in executive functions may be related. For example, in an MRI study examining regional differences in brain activation during the EFT task, Ring *et al.* (1999) found that individuals with ASD showed greater activation in occipitotemporal regions, while control individuals showed task-dependent activation in the prefrontal cortex. Based on these differences, Ring *et al.* theorized that individuals with ASD might be less reliant on executive processes in CEFT task performance.

The absence of group differences on the executive function and perceptual processing measures suggests that the superior performance on EFT must be related to other processes. We directly tested how EF and the perceptual measures related to EFT performance by using linear regression to test whether the difference between the groups could be diminished by factoring in age, performance on these measures and the interactions between group and each of these measures. This model would test whether EF and the perceptual functions may predict EFT performance differently in the two groups.

We found that the group ($p < .05$) and age ($p < .001$) differences remained, but Spatial WM between errors, a composite of angular and distance bias, and the interaction between these two variables and group were not significantly related to EFT performance ($p > .50$). Therefore, differences in these processes could not account for EFT performance.

When we examined Block Design raw score using the same model (group, age, Spatial WM, bias composite, group by Spatial WM, and group by bias), the variables that were significantly related were age ($p < .05$) and Spatial WM between errors ($p < .05$). Group and the interactions between these functions and group were not significant.

Therefore, we found no evidence to suggest that working memory or perceptual functioning were differentially related to CEFT and Block Design task performance in the two groups.

Group differences in Asperger's syndrome, Autism, and Controls

Table IV shows the differences between the groups classified as having Asperger's syndrome (AS), high functioning autism, and in the control group. There was no difference between these three groups in chronological age ($p < .75$). Nine out of the twenty-four children in the ASD group did not qualify as having abnormal language development as assessed by parent's responses on the ADI-R, and therefore could be considered to have AS. In order to qualify as having abnormal language development the child's onset of first words needed to be delayed past 24 months or the onset of phrase speech was delayed past 34 months. In addition, if a parent responded that their child had experienced a loss of language the child was included in the HFA group. The classifications based on the ADI-R matched the clinician's prior diagnosis in all but two cases. In these cases the child had been classified as having Asperger's syndrome but the parent had reported early language delay on the ADI-R.

Similar to previous studies, we found that the Asperger's group had a higher PPVT-III standard score than the group with autism ($p < .05$). We also found that both the ASD groups were quicker to find the embedded figures than controls ($p < .05$ for both). We found no differences between the groups with Asperger's syndrome and autism on spatial tasks, executive function measures or the perceptual measures. These findings are consistent with the findings of other recent studies that have examined the overlap between Asperger's syndrome and autism on neuropsychological tasks (Macintosh & Dissanayake, 2004; Miller & Ozonoff, 2000; Ozonoff & Griffith, 2000; Ozonoff, South, & Miller, 2000). These studies have also shown that differences between Asperger's syndrome and high functioning autism may be more related to disorder severity than underlying differences in the neuropsychological profiles.

DISCUSSION

In sum, while this group with ASD has a strength relative to controls on the CEFT, this strength cannot be fully explained by differences in Spatial WM or by a local processing bias. Despite the evidence for a strength on this task, there was no difference in performance on the computerized Morris Water Maze, suggesting that individuals with ASD are not generally superior across the spatial domain. Therefore, the present study has found evidence for intact, but not superior or impaired function in spatial processes across the autism spectrum. We have also found intact functioning on processes related to good performance on spatial tasks, such as normal perceptual functioning and intact spatial working memory.

In addition, we found no evidence that individuals with ASD develop spatial skills at a faster rate than controls across the ages studied. In fact, on the CEFT the ASD group had better performance at younger ages, but both groups had equivalent performance levels at older ages. On the Water Maze task we found that the rate of development was slower in the ASD group than in controls. Although these findings should be interpreted carefully because of the cross-sectional design and limited age-range, they suggest that children with ASD are not developing enhanced spatial abilities with practice across the ages in this study.

These results may inform us about the cognitive profile in the broader autism spectrum. Some researchers have claimed that Asperger's syndrome is on a continuum with Nonverbal Learning Disability, a population proposed to have deficits in EF and spatial function. The present study included participants with Asperger's syndrome, autism, and controls and found that there was no difference between these groups on spatial cognitive and EF measures. These results suggest that Asperger's syndrome and autism may not be distinct disorders in terms of these cognitive functions, but that Asperger's syndrome and Nonverbal Learning Disability may be distinct.

The present study also found evidence to contradict both central coherence theory and executive function theory. We found that individuals with ASD were biased by the global form on both of our tasks. They showed slowed processing on the Banks and Prinzmetal task in the condition that had a distracting global form (condition 1), and their location estimates on the Huttenlocher task had the typical bias to the center of the quadrant.

Other studies examining central coherence have offered explanations for why we might have not found processing biases on these tasks. For instance, Mottron *et al.* (1999) claimed that local bias might be evident only over a longer time course and in the face of greater processing demands.

Similarly, Jolliffe and Baron-Cohen (2001) claimed that a deficit in global processing in autism might not appear at the perceptual level, but may be a representational deficit. Others, based on similar findings to the present study, have proposed that the Embedded Figures findings may not reflect perceptual processing deficits, but enhanced local processing with intact global processing (Mottron *et al.*, 2003; Mottron *et al.*, 2000). More research is needed to explore how global and local processing deficits might manifest at a representational level and what mechanisms may underlie the strength in EFT task performance.

From the tasks presented here and in other studies, there seems to be substantial evidence that there are no perceptual processing deficits in ASD. Therefore, there is some disagreement between clinical observations of "locally focused" children with ASD and how these same children may perform on tests of hierarchical perceptual processing such as the ones used in the current study. One explanation could be that these types of tests do not tap the cognitive processes that make the children seem "locally" focused. Another possibility is that these clinical symptoms are not representative of all children with ASD.

The present study showed no perceptual processing deficit in this group on two convergent measures, thus resolving a potential inconsistency between a perceptual bias and intact spatial function in this group. In addition to resolving this inconsistency, the potential inconsistency involving EFs and intact spatial performance was resolved by the current finding of no Spatial WM deficit. While the absence of Spatial WM deficits is consistent with the past literature (Griffith *et al.*, 1999; Ozonoff & Strayer, 2001), we did not replicate a set-shifting deficit on the ID/ED task, despite adequate power to detect these effects. While all null results should be interpreted cautiously, we feel confident that the results of the study are valid for a number of reasons. First, we have replicated the strength on the CEFT. Also, while we did not find group differences on a number of measures, we did find that most measures were related to background measures such as age, and importantly, Block Design standard scores.

Although the present findings are contradictory to past evidence claiming a specific deficit in set-shifting in autism (Hughes *et al.*, 1994; Pennington & Ozonoff, 1996), recent evidence suggests that EF deficits may be less pervasive in autism than was originally thought. In fact, recent studies have shown intact performance on EF measures in groups with ASD when extraneous task demands have been minimized. McMahon-Griffith (doctoral dissertation, 2002) has found that lessening the amount of experimenter feedback on tasks such as the WCST can help improve performance in those with ASD to a level equivalent to typical performance. Also, other studies (Ozonoff, 1995; Pascualvaca, Fantie, Papageorgiou, & Mirsky, 1998) have found that the deficits on EF measures were greater when administered by humans than when administered by computer. In the present study the measures of EF were administered with very little feedback or interaction from the experimenter, with most of the interaction taking place when the task instructions were presented to the child.

While many of the findings of set-shifting deficits in Table I could be attributed to human administration, the most striking contradiction to the present ID/ED findings are the findings of Hughes *et al.* (1994). Hughes *et al.* also administered the CANTAB ID/ED task with computer administration. One difference between the methods of the current study and Hughes *et al.* is the mental age level of the groups studied. The participants in the current study, on average, had scores on the PPVT-III and Block Design task that were average or above average. The group studied in Hughes *et al.* was substantially lower in general intellectual ability than the group in the present sample, requiring the use of MA matched typically developing comparisons while the groups in the present study were matched on chronological age. Further research examining EF deficits in autism should clarify the conditions in which we may find deficits in this group, both in administration style and in sample characteristics.

Despite the inconsistencies in the present literature regarding the EF profile in autism, it seems that we have a fair amount of evidence for intact spatial working memory. The finding of no deficit in the present study helps to explain how those with ASD can develop intact performance on spatial tasks reliant on EF.

Earlier we mentioned three possibilities for how the intact spatial profile in autism may develop in relation to the profile of executive functions: (1) Spatial WM is intact, while other EFs are impaired, (2) individuals with autism have developed strategies less reliant on executive functions, and (3) the deficits across areas of executive functions have been overstated in the past. While we have some support to suggest the first and third possibilities, careful analyses of the conditions in which we may find deficits in EFs are needed. In addition, we have found no evidence that spatial skills in autism were related to executive functions in a different way than controls, thus contradicting the second possibility.

In sum, our search to relate the uneven profile of function in autism to these two theories for core cognitive deficits in ASD has left us with little support for either theory. It has been a challenge for cognitive theories of autism to explain the symptoms of this disorder and the uneven profile of cognitive functions. Recent research on autism has moved toward a closer analysis of the social deficits underlying autism, with some studies beginning to link deficits in social processes to the cognitive profile. For instance, Jarrold, Butler, Cottington, and Jimenez (2000) have shown that performance on EFT was related to theory of mind performance in ASD. We then wonder whether it may be possible that intact spatial function and enhanced performance on EFT may develop due to the reallocation of resources from the systems driving social perception and awareness (see Mottron *et al.*, 2000 for a discussion of the "overdevelopment" of perceptual systems in ASD).

Further research may try to examine how enhanced perceptual performance and intact spatial function may relate to deficits in the perception of social information. It would be particularly important to track the development of EFT over time to see if performance may be enhanced over the course of development. While developmental differences were not evident in the current study, it would be important to track these processes at earlier ages.

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REFERENCES

Baddeley, A. D. (1986). *Working memory*. Oxford: Claredon Press.

Banks, W. P., & Prinzmetal, W. (1976). Configural effects in visual information processing. *Perception & Psychophysics*, *19*, 361–367.

Bennetto, L., Pennington, B. F., & Rogers, S. J. (1996). Intact and impaired memory functions in autism. *Child Development*, *67*(4), 1816–1835.

Brian, J. A., & Bryson, S. E. (1996). Disembedding performance and recognition memory in autism/PDD. *Journal of Child Psychology and Psychiatry*, *37*, 865–872.

Bruininks, R. K., Woodcock, R. W., Weatherman, R. F., Hill, B. K. (1996). *Scales of independent behavior – revised (SIB-R)*. The Riverside Publishing Company.

Caron, M. J., Mottron, L., Rainville, C., & Chouinard, S. (2004). Do high functioning persons with autism present superior spatial abilities? *Neuropsychologia*, *42*(4), 467–481.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge: Cambridge University Press.

CeNeS (1999). The temporal stability ('test-retest reliability') of main outcome measures from CANTAB tests [On-line]. Available: http://www.cenes.com/cognition/reliability.html.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155–159.

Dunn, L. M., & Dunn, L. M. (1997). *Peabody picture vocabulary test* (3rd ed.). Circle Pines, MN: AGS Publishing.

Freeman, B. J., Ritvo, E. R, Yokota, A., Childs, J. *et al.* (1988). WISC–R and vineland adaptive behavior scale scores in autistic children. *Journal of the American Academy of Child & Adolescent Psychiatry*, *27*(4), 428–429.

Frith, U. (1989). *Autism: Explaining the enigma*. Oxford: Basil Blackwell.

Frith, U., & Happe, F. (1994). Autism: Beyond "theory of mind". *Cognition*, *50*(1–3), 115–132.

Grandin, T. (1995). How people with autism think. In: E. Schopler, & G. B. Mesibov (Eds.), *Learning and cognition in autism*. New York, NY, USA: Plenum Press.

Griffith, E. M., Pennington, B. F., Wehner, E. A., & Rogers, S. J. (1999). Executive functions in young children with autism. *Child Development*, *70*(4), 817–832.

Griffith, E. M. (2002). The use of feedback in autism, Doctoral Dissertation.

Happe, F. G. E. (1996). Studying weak central coherence at low levels: Children with autism do not succumb to visual illusions.

A research note. *Journal of Child Psychology and Psychiatry*, *37*, 873–877.

Happe, F. G. (1999). Autism: Cognitive deficit or cognitive style? *Trends in Cognitive Sciences*, *3*, 216–222.

Hughes, C., Russell, J., & Robbins, T. W. (1994). Evidence for executive dysfunction in autism. *Neuropsychologia*, *34*(3), 477–492.

Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, *98*(3), 352–376.

Jarrold, C., Butler, D. W., Cottington, E. M., & Jimenez, F. (2000). Linking theory of mind and central coherence bias in autism and in the general population. *Developmental Psychology*, *36*(1), 126–138.

Jolliffe, T., & Baron-Cohen, S. (1997). Are people with autism faster than normal on the embedded figures test? *Journal of Child Psychology and Psychiatry*, *38*, 527–534.

Jolliffe, T., & Baron-Cohen, S. (2001). A test of central coherence theory: Can adults with high-functioning autism or Asperger syndrome integrate objects in context? *Visual Cognition*, *8*(1), 67–101.

Koczat, D. L., Rogers, S. J., Pennington, B. F., & Ross, R. G. (2002). Eye movement abnormality suggestive of a spatial working memory deficit is present in parents of autistic probands. *Journal of Autism & Developmental Disorders*, *32*(6), 513–518.

Klin, A., Volkmar, F., Sparrow, S. S, & Cicchetti, D. (1995). Validity and neuropsychological characterization of Asperger syndrome: Convergence with nonverbal learning disabilities syndrome. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *36*, 1127–1140.

Lord, C., Rutter, M., & Le Couteur, A. (1994). Autism Diagnostic Interview Revised: A revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental disorders*, *24*, 659–686.

Lowe, C., & Rabbitt, P. (1998). Test/re-test reliability of the CANTAB and ISPOCD neuropsychological batteries: Theoretical and practical issues. *Neuropsychologia*, *36*(9), 915–923.

Luciana, M., & Nelson, C. A. (1998). The functional emergence of prefrontally-guided working memory systems in four to eight year old children. *Neuropsychologia*, *36*(3), 273–293.

Macintosh, K. E., & Dissanayake, C. (2004). Annotation: The similarities and differences between autistic disorder and Asperger's disorder: A review of the empirical evidence. *Journal of Child Psychology & Psychiatry*, *45*(3), 421–434.

McEvoy, R., Rogers, S. J., & Pennington, B. F. (1993). Executive function and social communication deficits in young autistic children. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *34*(4), 563–578.

Miller, J. N., & Ozonoff, S. (2000). The external validity of Asperger's disorder: Lack of evidence from the domain of neuropsychology. *Journal of Abnormal Psychology*, *109*, 227–238.

Minshew, N. J., Luna, B., & Sweeney, J. A. (1999). Oculomotor evidence for neocortical systems but not cerebellar dysfunction in autism. *Neurology*, *52*(5), 917–922.

Minshew, N. J., Goldstein, G., Muenz, L. R., & Payton, J. B. (1992). Neuropsychological functioning of nonmentally retarded autistic individuals. *Journal of Clinical and Experimental Neuropsychology*, *14*, 749–761.

Morgan, B., Maybery, M., & Durkin, K. (2003). Weak central coherence, poor joint attention, and low verbal ability: Independent deficits in early autism. *Developmental Psychology*, *39*(4), 646–656.

Mottron, L., Burack, J. A., Iarocci, G., Belleville, S., & Enns, J. T. (2003). Locally oriented perception with intact global processing among adolescents with high-functioning autism: Evidence from multiple paradigms. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *44*(6), 904–913.

Mottron, L., Peretz, I., & Menard, E. (2000). Local and global processing of music in high-functioning persons with autism: Beyond central coherence? *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *41*(8), 1057–1065.

Mottron, L., & Belleville, S. (1993). A study of perceptual analysis in a high-level autistic subject with exceptional graphic abilities. *Brain and Cognition*, *23*(2), 279–309.

Mottron, L., & Belleville, S. (1995). Perspective production in a savant autistic draughtsman. *Psychological Medicine*, *25*(3), 639–648.

Mottron, L., Belleville, S., & Menard, E. (1999). Local bias in Autistic subjects as evidenced by graphic tasks: Perceptual hierarchization or working memory deficit? *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *40*(5), 743–755.

Mottron, L., Burack, J. A., Stauder, J. E. A., & Robaey, P. (1999). Perceptual processing among high-functioning persons with autism. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *40*(2), 203–211.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Owen, A. M., Doyon, J., Petrides, M., & Evans, A. C. (1996). Planning and spatial working memory: A positron emission tomography study in humans. *European Journal of Neuroscience*, *8*, 353–364.

Ozonoff, S., & Strayer, D. L. (2001). Further evidence of intact working memory in autism. *Journal of Autism & Developmental Disorders*, *31*(3), 257–263.

Ozonoff, S., Strayer, D. L., McMahon, W. M., & Filloux, F. (1994). Executive function abilities in autism and Tourette syndrome: an information processing approach. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *35*, 1015–1032.

Ozonoff, S., South, M., & Miller, J. N. (2000). DSM-IV-defined Asperger syndrome: Cognitive, behavioral and early history differentiation from high-functioning autism. *Autism. Special Issue: Asperger syndrome*, *4*(1), 29–46.

Ozonoff, S., Griffith, E. M. (2000). Neuropsychological function and the external validity of Asperger syndrome. In: A. Klin, & F. R. Volkmar *et al*. (Eds.), *Asperger syndrome*. (pp. 72–96). New York, NY, US: Guilford Press.

Ozonoff, S. (1995). Reliability and validity of the Wisconsin Card Sorting Test in studies of autism. *Neuropsychology*, *9*(4), 491–500.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *32*(7), 1081–1105.

Ozonoff, S., & McEvoy, R. E. (1994). A longitudinal study of executive function and theory of mind development in autism. *Development and Psychopathology*, *6*, 415–431.

Pani, J. R., Mervis, C. B., & Klein, B. P. (1999). Global spatial organization by individuals with Williams syndrome. *Psychological Science*, *10*, 453–458.

Pascualvaca, D., Fantie, B., Papageorgiou, M., & Mirsky, A. (1998). Attention capacities in children with autism: Is there a general deficit in shifting focus? *Journal of Autism and Developmental Disorders*, *28*, 467–478.

Pennington, B. F. (2002). *The development of psychopathology: Nature and nurture*. New York, NY, US: Guilford Press.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *37*, 51–88.

Pennington, B. F., Bennetto, L., McAleer, O., & Roberts, R. J. (1996). Executive functions and working memory: Theoretical and measurement issues. In: G. R. Lyon, & N. A. Krasnegor (Eds.), *Attention, memory, and executive function*. (pp. 327–348). Baltimore, MD: Paul H. Brookes Publishing Co.

Petrides, M., & Milner, B (1982). Deficits on subject-ordered tasks after frontal-and temporal-lobe lesions in man. *Neuropsychologia*, *20*(3), 249–262.

Plaisted, K. C, Swettenham, J., & Rees, L. (1999). Children with autism show local precedence in a divided attention task and global precedence in a selective attention task. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *40*(5), 733–742.

Prior, M., & Hoffmann, W. (1990). Brief report: Neuropsychological testing of autistic children through an exploration with frontal lobe tests. *Journal of Autism & Developmental Disorders*, *20*(4), 581–590.

Rinehart, N. J., Bradshaw, J. L., Moss, S. A., Brereton, A. V., & Tonge, B. J. (2000). Atypical interference of local detail on global processing in high-functioning autism and Asperger's disorder. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *41*(6), 769–778.

Ring, H. A., Baron-Cohen, S., Wheelright, S., Williams, S. C. R., Brammer, M., Andrew, C., & Bullmore, E. T. (1999). Cerebral correlates of preserved cognitive skills in autism: A functional MRI study of embedded figures task performance. *Brain*, *122*, 1305–1315.

Rumsey, J. M. (1985). Conceptual problem-solving in highly verbal, nonretarded autistic men. *Journal of Autism & Developmental Disorders*, *15*(1), 23–36.

Rumsey, J. M., & Hamburger, S. D. (1988). Neuropsychological findings in high-functioning men with infantile autism, residual state. *Journal of Clinical & Experimental Neuropsychology*, *10*(2), 201–221.

Russell J. (Eds.) (1997). *Autism as an executive disorder*. London: Oxford University Press.

Russell, J., Jarrold, C., & Henry, L. (1996). Working memory in children with autism and with moderate learning difficulties. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *37*(6), 673–686.

Sattler, J. M. (2001). *Assessment of children: Cognitive applications* (4th ed.). Jerome M. Sattler, Publisher, Inc.

Schneider, S. G., & Asarnow, R. F. (1987). A comparison of cognitive/neuropsychological impairments of nonretarded autistic and schizophrenic children. *Journal of Abnormal Child Psychology*, *15*(1), 29–45.

Selfe, L. (1983). *Normal and anomalous representational drawing in children*. London: Academic Press.

Shah, A. (1988). *Visuo-spatial islets of abilities and intellectual functioning in autism*. London: University of London.

Shah, A., & Frith, U. (1983). An islet of ability in autistic children: A research note. *Journal of Child Psychology and Psychiatry*, *24*, 612–620.

Shah, A., & Frith, U. (1993). Who do autistic individuals show superior performance on the Block Design task? *Journal of Child Psychology and Psychiatry*, *34*, 1351–1364.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *The Journal of Experimental Psychology: General*, *125*(1), 4–27.

Stone, W. L, Ousley, O. Y., Hepburn, S. L., Hogan, K. L., & Brown, C. S. (1999). Patterns of adaptive behavior in very young children with autism. *American Journal on Mental Retardation*, *104*(2), 187–199.

Sigman, M. (1987). Cognitive abilities in autism. In: D. J. Cohen, A. M. Donnellan, & R. Paul (Eds.), *Handbook of autism and pervasive developmental disorders*. New York, NY, USA: John Wiley and Sons.

Thomas, K., Hsu, M., Laurance, H. E, Nadel, L., & Jacobs, W. (2001). Place learning in virtual space III: Investigation of spatial navigation training procedures and their application to fMRI and clinical neuropsychology. *Behavior Research Methods, Instruments & Computers*, *33*(1), 21–37.

Witkin, H. A., Oltman, P. K., Raskin, E., & Karp, S. A. (1971). *A manual for the embedded figures tests*. Palo Alto, CA: Consulting Psychologists Press.