Neuropsychologia 49 (2011) 848–857

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Enhanced mental image mapping in autism

I. Soulières[a,b,*], T.A. Zeffiro[a], M.L. Girard[b], L. Mottron[b,c]

[a] Neural Systems Group, Massachusetts General Hospital, Harvard Medical School, Boston, United States
[b] Centre d'excellence en Troubles envahissants du développement de l'Université de Montréal (CETEDUM), Hôpital Rivière-des-Prairies, Montréal, Canada
[c] Département de psychiatrie, Université de Montréal, Canada

ARTICLE INFO

Article history:
Received 22 April 2010
Received in revised form 12 January 2011
Accepted 13 January 2011
Available online 21 January 2011

Keywords:
Mental rotation
Visual imagery
Discrimination
Perception
Enhanced perceptual functioning model
Autism

ABSTRACT

The formation and manipulation of mental images represents a key ability for successfully solving visuospatial tasks like Wechsler's Block Design or visual reasoning problems, tasks where autistics perform at higher levels than predicted by their Wechsler IQ. Visual imagery can be used to compare two mental images, allowing judgment of their relative properties. To examine higher visual processes in autism, and their possible role in explaining autistic visuospatial peaks, we carried out two mental imagery experiments in 23 autistic and 14 age and IQ matched, non-autistic adolescents and adults. Among autistics, 11 had significantly higher Block Design scores than predicted by their IQ. Experiment 1 involved imagining a letter inside a circle, followed by a decision concerning which of two highlighted portions of the circle would contain the greater proportion of the letter. Experiment 2 involved four classic mental rotation tasks utilizing two- and three-dimensional geometric figures, hands and letters. Autistics were more accurate in the formation and comparison of mental images than non-autistics. Autistics with a Block Design peak outperformed other participants in both speed and accuracy of mental rotation. Also, Performance IQ and Block Design scores were better predictors of mental rotation accuracy in autistic compared to non-autistic participants. The ability to form, access and manipulate visual mental representations may be more developed in autistics. We propose two complementary mechanisms to explain these processing advantages: (1) a global advantage in perceptual processing, discussed in the framework of the enhanced perceptual functioning model, and (2) particular strengths in *veridical mapping*, the ability to efficiently detect isomorphisms among entities and then to use these mappings to process stimulus characteristics, thereby facilitating judgments about their differences.

1. Introduction

Perceptual strengths in autism are observed in both visual (Dakin & Frith, 2005) and auditory (Gomot, Belmonte, Bullmore, Bernard, & Baron-Cohen, 2008) modalities, spanning multiple processing domains within each modality (Mottron, Dawson, Soulières, Hubert, & Burack, 2006). Whereas previous research was aimed at discovering how unique impairments might explain these relative advantages, recent systematic studies indicate that perceptual enhancement in autism reflects a distributed advantage in a large range of tasks, including perceptual discrimination and pattern detection, as well as cognitive functions that rely on perceptual inputs, including perceptual memory and attention to perceptual targets. Although the complex interplay between perceptual and cognitive processes in autism is not fully understood, there are indications that enhanced performance in perceptual tasks is associated with an overall enhanced and relatively autonomous role for perception in cognitive tasks, evidenced by a less automatic role of contextual influences and a diminished influence of knowledge on perception (Mitchell, Mottron, Soulières, & Ropar, 2010; Ropar & Mitchell, 2002).

However, surprisingly few studies have examined tasks relying on pattern *manipulation* in autistics. This study utilizes mental rotation tasks to investigate the access and manipulation of visual images in autism. A large fraction of autistics reliably excel in types of reasoning involving visuospatial abilities like the Block Design tasks, demonstrating a phenotypic "peak" compared to their performance on other subtests of the Wechsler Intelligence Scales (Caron, Mottron, Berthiaume, & Dawson, 2006; Shah & Frith, 1993). Performance on Raven's Progressive Matrices has also been investigated in autism and found to be higher than expected based on their Wechsler IQ (Dawson, Soulières, Gernsbacher, & Mottron, 2007; Hayashi, Kato, Igarashi, & Kashima, 2008). Some of the perceptual processes involved in Block Design tasks and Raven's Progressive Matrices include the creation, access and manipulation of visual mental images. Visual mental imagery is considered a special case of visual perceptual access without sensory input (Kosslyn, Ganis, &

* Corresponding author at: CETEDUM, Hôpital Rivière-des-Prairies, 7070 Blvd Perras, Montréal, Québec H1E 1A4, Canada. Tel.: +1 1514 323 7260x4579.
E-mail address: isabelle@nmr.mgh.harvard.edu (I. Soulières).

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doi:10.1016/j.neuropsychologia.2011.01.027

Thompson, 2001). In this view, not only do visual imagery and perception both elicit similar activity in visual cortex, they also rely on the same content-specific representations within visual areas (Stokes, Thompson, Cusack, & Duncan, 2009). Therefore, autistic visual skills may trigger advantages in visual imagery. In contrast, diminished top-down perceptual effects in autistics could bring difficulties in conscious and voluntary manipulation of visual images.

Visual mental imagery tasks may optionally involve a spatial manipulation component, such as rotation. Some tasks require a size, resemblance or identity judgment to achieve visual comparison of two mental images. Examples include questions such as "Is an elephant larger than a camel?" or "Does an "8" resemble a pair of spectacles?". However, a classic experimental task used to investigate visual mental imagery involves comparing two images using mental rotation. In a widely replicated study, Shepard and Metzler (1971) studied mental rotation of pairs of three-dimensional geometric shapes that were either identical or mirror images of each other. The shapes were rotated by various angles relative to each other, requiring the participants to mentally rotate one shape to judge if it was identical to the other. In that experiment, and in many other variations using letters, objects, tools, or hands, the observed response times in typical subjects increase gradually as the angle of rotation between the two shapes increases, suggesting that participants are performing mental rotation of the shapes to complete the task. In these studies, accuracy often decreases as the angle of rotation increases.

Some preliminary findings are indicative of a relative strength in mental rotation and visual mental imagery in autistics. In one study, a mixed group of autistic and Asperger children, aged 9–16 years old, outperformed control children in a mental rotation task involving three-dimensional geometric shapes, displaying faster response times (Falter, Plaisted, & Davis, 2008). A similar pattern was also found in an exploratory fMRI experiment (Silk et al., 2006), in which autistic participants were 15% faster than non-autistic participants, although the speed differential did not reach statistical significance in the relatively small sample examined. In another study, autistic children, aged 4–12 years old, were better than non-autistic children at mental rotation when matched on verbal mental age using the British Picture Vocabulary Scale. While their performance seemed comparable to that of a small control group matched on mean chronological age but with higher intellectual level, no statistical support to this inference was provided (Hamilton, Brindley, & Frith, 2009).

Our principal goal was to investigate the creation, access and manipulation of visual images in autism using varying numbers of stimulus dimensions, materials and manipulations in order to assess the role of perception and manipulation in explaining predicted differences in autistics' visual processing skills. In Experiment 1 we assessed the ability to form a mental representation of an object and to map this representation to another two-dimensional image, without rotation. This task allowed group comparisons of the ability to create and map pairs of visual mental images, in contrast to the mental rotation tasks, which require additional spatial manipulation. Strength in this sphere, in addition to classical mental rotation tasks, would indicate that rotation is only one among many operations involving mapping between visual representations in which autistics exhibit strong abilities.

In Experiment 2 we utilized four mental rotation same-different tasks, including (1) images of three-dimensional geometric figures, (2) images of two-dimensional geometric figures, (3) drawings of hands, and (4) letters. We varied the task to investigate the robustness of the predicted differences with respect to both different stimulus types and the nature of the information manipulated. Using both two- and three-dimensional figures revealed whether performance is differentially influenced by task complexity in autistics. The use of hands as stimuli allowed examination of whether mental rotation mechanisms based on sensorimotor representations might operate differently in autism. Whereas mental rotation relies by default on analog spatial representations, stimuli such as hands additionally elicit representations in the sensorimotor system (Zacks, 2008). Since autistics may have atypicalities in sensorimotor development (Minshew, Goldstein, & Siegel, 1997; Noterdaeme, Mildenberger, Minow, & Amorosa, 2002) and exhibit different patterns of brain activity during visuomotor tasks including imitation (Muller, Cauich, Rubio, Mizuno, & Courchesne, 2004; Muller, Pierce, Ambrose, Allen, & Courchesne, 2001), the autistic strength in mental rotation may not be seen with stimuli likely to involve sensorimotor representations. Finally, the use of letters, a class of stimuli with which our participants were highly familiar, explored how mental rotation abilities are differentially influenced by familiarity.

A second objective of the study was to evaluate the aggregation of mental imagery skills with other visuospatial abilities at the individual level in autistics. Do autistic individuals who exhibit strengths in Block Design tasks compared to their estimated IQ also exhibit enhanced performance in mental rotation? Our design subdivided autistics into two groups according to their performance on Block Design relative to their average level in the other IQ subtests. Although visuospatial abilities, and more specifically Block Design performance, range over a continuum, grouping autistic participants with Block Design performance higher than their other cognitive abilities allowed examination of the degree of aggregation of visuospatial abilities in a group representing one end of the continuum. Using correlation analysis also allowed examination of the aggregation of visuospatial strengths in all autistic, relative to non-autistic, participants.

2. Method

2.1. Participants

Twenty-three autistic adolescents and young adults were randomly recruited from the database of the Specialized Clinic for Pervasive Developmental Disorders of Rivière-des-Prairies Hospital. The diagnosis of autism was established with a structured parent interview, the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994) in 20 participants, and then validated with the Autism Diagnosis Observation Schedule (ADOS-G, module 3 or 4; Lord et al., 2000) in 17 participants. In the other cases, formal ADI-R or ADOS-G was replaced by a structured interview based on those instruments. Participants from the clinical group met the diagnostic criteria for autism according to both instruments. None of the participants had a known brain lesion or comorbid genetic, neurologic or psychiatric condition. Only one autistic participant took psychoactive medication (Seroquel, 100 mg per day, no medication on the day of testing).

Autistic participants were subdivided in two groups based on their relative performance on the Block Design subtest of the Wechsler Intelligence scales (WAIS-III or WISC-III). According to the definition given in the test, a peak (or significant strength) in the Block Design subtest corresponds to a difference of at least 3.9 between the standard score on Block Design subtest and the average of all subtest standard scores from that participant. A difference of 3.9 in favor of Block Design is seen in less than 5% of the typical population (Wechsler, 1997). This definition of a Block Design performance peak implies better visuospatial abilities than expected from a given participant's average ability level. Among the 23 autistic participants, 11 were considered to have a significant Block Design performance peak. This ratio is comparable to that of 47% found in an autism database of 92 autistic subjects by Caron et al. (2006). In this group, the difference between the Block Design and individual average subtest score ranged from 4.4 to 7.9, discrepancies seen in less than 2% of the population (Wechsler, 1997). The twelve other autistic participants, the no-peak autistic subgroup, had smaller differences between their Block Design score and average subtest score (ranging from −1.2 to 2.8).

Data obtained from the autistic participants were compared to a group of 14 participants with typical development recruited from the same database. Non-autistic participants were screened with a questionnaire identifying any personal or familial history of neurological or psychiatric disorders. None of the non-autistic participants took psychoactive medication.

All participants completed one of the Wechsler Intelligence scales (WAIS-III or WISC-III). The three groups did not differ in terms of Full Scale IQ, $F(2, 36) = 0.04$, $p = .96$, Verbal IQ, $F(2, 36) = 2.34$, $p = .11$, and age, $F(2, 36) = 0.48$, $p = .62$ (see Table 1). There was a significant between-group difference in Performance IQ, $F(2, 36) = 4.93$, $p = .01$. The Performance IQ difference was entirely driven by the difference in Block Design score (respectively 15.9, 11.6 and 10.4 in the autistic Block Design peak, autis-

Table 1
Participant characteristics. No significant between-group differences were found for all characteristics listed in the Table (all $ps > .10$), except Performance IQ ($p = .01$; due to the higher Block Design score in the autistic Block Design peak group). Age is given in years. Manual preference is estimated using Edinburgh scores (−100 exclusively left handed to +100 exclusively right handed). ADI-R: Autism Diagnostic Interview-Revised. BD: Block Design subtest.

	Non-autistic group	Autistic groups	
		BD peak	No-peak
Sample size (sex)	14 (12M, 2F)	11 (10M, 1F)	12 (10M, 2F)
Age			
M (SD)	19.4 (3.8)	20.6 (7.02)	21.4 (4.6)
Range	14–26	14–34	16–29
Full scale IQ			
M (SD)	103.0 (10.5)	101.7 (13.1)	102.1 (11.5)
Range	(87–119)	(81–120)	(90–118)
Verbal IQ			
M (SD)	106.4 (11.1)	94.3 (17.2)	103.2 (14.3)
Range	(92–127)	(72–121)	(86–124)
Performance IQ			
M (SD)	99.1 (10.2)	110.4 (8.9)	99.5 (10.2)
Range	(82–113)	(95–123)	(77–118)
Manual preference			
M (SD)	51.4 (59.4)	84.4 (20.6)	74.6 (48.7)
Range	(−80–100)	(30–100)	(−75–100)
ADI-R			
M (cut-off)			
Social		23.3 (10)	22.0
Communication		18.0 (8)	17.6
Behavior		8.1 (3)	6.0

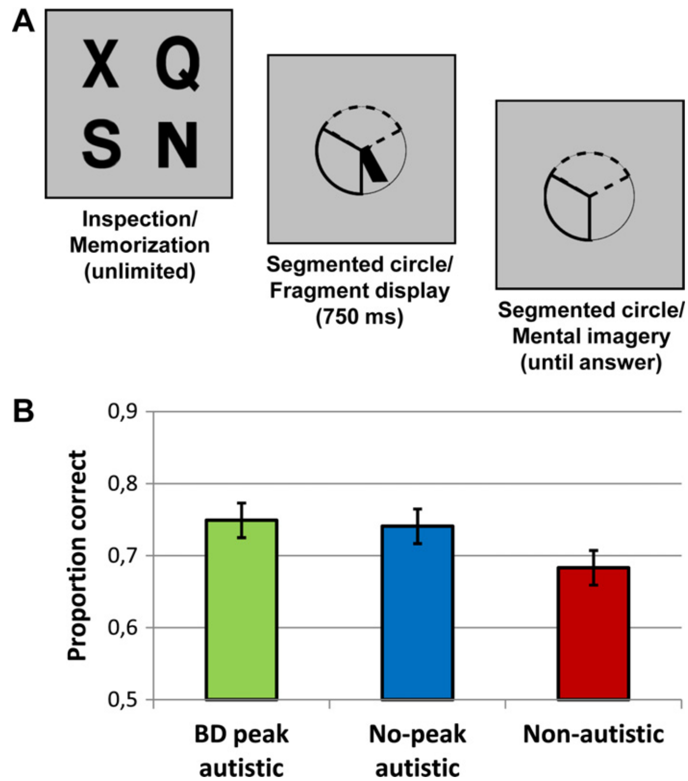

Fig. 1. Procedure and results in Experiment 1. (A) Trial sequence used in the visual mental imagery task. On each trial, a display first appears with 4 characters for inspection and memorization. Once the participant is ready, a fragment of one character is displayed for 750 ms in a segmented circle. The participant has to indicate which portion of the circle (dashed or solid line) would contain the major part of the whole character. (B) Proportion correct in the visual mental imagery task, for the three groups. Error bars: standard error from the mean. BD: Block Design subtest.

tic no-peak and non-autistic groups, $F(2, 36) = 18.22$, $p < .01$), the other Performance scale subtest scores being similar in the three groups. Manual preference, assessed using the Edinburgh Handedness Inventory, did not differ among groups. All participants had normal or corrected-to-normal visual acuity, estimated using a Snellen chart. Each participant (or his legal representative if the participant was minor) gave informed consent to participate in the study and received monetary compensation for participation. The study was formally approved by the ethics committee of Rivière-des-Prairies Hospital.

2.2. General procedure

The testing session was conducted individually in a 1.2 m × 1.2 m × 1.8 m booth with a computer monitor placed at one end. The entire inner surface of the booth was black to prevent visual distractions. Noise level and ambient light were minimized. The stimuli were viewed on a 19 inch monitor with a refresh rate of 120 Hz placed at a viewing distance of approximately 65 cm. All experiments were built with E-Prime© Version 1.2 (Psychology Software Tools Inc.). The order of the experiments and tasks was counterbalanced across participants and the trial presentation order was randomized each time. The testing session lasted approximately one hour, including short breaks between the tasks.

2.3. Data analysis

Outlier removal was done in two steps. First, trials with extremely long response times (RT) were removed using a fixed cut-off adjusted for each task based on the RT distribution. The cut-offs were 10,000 ms for Experiment 1 and 15,000 ms for Experiment 2, except for Task 2a, where it was adjusted to 17,000 ms because the mean RT was more than 2000 ms longer than on the other mental rotation tasks. Second, trials with RT greater than 3 standard deviations from an individual participant's mean were removed. This two-step procedure resulted in a loss of approximately 2–6% of the trials in each task and yielded no empty cells. The outlier removal rate did not differ between groups. The statistical analyses were performed using SPSS 17.0 (SPSS Inc., Chicago, IL, USA). The alpha level was set at 0.05 for all analyses.

3. Experiment 1: visual mental imagery

This visual mental imagery task assessed the ability to form and access mental representations. Participants imagined a specified alphanumeric character in a circle and then decided which of two highlighted portions of the circle would contain the greater proportion of the character (see Fig. 1a for the sequence involved in an example trial). In terms of cognitive processes, this task involves encoding the shape of the potential characters and the circle, mapping the character in front of the circle and making a decision about the spatial location of the letter inside the circle (e.g. "Is the letter mainly covering portion A or B of the circle?"). This task shares the encoding, mapping and decision processing aspects with the mental rotation tasks used in Experiment 2, but differs in that mapping requires stimulus translation in Experiment 1 as contrasted with rotation in Experiment 2.

3.1. Stimuli and procedure

Each trial started with the presentation of a frame containing four target characters randomly selected from a set of alphanumeric characters (4, 5, 9, D, F, G, L, M, R, T, and V), for inspection and memorization by the participants. The characters were viewed on a grey background, and each subtended a visual angle of 3.5° × 3.5°. A fragment of one of the characters then appeared in a segmented circle for 750 ms, followed by the segmented circle alone. Participants were asked to first form a mental image of the character identified by the fragment, as if it was present in the segmented circle, and then identify which of the two delineated sections of the circle would contain the largest proportion of the character. Participants were instructed to respond as rapidly and accurately as possible by pressing one of two keys on a keyboard. There was a practice block of 15 trials, followed by a block of 30 trials. In order to familiarize the participants with the process of representing characters inside the circle, the practice phase also included the presentation of each character inside the circle.

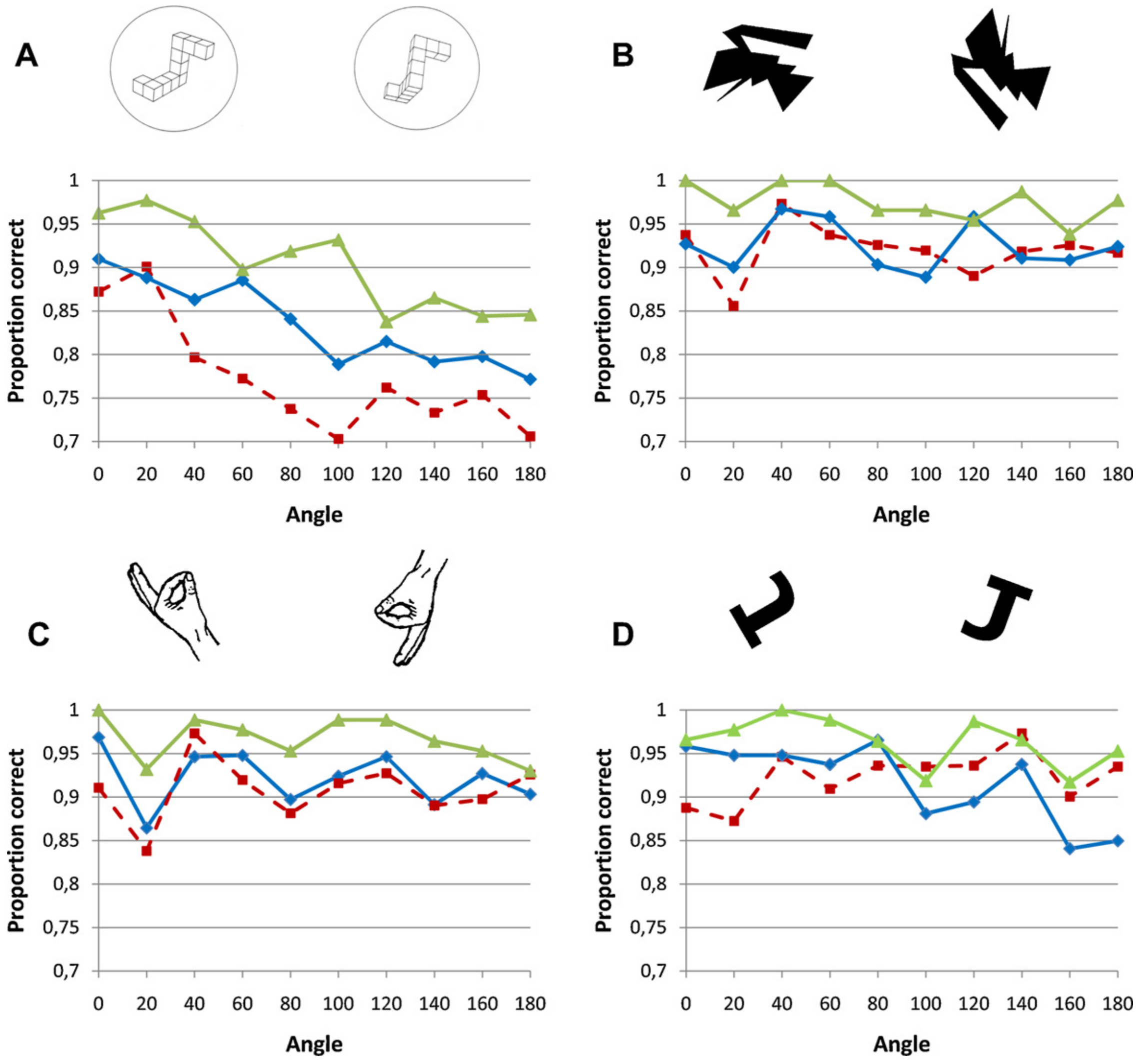

Fig. 2. Proportion correct in Experiment 2 as a function of rotation angle of the two stimuli, in the three groups. Results are presented separately for each mental rotation task, (A) three-dimensional figures, (B) two-dimensional figures, (C) hands, and (D) letters. Solid green line (triangles): autistic Block Design peak group. Solid blue line (diamonds): autistic no-peak group. Dashed red line (squares): non-autistic group.

3.2. Results

The two autistic groups had a higher proportion of correct answers (M respectively .75 and .74 in the Block Design peak and no-peak groups, SD respectively .08 and .09) than the non-autistic group (M = .68, SD = .10), though this difference did not reach significance in the three-group analysis, $F(2, 36) = 1.84$, $p = .17$. However, comparing the autistic to the non-autistic participants revealed a trend for higher accuracy in autistics, $F(1, 36) = 3.73$, $p = .06$. The mean RT was shorter in autistics with a Block Design peak (2926 ms) than in autistics with no-peak (3315 ms) and non-autistics (3281 ms), but this difference was not significant, $F(2, 36) = 0.46$, $p = .63$.

The trend for higher accuracy in autistics either with or without a Block Design peak suggests that they may enjoy enhanced abilities to create and compare visual mental images, relatively to non-autistics.

4. Experiment 2: mental rotation

In this experiment, we administrated 4 mental rotation same-different tasks, utilizing (1) three-dimensional geometric figures, (2) two-dimensional geometric figures, (3) drawings of hands, and (4) letters. Examples of stimuli for each task are displayed in Fig. 2.

4.1. Procedure

Each trial involved simultaneous presentation of two stimuli, each subtending 4.5–7° of visual angle, with a horizontal separation of 10°. Participants indicated as rapidly and accurately as possible, by pressing one of two keys, whether the two stimuli were identical or different. On 50% of the trials ("same" trials), the two stimuli were identical, but rotated up to 180° one relative to the other. In the other half of the trials ("different" trials), the test stimulus was the mirror image of the target stimulus, also rotated up to 180°. A fixation cross was presented for 500 ms before a trial began, followed by presentation of the two stimuli until a response was made. There were 8 trials for each of the 10 possible angles of rotation (0–180° by 20° increments) for a total of 80 trials. Fifteen initial practice trials were presented, using different figures from those used in the main task. The left-right position of the response buttons, "same" or "different", was counterbalanced across participants.

4.2. Data analysis

Repeated measures analyses of variance with Angle (10 rotation angles) as a within-subject factor and Group (autistic Block Design peak, autistic no-peak and non-autistic groups) as a between-

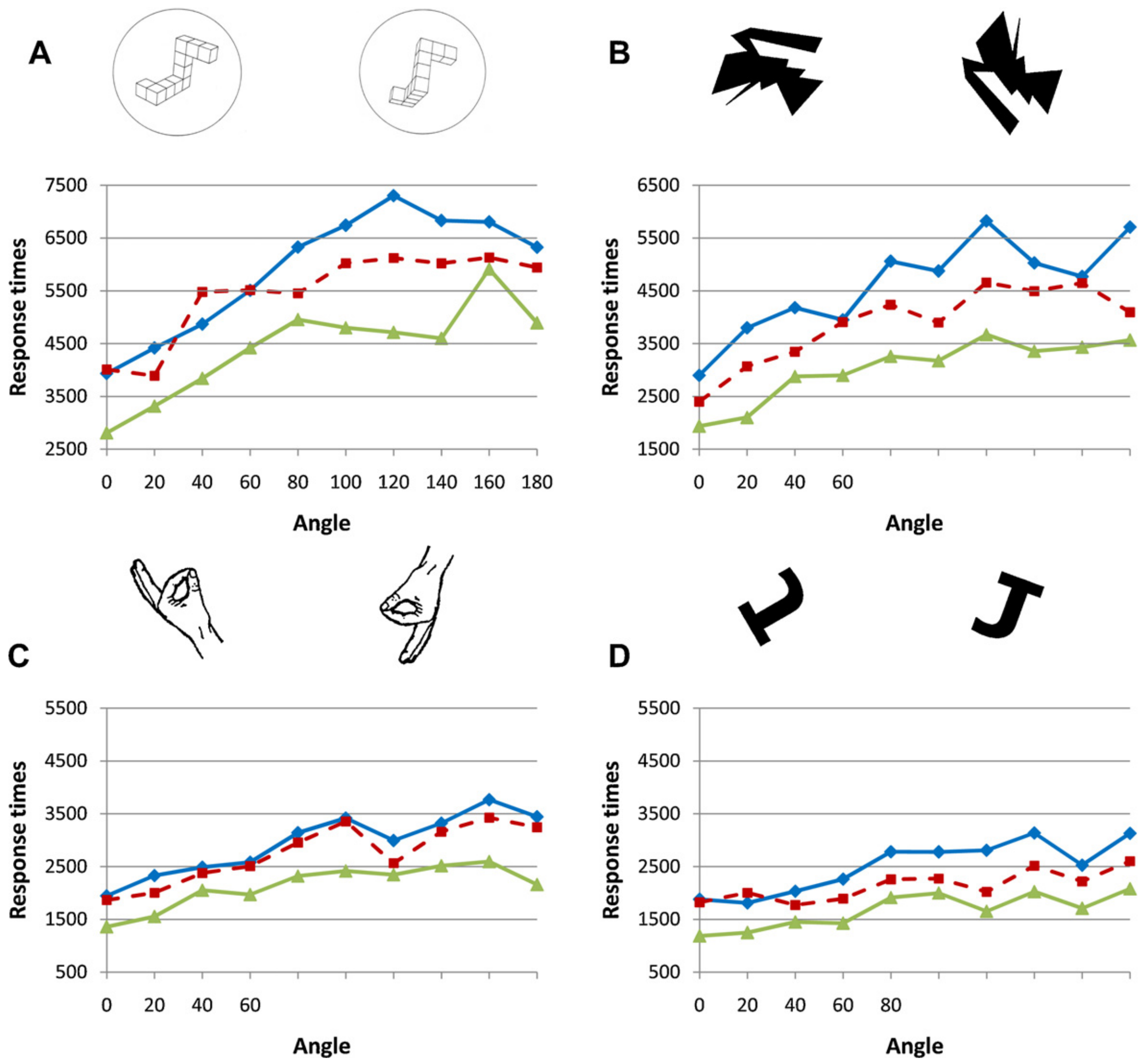

Fig. 3. Response times in Experiment 2 as a function of rotation angle of the two stimuli, in the three groups. Results are presented separately for each mental rotation task, (A) three-dimensional figures, (B) two-dimensional figures, (C) hands, and (D) letters. Solid green line (triangles): autistic Block Design peak group. Solid blue line (diamonds): autistic no-peak group. Dashed red line (squares): non-autistic group.

subject factor were conducted separately on the two dependent variables, proportion of correct answers and median RT, for each of the four mental rotation tasks. Correlation analyses were conducted on the proportion of correct answers in the four mental rotation tasks, Full Scale IQ, Verbal IQ, Performance IQ and Block Design subtest score. Spearman's rank correlations were computed separately for each group.

4.3. Results

4.3.1. Mental rotation of three-dimensional figures

Stimuli. This task included drawings of four different three-dimensional cube objects, the classic mental rotation stimuli designed by Shepard and Metzler (1971).

Results. The results from one non-autistic participant were excluded because of extremely slow response times evidenced by a mean RT of more than 16,000 ms, lying approximately 6 standard deviations from the non-autistic group mean. The mean proportion of correct answers was .90 in the autistic Block Design peak group, .84 in the autistic no-peak group and .77 in the non-autistic group (see Figs. 2a and 3a). A Group by Angle analysis of variance revealed a significant effect of Group, $F(2, 33) = 4.14$, $p = .03$, and Angle, $F(9, 297) = 5.84$, $p < .01$, with no interaction, $F(18, 297) = 0.64$, $p = .87$. A pairwise comparison confirmed that the autistic Block Design peak group performed significantly better than the non-autistic group, $p < .01$.

Mean RT was about 1000 ms faster in the autistic Block Design peak group (4426 ms) than in the non-autistic group (5458 ms) and the autistic no-peak group (5906 ms). The analysis of variance revealed a significant effect of Angle, $F(9, 297) = 17.37$, $p < .01$, but the effect of Group did not reach significance, $F(1, 33) = 2.51$, $p = .09$.

In sum, autistics with a Block Design peak exhibited enhanced mental rotation of three-dimensional geometric figures, in the form of a higher proportion of correct answers than seen in non-autistics. This was concomitant with a trend for faster RTs in autistics with a Block Design peak.

4.3.2. Mental rotation of two-dimensional figures

Stimuli. Drawings of four different 20-point geometrical figures inspired by Cooper (1975) and their mirror images were used in this task.

Results. The mean proportion of correct answers was .98 in the autistic Block Design peak group, .93 in the autistic no-peak group and .92 in the non-autistic group (see Figs. 2b and 3b). The Group by Angle analysis of variance revealed an effect of Angle, $F(9, 306) = 1.97$, $p = .04$, and a trend for an effect of Group, $F(1, 34) = 3.04$,

Table 2
Matrix of correlations among mental rotation task accuracies and IQ measures in autistics and non-autistics. "Mean Rotation" represents the mean performance across all 4 mental rotation tasks. FSIQ: Full Scale IQ. VIQ: Verbal IQ. PIQ: Performance IQ.

	2D figures	Hands	Letters	FSIQ	VIQ	PIQ	Block Design
Autistics ($n = 23$)							
3D figures	.34	.55**	.35†	.05	−.19	.37†	.28
2D figures		.53**	.29	−.10	−.38†	.50*	.33
Hands			.37†	.27	.02	.61**	.52**
Letters				.00	.21	.28	.33
Mean rotation				.04	−.26	.54**	.48*
Non-autistics ($n = 14$)							
3D figures	.67*	.31	.53†	.22	.24	.20	.25
2D figures		.60*	.64*	.24	.27	.10	.21
Hands			.58*	−.03	.29	−.32	−.14
Letters				.04	.08	−.09	.18
Mean rotation				.27	.36	.07	.21

† $.05 < p < .10$.
* $.01 < p < .05$.
** $p < .01$.

$p = .06$, with no interaction, $F(18, 306) = 0.57$, $p = .92$. The autistic Block Design peak group performed significantly better than the non-autistic group in a pairwise comparison, $p = .03$.

Mean RTs were again the shortest in the Block Design peak group (3028 ms; 4609 ms in the no-peak group and 3875 ms in the non-autistic group). The analysis of variance revealed a significant effect of Angle, $F(9, 306) = 25.27$, $p < .01$, and of Group, $F(1, 34) = 3.84$, $p = .03$. Pairwise comparisons revealed significantly shorter RTs in the Block Design peak group than in the no-peak group, $p < .01$, but the difference between the autistic Block Design peak group and the non-autistic group was not statistically significant, $p = .13$.

Autistics with a Block Design peak were faster than other participants for mental rotation of two-dimensional figures. There was also a trend towards a higher proportion of correct answers ($p = .06$) in the autistic Block Design peak group with two-dimensional figures, but the between-group effect was smaller than for the mental rotation of three-dimensional figures. Ceiling effects might have masked the between-group differences in the current task. Alternatively, as difficulty increased from 2D to 3D tasks, between-group differences might be more evident. The number of features to manipulate and the complexity of the mapping processes required, are greater for 3D figures than for 2D figures.

4.3.3. Mental rotation of drawings of hands

Stimuli. This task used 4 different drawings of hand gestures (Sperry, 1968) and their mirror images.

Results. The mean proportion of correct answers was .97 in the autistic Block Design peak group, .92 in the autistic no-peak group and .90 in the non-autistic group (see Figs. 2c and 3c). The Group by Angle analysis of variance revealed a significant effect of Group, $F(1, 34) = 3.9$, $p = .03$, and of Angle, $F(9, 306) = 4.15$, $p < .01$, with no interaction, $p = .92$. A pairwise comparison confirmed that the autistic Block Design peak group's accuracy was significantly higher than that of the non-autistic group, $p = .01$.

The mean RT was 2128 ms in the autistic Block Design peak group, 2943 ms in the autistic no-peak group and 2746 ms in the non-autistic group. The analysis of variance revealed a significant effect of Angle, $F(9, 306) = 19.59$, $p < .01$, as well as a trend for an effect of Group, $F(1, 34) = 2.78$, $p = .08$, with no interaction, $p = .84$.

In sum, the autistic Block Design peak group outperformed the other participants in accuracy of hand mental rotation, with a trend for shorter response times.

4.3.4. Mental rotation of letters

Stimuli. The stimuli used were non-symmetrical letters (F, G, J and P) and their mirror counterparts, displayed in black on a white background.

Results. The mean proportion of correct answers was .96 in the autistic Block Design peak group and .92 in the other two groups. The analysis of variance revealed an effect of Angle, $F(9, 306) = 2.67$, $p < .01$, with no effect of Group, $F(1, 34) = 2.06$, $p = .14$, but with a trend for an interaction, $F(18, 306) = 1.52$, $p = .08$. Inspection of Fig. 2d suggests that this trend for an interaction arose from non-autistics showing a relatively constant accuracy with increasing angle of rotation, while autistics displayed a decrease in accuracy with increasing angle of rotation, effects more evident in the no-peak group. Mean RT was 1669 ms in the autistic Block Design peak group, 2515 ms in the autistic no-peak group and 2137 ms in the non-autistic group (see Fig. 3d). The analysis of variance revealed a significant effect of Group, $F(1, 34) = 4.02$, $p = .03$, and Angle, $F(9, 306) = 18.82$, $p < .01$, with no interaction, $p = .23$. Pairwise comparisons confirmed significantly shorter RTs in the autistic Block Design peak group than in the autistic no-peak group, $p < .01$, but the difference with the non-autistic group did not reach significance, $p = .11$.

Mental rotation of letters tended to elicit faster RTs in autistics with a Block Design peak than in other participants, but their higher proportion of correct answers was not significant. While different trends in autistics and non-autistics were seen in the proportion of correct answers according to increasing rotation angle, the interaction did not reach significance. Only autistic participants showed decreased performance as the angle of rotation increased. Data from non-autistic participants revealed no performance penalty when the angle of rotation increased. This suggests that the familiarity with the stimuli to be rotated affected mental rotation differentially in autistics and non-autistics.

4.3.5. Correlation analyses between mental rotation tasks and IQ

Correlation analyses were conducted to document how performance in various mental rotation tasks aggregates at the individual level, and if IQ or Block Design scores predict mental rotation performance. Data from the two autistic groups were pooled to achieve a reasonable sample size for correlation analyses. In autistic participants, performance on the different mental rotation tasks was significantly correlated (see Table 2). Interestingly, mental rotation performance correlated positively with Performance IQ and Block Design score. In the non-autistic group, performance on the different mental rotation tasks was also correlated. Contrary to the pattern found in the autistic group, there was no significant correlation between performance on the mental rotation tasks and the Performance IQ, or between mental rotation performance and Block Design score. Fisher z transforms of the correlation coefficients revealed a trend for a higher correlation between Performance IQ and overall mental rotation performance, $z = 1.42$, $p = .07$, in autistics than in non-autistics.

5. Discussion

Our findings demonstrate that the overall ability to form, access and manipulate visual mental images is unambiguously enhanced in some autistics. These abilities were evidenced as better accuracy and shorter response times in visual mental imagery operations in autistics with a Block Design peak, that is, Block Design subtest performance that was significantly higher than performance on other IQ subtests. Examining a range of stimulus materials and manipulations, we found that complex 3D geometric figures were best at revealing differing abilities between groups. Autistics with no particular strength in Block Design also showed enhanced abilities to process mental images in some circumstances (Exp. 1). Concerning manipulation and rotation of mental images (Exp. 2), their accuracy lay between that of autistics with a Block Design peak and non-autistics, while their response times were generally the slowest. In the autistic participants, performance in a substantial fraction of the mental rotation tasks was correlated with Block Design score and Performance IQ. The relation between mental imagery abilities and overall enhanced perceptual functioning in autism are discussed below in relation to possible underlying cognitive architectures and their putative neural mechanisms.

5.1. Enhanced mental imagery and overall enhanced perception in the autistic spectrum

Our findings of enhanced visual mental imagery abilities in autistics extend those of Falter et al. (2008) to adolescent and adults, and demonstrate effects using multiple stimulus materials, with and without manipulation of the constituent mental images. We additionally identified an autistic subgroup with more strongly enhanced mental rotation skills. Enhanced mental imagery in autistics is consistent with prior reports of superior visuospatial abilities for static material (Dakin & Frith, 2005), and, more generally, with overall enhanced perceptual functioning (Mottron et al., 2006). Strengths in perceptual discrimination, visual search, visual memory, and Block Design task performance have been reliably demonstrated in autistics (Caron et al., 2006; de Jonge, Kemner, & van Engeland, 2006; O'Riordan, 2004; O'Riordan & Plaisted, 2001; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; Plaisted, O'Riordan, & Baron-Cohen, 1998; Shah & Frith, 1993). In addition, Caron et al. (2006) demonstrated that some of these visuospatial advantages tend to *aggregate within the same individuals*. Accordingly, autistics with a relative advantage in the Block Design subtest also showed superior performance on perceptual encoding, perceptual matching, visual search, and visual memory relative to Wechsler-IQ matched non-autistics. We observed a similar tendency in our autistic group with a relative advantage in Block Design, identified using the same criteria as in Caron et al. (2006). This group displayed enhanced and faster performance than non-autistics in all four mental rotation tasks, despite equivalent IQ levels. Moreover, performance in mental rotation was correlated with Block Design scores and Performance IQ in our autistics only.

Processing advantages in multiple low-level perceptual and pattern processing tasks characterize a certain subgroup of individuals in the autistic spectrum. Recent findings suggest that, within the autistic spectrum, visuospatial peaks are limited to individuals with a language delay (Mottron, Soulières, Simard-Meilleur, & Dawson, 2008), and therefore do not include individuals with Asperger syndrome, a finding strikingly similar to that observed with respect to pitch discrimination peaks in the auditory modality (Jones et al., 2009). All these findings highlight the importance of distinguishing subtypes within the autism spectrum, as some cognitive atypicalities might be masked by averaging data from individuals having different cognitive profiles. Heterogeneity in cognitive strengths, classically associated with savant syndrome, may more broadly characterize the autistic spectrum, allowing identification of different subgroups, perhaps with autistics displaying visuospatial strengths and Asperger individuals verbal strengths (Koyama, Tachimori, Osada, Takeda, & Kurita, 2007).

5.2. Cognitive architecture of mental imagery in non-autistics

Mental rotation tasks involve several cognitive operations, such as encoding the shape and orientation of objects, then mentally rotating object A to match the orientation of object B, then comparing the rotated object A to object B to decide whether the two objects are identical (Carpenter & Just, 1978). The slope of RT with rotation angle indexes the rotation operation, whereas the intercept indexes the speed and ease of other mental imagery operations (Just & Carpenter, 1985).

The rotation operation can rely on different mechanisms ranging along a piecemeal-to-holistic continuum. Piecemeal mental rotation (e.g. rotating an object part by part) is more likely for new or complex structures, such as 3D cube figures. In contrast, holistic mental rotation (e.g. globally rotating the whole object), may be more likely used for familiar structures, such as letters. Holistic processing is inferred when the error rate does not increase with angular disparity, whereas piecemeal processing is hypothesized when error rate increases with angular disparity. The increasing error rate with increasing angular disparity results from mismatches due to interference, noise and decay in the visual buffer, the short term memory storage for both perceptually and imagery driven representations (Amorim, Isableu, & Jarraya, 2006; Kosslyn, 1981, 1991).

Visual mental imagery may rely on the same brain mechanisms as visual perception (Kosslyn, Ganis, et al., 2001; Sparing et al., 2002). For example, mentally rotating an object elicits very similar cortical activity as *seeing* the same object being rotated (Shelton & Pippitt, 2006). A recent meta-analysis of 32 mental rotation imaging studies confirmed that task-related activity is mainly found in the same networks that would be involved if one was looking at the object being rotated, including posterior parietal and inferotemporal cortex. More specifically, the meta-analysis revealed that brain activity associated with mental rotation consistently involves activity around the intra-parietal sulcus, extending towards occipital regions near the temporal-occipital and lateral occipital sulci (Zacks, 2008). This study hypothesized two main brain mechanisms for mental rotation. First, there is a rotation mechanism relying on analog spatial representations, based in posterior parietal and occipital cortex. The second rotation mechanism relies on sensorimotor representations and is based in cortical regions around the precentral sulcus. This movement simulation mechanism would be selectively recruited when the stimuli to rotate or the experimental conditions are well matched to this strategy, as in the case of hand stimuli (Kosslyn, DiGirolamo, Thompson, & Alpert, 1998) or following specific instructions to imagine rotating stimuli with hands (Kosslyn, Thompson, Wraga, & Alpert, 2001). Presumably, more purely perceptual mechanisms would be recruited with other types of stimuli.

5.3. Cognitive architecture of mental imagery in autism

How similar to typical cognitive architectures are the mechanisms supporting the autistic advantage in mental imagery? In our study, no selective advantage in the rotational aspect of the task was found in autistics, the slopes as a function of rotation angle being similar in both groups. This suggests that autistics would mainly differ from non-autistics in the ability to form and compare mental images, rather than in the rotation process itself.

Concerning rotation mechanisms, both autistics and non-autistics showed accuracy decreases as angle increased for 3D cube figures, suggesting utilization of a piecemeal approach. The letter rotation findings were unique in suggesting different accuracy trends as a function of angle in the three groups. Whereas autistics showed a decline in performance as angle increased, non-autistics maintained a similar level of accuracy independent of rotation angle. This suggests differing rotation mechanisms: non-autistics plausibly used their knowledge and linguistic concepts of letters to rotate them in a holistic fashion, whereas autistics may have processed the letters with reference to their perceptual features, using piecemeal rotation. This would explain why modifying the usual presentation angle was more detrimental to autistics than to non-autistics. This interpretation agrees with the observation that autistics are more likely to use visual processing mechanisms in tasks relying on letter comparison, such as N-Back tasks (Koshino et al., 2005).

Autism is characterized by difficulties in imitating static or dynamic hand gestures (Rogers, Bennetto, McEvoy, & Pennington, 1996; Vanvuchelen, Roeyers, & De Weerdt, 2007). The inclusion of hand stimuli in our study allowed testing one component of gesture imitation, that is, mental rotation of both spatial and sensorimotor representations. One explanation for gesture imitation difficulties in autism would be impairments in manipulating body-part representations (Smith & Bryson, 1994; but see Vanvuchelen et al., 2007), and therefore one might expect a selective difficulty with motor imagery in autism. However, no difficulty was observed in hand rotation. On the contrary, autistics with a Block Design peak responded more accurately than non-autistics, with a trend for shorter response times. Autistics with no Block Design peak responded as accurately and rapidly as non-autistics. As there is no reason why the autistic individuals under study would not exhibit the sensorimotor atypicalities involving difficulties with hand posture imitation generally observed in this population, an interpretation of our results is that the imitation impairments in autism do not reflect underlying problems with spatial manipulation of body-part visual representations. The locus of the gestural imitation impairment in autism may be found at a subsequent processing stage in the perception-action cycle.

Some of the areas involved in mental rotation using analog spatial representations coincide with areas of increased activity in autistics during a variety of visual perceptual tasks that are generally performed well by autistics. For example, while searching for a target figure embedded in a complex figure, autistic spectrum adolescents showed higher activity than non-autistic peers in occipito-parietal cortex, including the calcarine sulcus and right extra-striate cortex (Manjaly et al., 2007). Visual search for a target among distracters also elicited increased activity in parieto-occipital cortex in autistic adolescents relative to non-autistic peers, mainly in the middle occipital gyrus extending to inferior parietal cortex and the precuneus (Keehn, Brenner, Palmer, Lincoln, & Muller, 2008).

Three fMRI studies comparing autistics and non-autistics used tasks requiring visual mental imagery and image manipulation. In a study on sentence comprehension, Kana, Keller, Cherkassky, Minshew, and Just (2006) compared task-related activity for sentences with high versus low visual imagery. In non-autistics, increased activity was seen in the intra-parietal sulcus and inferotemporal areas for sentences with high imagery relative to those with low imagery. In autistics, these areas were equally active in both conditions. In a direct between-group comparison, autistics were found to have increased activity in the low-imagery condition in the intra-parietal sulcus, superior parietal lobule, cuneus and precuneus. Whereas non-autistics recruited more language-related areas to understand these sentences, autistics resorted to visual mental imagery to the same extent as they did for sentences with high visual imagery content.

In an exploratory fMRI experiment of 7 autistic or Asperger adolescents and 9 non-autistic adolescents involving mental rotation of three-dimensional geometric figures, autistics exhibited less activity in right inferior and medial frontal gyri (Silk et al., 2006). In fact, statistically significant task-related activity was found only in parietal cortex in the autistic group, whereas activity was also seen in a number of frontal regions in non-autistics. As autistics were slightly faster than non-autistics (5.5 s vs. 6.5 s; n.s.), solving the mental rotation problems relying more on visuospatial processes and less on working memory did not seem to penalize the autistics performance.

Finally, in a matrix reasoning study utilizing complex patterns of geometric figures as stimuli, we recently demonstrated an increased reliance on extrastriate cortical areas, and decreased reliance on prefrontal cortex, in autistics compared to non-autistics (Soulières et al., 2009). This difference in activity balance was accompanied by shorter response times in autistics – up to 42% faster for the more complex problems – with no between-group difference in accuracy.

In all three studies requiring visual mental imagery, autistics exhibited more task-related activity in posterior brain regions associated with visual mental imagery and less activity in prefrontal areas associated with working memory. An increased access to, or skill in, visual mental imagery could reduce the burden on working memory systems in autistics. Atypical allocation of visual cortex for a range of process types may be a task-independent phenomenon in autism. Using a quantitative meta-analysis of published functional imaging studies in which Activation Likelihood Estimation maps were computed for a broad range of visual tasks involving faces, objects, and words, we have observed relatively stronger, and more widespread, processing in autistics compared to nonautistics in temporal, occipital, and parietal regions (Samson, Mottron, Soulières, & Zeffiro, in press).

5.4. Cognitive architecture of visuospatial processes in autism

Cognitive mechanisms accounting for autistic visuospatial strengths may originate from either atypical "bottom-up" or "top-down" influences. Representations of shapes and patterns in visual cortex could be "sharper" in autism, as evidenced by better processing of fine visual detail (Bertone, Mottron, Jelenic, & Faubert, 2005). In addition, diminished (Ropar & Mitchell, 2002) or optional (Mottron et al., 2006) top-down influences may result in less modulation or distortion of perceptual input by prior knowledge, expectation and context (Loth, Carlos Gomez, & Happe, 2008; Soulières, Mottron, Saumier, & Larochelle, 2007). In sum, more veridical representations, less subject to top-down contextual influences of all sorts, could be beneficial to visual mental imagery processing, and in particular to the mapping of two images using mental rotation.

There are indications that the atypical autistic performance pattern for visuospatial tasks does not solely reflect quantitative differences in the functioning of cognitive subcomponents in what are otherwise similar cognitive architectures. First, the observation that performance on the Block Design subtest predicts overall mental rotation accuracy *only in autistic participants* suggests that the processing mechanism employed is somewhat unique to autism. Second, the differing effects with respect to increasing angle of rotation in autistic and non-autistic groups in the case of letter rotation also suggests reliance on different processing mechanisms. Other findings supporting qualitatively different visuospatial processes include the absence of deleterious effects on autistic performance with respect to: (1) increasing perceptual cohesiveness of the target figure in the Block Design task (Caron et al., 2006 experiment 1), or (2) increasing target number in visual search tasks (O'Riordan et al., 2001).

Of interest is the possible relation that autistic visual processing skills have with reasoning and general intelligence. We found that perceptual and visuospatial skills predict reasoning abilities only in autistics. Supporting this claim is the correlation found between accuracy in mental rotation tasks and non-verbal abilities such as Performance IQ only in autistics. Consistent with this finding, Block Design performance was significantly correlated with performance on the Raven's Progressive Matrices, another test of reasoning and intelligence, only in autistics (Mottron, Soulières, Gernsbacher & Dawson, 2009). This empirical finding may reflect the sorts of "visual thinking" (Grandin, 1995, 2009) described by some autistics, in which they describe their reasoning processes as being made of series of images, instead of words, or more generally to the "Thinking in Pictures" hypothesis (Kunda & Goel, 2010). In this account, visual thinking relies on visual mental imagery and image manipulation. Enhanced visual mental imagery in autistics could facilitate the development of visual reasoning, which might become relatively more efficient than generally is the case in non-autistics. As recent findings suggested a different balance between "visual" and "verbal" thinking in autistic versus non-autistic individuals (Kana et al., 2006; Sahyoun, Belliveau, Soulières, Schwartz, & Mody, 2010), enhanced visual mental imagery abilities could lead to this sort of privileged reliance on visual thinking to solve problems.

Beside a superior role of visual imagery, we have proposed elsewhere that one, among other, possible mechanisms describing the difference between autistic and non-autistic cognition is heavier reliance on *veridical mapping,* the detection of similarity among patterns in vision or audition (Mottron, Dawson, & Soulières, 2009). Veridical mapping consists of a parallel, one-to-one mapping among elements sharing a common phenomenal or abstract property, such as isomorphism. These mappings can be used to either extract structure from noise, as soon as the structure is expressed with redundancy, or to detect differences between structures that are otherwise isomorphic. Veridical mapping would contribute to the choice of materials associated with savant abilities, to the types of operations characterizing the savant's manipulation of these materials, as well as to peaks of abilities in non-savant autism.

Mental rotation tasks consist of a mapping process between two isomorphic 2D or 3D patterns, followed by an explicit estimate of stimulus differences resulting from this mapping. Mental images to be compared shares a common metric and overall shape, and therefore mental rotation tasks can be considered a specific case of veridical mapping. This mechanism would function mainly in a feedforward manner, initially less dependent on explicit verbal knowledge and reasoning, thereby profoundly different from trial and error, feedback driven, top-down processes. As it has been demonstrated for 3D drawing and calendar calculation in savant autism, this mapping is independent of the conscious use of strategies and algorithms, even if it can be secondarily accessed by conscious processes.

The difference in correlation patterns between mental imagery performance and PIQ in the autistic and non-autistic groups might plausibly reflect one aspect of the difference between autistic and non-autistic intelligence, in the form of different contributions of perceptual processes to reasoning abilities. A novel aspect of this account is that the contribution of enhanced perception to intelligent behavior is not conceived as reflecting mere superiority or higher storage accuracy, but rather representing relatively complex, although bottom-up, processes of pattern detection and manipulation. A similar conclusion had been drawn with regard to savant autistic draughtsmen, who modify, and eventually distort, the three-dimensional objects they otherwise draw realistically (Mottron & Belleville, 1995).

Acknowledgements

We thank Dr Stephen Kosslyn for access to some of the stimuli, Dr Jean-Philippe Lafrance for help with statistical analyses and Elise B. Barbeau, Isabelle Simard and Jennifer Lepage-Hamel for data collection. We also thank the participants and their family for their time and commitment. This work was supported by grant 2706 from Autism Speaks to L. Mottron, T. Zeffiro and I. Soulières, a post-doctoral award from the Canadian Institutes of Health Research (CIHR) to I. Soulières, and a National FRSQ fellowship to L. Mottron.

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