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## **Assessment of visual mental imagery abilities in autism.**

C. BLED\*, Q. GUILLON\*, L. MOTTRON \*\*, I. SOULIERES\*\*\*, L. BOUVET\*

\*Université Toulouse Jean Jaurès, Laboratoire CERPPS-E.A. 7411, Toulouse, France.

\*\* Psychiatry Department, Université de Montréal, Montreal (Quebec), Canada

\*\*\*Psychology Department, Université du Québec à Montréal, C.P. 8888 succursale Centre-ville, Montreal (Quebec), H3C 3P8, Canada

**Corresponding Author:** Dr Clara Bled, Teaching and research associate, Jean Jaurès University, Toulouse, France. CERPPS Laboratory (EA 7411). 5, allée Antonio Machado, 31058 Toulouse, FRANCE. E-mail: [clara.bled@univ-tlse2.fr](mailto:clara.bled@univ-tlse2.fr). Tel : +33 (0)646 840 569.

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**Patient consent statement:** All participants read an information sheet with explanations concerning the study and indicated their consent before beginning.

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# **Assessment of visual mental imagery abilities in autism.**

## **Abstract**

Autistic individuals have an atypical role, performance and autonomy in perceptual functioning, including significant visuospatial abilities. As mental imagery and perception share common underlying mechanisms, the question of the mental imagery abilities of autistic individuals thus arises. While enhanced mental imagery capacities have been demonstrated in autism, with significant abilities to manipulate mental images, the other stages of mental imagery (generation, maintenance, inspection) remain to be explored in autism.

Forty-four autistic adults and 42 typical participants performed 4 tasks to assess different stages of mental imagery: the Image generation task (mentally generating a letter on a grid and indicating whether it passes over a probe located in the grid), the Visual pattern test (maintaining visual patterns in memory), the Image scanning test (inspecting mental images) and the Mental rotation test (mentally manipulating representations of geometric figures).

Autistic and typical individuals were equivalent in the generation and the manipulation of mental images, both in accuracy and response time. Visual span on the Visual pattern test was significantly higher in the autistic group, indicating better maintenance of mental images. As for the inspection of mental images, response times were influenced by the distance to inspect in the typical group but not in the autistic group. Autistic participants were equally fast regardless of distance.

The preserved, greater or differently influenced visual mental imagery abilities that we found in this study confirm the atypical perceptual functioning in autism. These atypicalities in mental imagery processing can be linked with a bias towards a more local processing of information and a lesser top-down effect (weaker influence of knowledge).

**Keywords:** autism, mental imagery, cognitive style, generation, maintenance, scanning, manipulation.

Autism is a neurodevelopmental disorder characterized by impairments in social communication and interaction, as well as restricted and repetitive patterns of behavior or interests (Diagnostic and Statistical manual of Mental disorders, fifth edition (DSM-5); American Psychiatric Association, 2013). The latest version of the DSM includes symptoms of hyper- or hyporeactivity to sensory input or unusual interests in sensory aspects of the environment as a diagnostic criterion.

However, the term “sensory” may be too restrictive (Bertone et al., 2005; Mottron, 2019; Samson et al., 2011) as higher levels of perceptive functioning, such as mental imagery, are also atypical in autism. Mental imagery is defined as the evocation of a representation and its associated sensory information in the absence of a direct external stimulus (Pearson et al., 2015). For instance, visual mental imagery, which is a complex perceptual behavior, has anecdotally been indicated as an autistic strength (Grandin, 2009). Furthermore, autism entails a particular “way of thinking” which is often described as “thinking in pictures”. Autistic individuals report using mental visual representation, and hence mental imagery, more frequently than typical participants (Bled et al., 2021). Mental imagery seems to play a significant part in the daily thinking of autistic people and might explain a link between higher level representations (i.e., cognitive functioning) and the sensory particularities in autism. However, this cognitive mechanism has seldom been studied so far. The objective of this study was therefore to reach a better understanding of mental imagery abilities in autism and to answer our question of possibly more fully developed mental imagery in autism.

As visual mental imagery and perception activate the same neural networks and rely on the same content-dependent representations in visual areas (Kosslyn et al., 2006), it is possible that the enhanced visual abilities described in autism, being more independent of higher order / top-down influences (Bertone et al., 2005; Caron, 2006; Samson et al., 2011; Soulières et al., 2009), could induce enhanced visual mental imagery abilities. Indeed, autistic individuals perform very well on visual-spatial tasks requiring the formation and manipulation of visual mental representations (i.e., the Wechsler Block Design subtest or Raven's Progressive Matrices) (Caron et al., 2006; Soulières et al., 2009). The Enhanced Perceptual Functioning (EPF) theory suggests a higher role, autonomy and performance of perceptive abilities in autism (Mottron & Gagnon, 2023; Mottron et al., 2006; Samson et al., 2011). Perception in autism is argued to be more precise and less likely to be altered by prior knowledge. EPF might consequently lead to more “accurate” and detailed visual perceptions but also to more “accurate” and detailed mental representations in autism.

As described earlier, mental imagery is a cognitive activity and entails the feeling of "perceiving" in the absence of a percept. Mental imagery plays a central role in cognition as it allows one to remember past events, plan the future, represent oneself in space or even make decisions. These various uses of mental imagery are made possible by its four different stages: generation, maintenance, inspection and manipulation of mental images (Kosslyn et al., 2006; Pearson et al., 2013). A mental image is indeed "generated" as it is constructed "step by step" (Koenig et al., 1991). Once generated, a mental image is subject to rapid decay with an average duration of only 250 ms (Kosslyn, 1994). This brief duration means that active maintenance of the image in our attention window is then required. Subsequently, this image can then be inspected or manipulated in space. The "scanning" of mental images is one possible form of inspection activity (i.e., moving from one point to another in a mental image) (Finke & Pinker et al., 1983). Mental images then can also be modified/transformed in space (Pearson et al., 2013).

Among the four stages of mental imagery, only the manipulation of mental images has been studied in autism, through mental rotation tasks. Several studies have shown superior performance of autistic compared to typically developed individuals on mental rotation tasks (Falter et al., 2008; Hamilton et al., 2009; Pearson et al., 2016; Soulières et al., 2011). However, other studies have failed to find a difference between autistic and typically developed participants in mental rotation performance (Beacher et al., 2012; Conson et al., 2013; Rhode et al., 2018; Silk et al., 2006). Moreover, a meta-analysis showed only a nonsignificant advantage for autistic individuals over typical individuals for other aspects of the mental rotation task (working memory, information processing or decision making), but none regarding the aspect of rotation in space per se (Muth et al., 2014).

Even if, from a behavioral perspective, results concerning mental rotation in autism remain contrasting, functional imaging studies confirm particularities in brain activation in autistic individuals during this type of task. Studies in functional magnetic resonance imaging (fMRI) showed decreased neuronal activity in regions associated with working memory and executive functions, but greater posterior brain activity (in visual areas), in autistic individuals compared to typical individuals during a mental rotation task (Hooven, 2004; Silk et al., 2006). Thus, autistic individuals engage visual perceptual areas more but involve their working memory less during this mental imagery task. These studies suggest differences in the strategies used for mental rotation in autistic versus typical individuals.

As for the generation of mental images, it has never been studied in autism. The Image

generation task is a paradigm first developed by Podgorny and Shepard (1978) and modified by Kosslyn et al. (1988) (Kosslyn, 1988; Podgorny & Shepard, 1978). This task evidences that mental images are generated in parts and not as a whole (the first parts of the images are created faster than the last part). Variations of this task have been used in neuroimaging studies of mental imagery in the typical population (Kosslyn et al., 1993) or in studies of group differences with depressed or anxious patients (Morrison et al., 2011; Zarrinpar et al., 2006) but never in people with neurodevelopmental conditions. A possible manifestation of superior mental imagery abilities in autism could be a faster and/or more detailed generation of mental images with results approaching those obtained in the simple perception condition.

Tasks involving the maintenance of visual information in short-term memory (i.e., visual working memory tests) have previously been studied in autism and showed that visuospatial working memory is compromised in autism (Kercood et al., 2014; Wang et al., 2017). However, maintenance of mental images, per se, has never been evaluated in this population. The Visual Pattern Test consists of a matrix, with some of its cells filled in black, which is presented for a short duration. Participants then have to reproduce the pattern previously seen. This test is used to measure the visual component of working memory (without spatial properties) (Della Sala et al., 1999), and is an indirect measure of the maintenance of mental images (Pearson et al., 2013). Image maintenance tasks have been used, for example, to study imagery processes in depression (Cocude et al., 1997).

The inspection of mental images has never been studied in autism either. The Image scanning test is based on a scanning paradigm first introduced by Finke and Pinker (1982) and later refined by Borst, Kosslyn, and Denis (2006) (Borst et al., 2006; Finke & Pinker, 1982). In this test, a pattern of dots is presented on the screen; the pattern is then removed and is replaced by an arrow. Participants have to decide whether the arrow points to a location previously occupied by one of the dots. As the distance between the arrow and the target dot increases, the time to make the decision increases, suggesting that participants scan their mental image (Kosslyn, 1988). Again, a possible manifestation of superior mental imagery abilities in autism could be a more detailed, and hence more accurate, inspection of mental images. The exploration of mental images may also be atypical and more locally driven than in the typical population.

In the end, a visual thinking style with a high use of visual mental representation in daily life activities is reported in autism (Bled et al., 2021). Furthermore, significant mental imagery abilities can be observed in autistic individuals. However, only their ability to manipulate

mental images has been investigated to date. Other stages of mental imagery remain to be explored in autism. In this paper, we systematically evaluated the four stages of mental imagery (generation, maintenance, inspection and manipulation) in autistic versus typical adults, to offer the first detailed characterization of this cognitive process in autism. This paper also aims to try and answer our hypothesis of significant mental imagery abilities in autism.

## **Material and method**

### **1. Participants**

A total of 44 adults (52 % of women; age range 18 to 50, *Mean* = 30.54, *SD* = 8.54) with a clinical diagnosis of autism based on DSM criteria (either DSM-IV or DSM 5) were included in the analyses. Participants were assessed with the Autism Diagnostic Observation Schedule (ADOS 2) (Lord et al., 2015) and/or the Autism Diagnostic Interview (ADI) (Rutter, Le Couteur, & Lord, 2003) and other standardized tools (e.g. Ritvo Autism Asperger Diagnostic Scale (Ritvo et al., 2011), Autism spectrum Quotient (AQ; Baron-Cohen et al., 2001)). All diagnoses were confirmed by a medical doctor in a specialized autism resource center (CRA), in a private practice or in a hospital.

A total of 46 typical participants (without any diagnosis of neurodevelopmental disorder) were also included (52 % of women; age range 21 to 47, *Mean* = 27.95, *SD* = 5.70).

The age difference between the groups was small (mean difference = 2.59; *d* = -0.36) and, given the nature of the tasks, is unlikely to account for any variations in task performance between the groups. The two groups did not significantly differ in terms of education level ( $\chi^2(5) = 9.48, p = .091$ ) or gender ( $\chi^2(1) = .01, p = .992$ ). Groups were also matched on scores in the Raven's Advanced Progressive Matrices (APM; Raven & Raven, 2003), which assess fluid reasoning and are a robust indicator of intellectual capacities in autistic individuals (Dawson et al., 2007), [*Mean* APM score for the Typical group = 26.24, *SD* = 5.94, *Mean* Autistic group = 24.79, *SD* = 7.89, mean difference = 1.45,  $t(84) = 0.99, p = .322, d = 0.21$ ].

Recruitment was conducted simultaneously on two sites: Toulouse (France) and Montreal (Canada). Participants were recruited by posting an advertisement in local clinical centers and associations for autistic adults (Centre Ressource Autisme (CRA) Midi Pyrénées (Toulouse, France) and Hôpital Rivière des Prairies (Montreal, Canada)), on social networks and forums about autism. Typical participants were recruited from the general population in both



Toulouse and Montreal.

Exclusion criteria were the presence of an associated neurological disorder (epilepsy, severe head injury or other), IQ less than 80, uncorrected vision or the daily use of a current pharmacological treatment affecting mental functioning (other than antidepressants and anxiolytics: three of our autistic participants were on antidepressant medication at the time of the appointments and two were on occasional anxiolytic medication). Autistic traits in typical participants were assessed using the Ritvo Autism and Asperger's Diagnostic Scale (RAADS 14; Eriksson et al., 2013), which is a 14-item self-report questionnaire. The higher the total score, the more "autistic traits" are present. Typical participants with a score above the cut-off score of 14 were eliminated (out of the initial 46 typical participants, 4 were eliminated).

## **2. General procedure**

The protocol was carried out over two sessions of about 2 hours. Participants were tested individually. Two questionnaires, four mental imagery tasks and the Matrices task were completed by all participants in the same order as follows: Advanced Progressive Matrices, Image scanning test, Ritvo Autism and Asperger's Diagnostic Scale (RAADS 14), Visual pattern test, Mental Rotation Test and Image generation task. This protocol was included in a larger project, in which participants also completed other tasks and questionnaires.

The questionnaires were administered online using *LimeSurvey*© software (software linked to the secure network of the University of Toulouse). Computerized tasks were created using the *PsychoPy*© software and were displayed on a 22" screen placed approximately 60 centimeters from the participant. All participants read an information sheet with explanations concerning the study and indicated their consent before beginning. A 50-euro gift voucher was offered to French participants and 80\$ to Canadian participants. This study was approved by the Research Ethics Committee of Toulouse University (file number 2019-139), by the Ethics Committee of Rivière-des-Prairies Hospital and is in accordance with the European General Data Protection Regulation (GDPR).

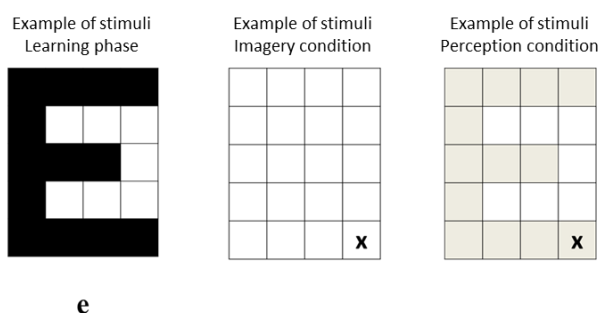
## **3. Measures**

The Image generation task (Morrison et al., 2011) is a computerized test assessing mental image generation abilities. In the learning phase, participants familiarized themselves with a set of two numbers (1, 7) and 12 uppercase letters (A, C, E, F, G, H, J, L, O, P, S, U) represented using black squares in 4\*5 grids. During the "Imagery condition", participants

were presented with a lowercase letter followed by an empty grid with only an “X” probe in one of the squares. Participants had to visualize the corresponding uppercase letter in the grid to indicate whether or not it would cover the “X” if it was actually displayed. This test consisted of 4 trials per letter (2 true and 2 false), for a total of 48 trials. Half of the “X” probes fall on a segment of the letter that is typically drawn early in the letter-writing process (i.e., early condition) and the other half on a segment of the letter that is typically drawn late in the letter-writing process (i.e., late condition). Hence, each stimulus was presented four times, once with each of the four possible “X” locations: (1) in a square on an early segment (i.e., true/early), (2) adjacent to a square on an early segment (i.e., false/early), (3) in a square on a late segment (i.e., true/late), and (4) adjacent to a square on a late segment (i.e., false/late). Trials were presented in a different random order to each participant. Participants were instructed to respond “Yes” or “No”, as quickly and accurately as possible, by pressing a corresponding key.

A control task was performed next. In this “Perception condition”, the same letters and grids as in the “Imagery condition” were used, although this time, grids were presented with the target letter in light grey. Participants no longer needed to mentally represent the letter in the grid to indicate whether or not it covers the “X” probe (see Figure 1). This “Perception condition”, like the “Imagery condition”, included 48 trials (12 true/early, 12 false/early, 12 true/late and 12 false/late). Before testing, a training phase was completed by participants using the two number stimuli (8 training trials in total with feedback).

Correct responses and reaction times were recorded for both Imagery and Perception tasks.



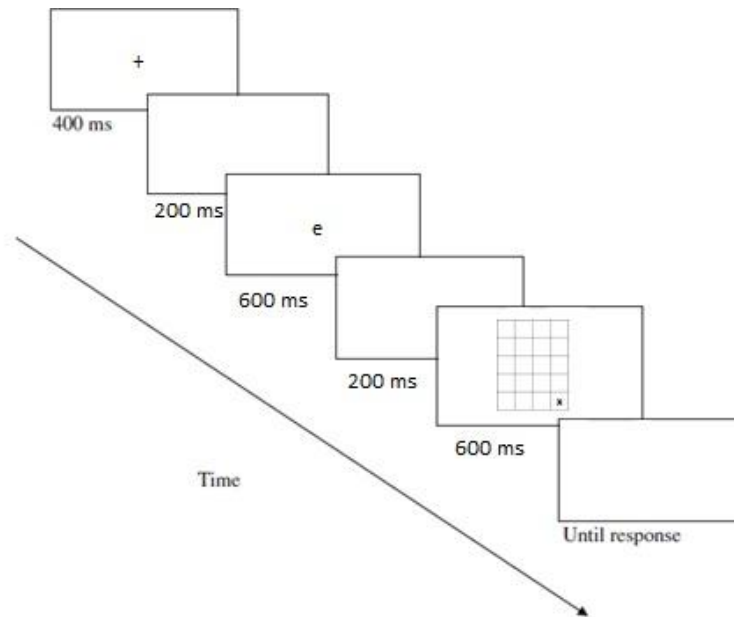


Figure 1. Examples of stimuli for the “Imagery condition” and the “Perception condition”. Example of an “Imagery” trial from the Image generation task.

The Visual pattern test (Della Sala et al., 1999) is a computerized test assessing the maintenance (retention) of mental images. Participants were asked to memorize a sequence of increasingly complex checkerboard patterns (with half of the boxes filled), starting with a  $2 \times 2$  grid (with two boxes filled) and progressing to the largest  $5 \times 6$  grid (with 15 boxes filled). The test consisted of two trials per level of difficulty, making 28 trials overall. Each pattern was shown to the participant for 3 seconds on the screen and then disappeared. A visual mask was then displayed for 500 ms (see Figure 2). Participants then had to reproduce the pattern from memory by marking the correct boxes in an empty grid of the same size on a paper notebook (with no time limit). The maximum number of boxes that the participant correctly recalled at least twice was recorded.

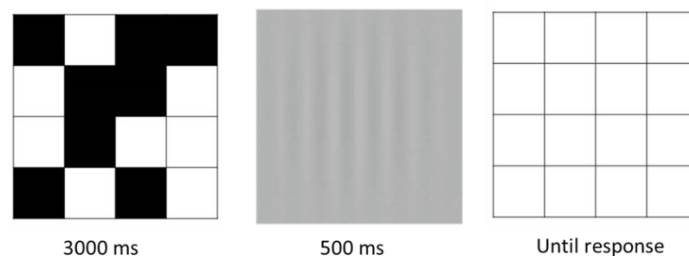


Figure 2. Example of a trial from the Visual pattern test.

The Image scanning test (Borst & Kosslyn, 2010) is a computerized test assessing mental

image inspection abilities. In the learning phase, participants had to learn the location of four black dots (7 mm in diameter) randomly positioned within a large white square (190 x 190 mm, 18 degrees angular distance) with a black frame. First, after participants had looked closely at the dots for as long as they deemed necessary, the dots disappeared from the screen. We asked participants to replace the locations of the four dots with four stickers (same shape, size and color as the learned dots), from memory within the white square on the screen. Once the stickers were positioned, the dots reappeared on the screen and participants were to note the differences between their responses and the real locations of the dots in order to correct their mental image. Again taking as long as they deemed necessary, they then repositioned the dots in the square on the screen with the four stickers and, once more, compared their response to the original pattern. This procedure was repeated until all dots were placed within 3.0 mm (from center to center) of their actual location two times in a row. On average, participants required 8 to 9 trials to memorize the pattern of dots.

After reaching the learning criterion, the participants completed the first testing phase. They had to indicate, as quickly as possible, whether or not an arrow displayed on the screen was pointing to one of the previously seen dots (see Figure 3).

There were 12 arrows per dot (6 “Yes trials” which pointed directly to the center of the dot and 6 “No trials” that missed the dot). All arrows and dots were placed within a virtual circle with a 90 mm radius to prevent the participants from using the black frame as a reference for memorizing the positions of the dots. Arrows were 15 mm long and each arrow was placed at one of two possible distances from the target dot. Distance 1 (Short) = 30 mm or distance 2 (Long) = 60 mm. There were thus 48 trials in total for the first testing phase and 48 trials in total for the second. Missing arrows (for the “No trials”) were tangent to a circle centered on a dot. Two sizes of circle were used, one with a 14.5 mm radius (Small) and another with a 26.5 mm radius (Large). Consequently, the arrow “missed” the dot with two possible angles: Small or Large (see Figure 4).

For the second part of this test (second testing phase), 4 new dots (a 90° rotation to the right of the first pattern) were presented and participants had to memorize these new locations in order to be able to indicate, for each arrow, whether or not it pointed to one of these new dots. The learning phase and testing phase were repeated a second time, with this new location of four dots.

Each testing phase started with 16 training trials during which feedback was provided before

the actual 48 trials of the test. Trials were presented in a different random order to each participant. Participants were instructed to respond, as quickly and accurately as possible, “Yes” or “No” to whether the arrow pointed directly to one of the dots previously learned by pressing a corresponding key. Correct responses and reaction times were recorded for both testing phases.

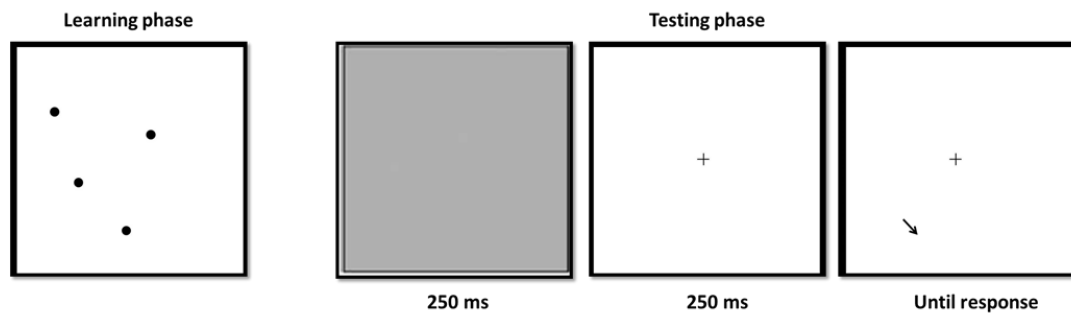


Figure 3. Example of a trial from the Image scanning test.

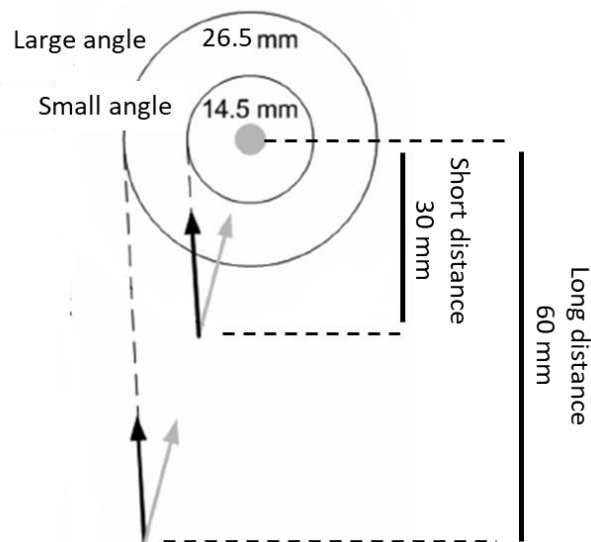


Figure 4. Examples of stimuli, for the “Yes trials” and “No trials”, at the two possible distances (Short vs. Long) and with the possible angles (Small vs. Large) for the missing arrows of the “No trials”.

Mental Rotation Test (MRT; Vandenberg & Kuse, 1978 French adaptation by Albaret & Aubert, 1996): The MRT assesses the manipulation of mental images. Participants compared drawings of three-dimensional geometric shapes with cubes. Each item consisted of a target shape and four comparison shapes. Two of the comparison shapes were rotated versions of the target shape, and the other two comparison shapes were rotated mirror images of the target shape (see Figure 5). Participants were to indicate which two of the four shapes were identical

to the target shape. There were two parts with 10 items each and participants had 3 minutes to complete each part of the test. Two points were awarded for each item with 2 correct answers, 1 point if only one of the shapes was chosen and it was correct, 0 points if at least one of the two choices was incorrect.

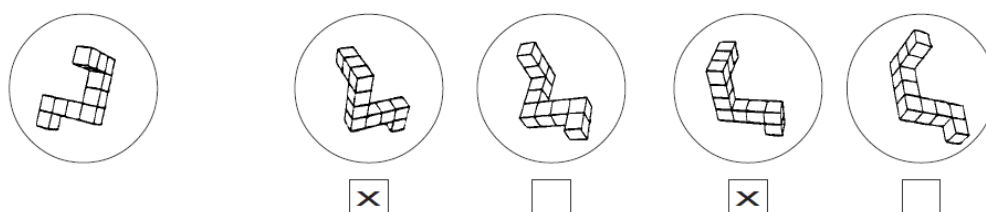


Figure 5. Example of a trial from the Mental rotation test.

#### 4. Data analyses

Between-group comparisons (Autistic / Typical and France / Canada) were made for correct responses and response times using repeated measures ANOVA and Student T-tests. In addition, Eta-squared ( $\eta^2$ ) or Cohen's d (d) were calculated to assess the effect size of the difference.

Given the binary categorical nature of some of our data (Yes / No choice, coded 1 or 0 respectively), data were also analyzed using generalized linear mixed models (GLMMs) as recommended by Jaeger (Jaeger, 2008). In addition to being more appropriate than ANOVA for analyzing binary data, which are often transformed into percentages for analysis, GLMMs enable the dependence between observations to be taken into consideration by including a random structure to the model (Baayen et al., 2008). To test the significance of the predictors, we used the likelihood ratio test ( $\alpha = .05$ ). Estimated marginal means from the different GLMM analyses are available in the supplementary data.

For between-group comparisons of response frequencies, we used the Pearson chi-square test. In order to evaluate possible relationships between our variables, Pearson correlation analyses were also performed.

Statistical significance was set to a p-value of .05 and analyses were performed using R software (R-Project for Statistical analyses R Core Team, 2016, version 4.1.2.).

## Results

### 1. Preliminary analyses: France-Canada comparison

To ensure that we could group participants recruited in Canada and France for our analyses, we began by performing inter-country comparisons.

For reaction times in the Image generation task, we found a main effect of group [ $F(1, 81) = 4.21, p = .043, \eta^2 = .018$ ] and recruitment location [ $F(1, 81) = 9.30, p = .003, \eta^2 = .040$ ] but no group\*recruitment interaction [ $F(1, 81) = 0.26, p = .611, \eta^2 = .001$ ]. Moreover, Post Hoc tests indicated that autistic participants did not differ between France and Canada ( $p = .428$ ) nor did the typical participants ( $p = .092$ ). No effect of the recruitment location was found for the accuracy of responses (see supplementary data).

Concerning scores on the Visual Pattern test, we found a main effect of group [ $F(1, 81) = 5.82, p = .018, \eta^2 = .059$ ] but no effect of recruitment location [ $F(1, 81) = 1.69, p = .198, \eta^2 = .005$ ] and no group\*recruitment interaction effect [ $F(1, 81) = 0.01, p = .907, \eta^2 = .001$ ]. Participants recruited in France and Canada did not differ and were therefore grouped together.

For reaction times in the Image scanning test, we found a main effect of group [ $F(1, 78) = 6.53, p = .013, \eta^2 = .065$ ] and recruitment location [ $F(1, 78) = 9.22, p = .003, \eta^2 = .092$ ] but no group\*recruitment interaction [ $F(1, 78) = 0.932, p = .337, \eta^2 = .009$ ]. Moreover, Post Hoc tests indicated that autistic participants did not differ between France and Canada ( $p = .882$ ) nor did the typical participants ( $p = .097$ ). No effect of the recruitment location was found for the accuracy of responses (see supplementary data).

For the Mental Rotation test scores, we did not find any effect of group [ $F(1, 82) = 0.14, p = .709, \eta^2 = .002$ ], recruitment location [ $F(1, 82) = 0.03, p = .865, \eta^2 = .001$ ] or group\*recruitment interaction [ $F(1, 82) = 0.12, p = .725, \eta^2 = .002$ ]. Again, Canadian and French participants were similar.

### 2. Main analyses

Main results for the Autistic group and the Typical group are presented in Table 1.

Table 1. Summary table for the results of the different mental imagery tests for the Autistic and Typical groups.

	Typical group		Autistic group	
	Mean	SD	Mean	SD
Image Generation Score (Imagery Condition) (%)	90.4	8.4	88.8	10.6
Image Generation RT (Imagery condition, Early Location) (ms)	1011	378	1153	307
Image Generation RT (Imagery condition, Late Location) (ms)	1105	397	1265	451
Visual Pattern Score	10.2	1.6	10.9	1.2
Image Scanning Score (Short Distance) (%)	74.4	12.7	67.2	14.4
Image Scanning Score (Long Distance) (%)	69.8	13.8	65.0	16.0
Image Scanning Reaction Time (Short Distance) (ms)	2078	731	2578	814
Image Scanning Reaction Time (Long Distance) (ms)	2313	903	2685	901
Mental Rotation Score	18.4	8.5	19.0	8.3

### First stage: generation of mental images

Regarding the accuracy for the generation of mental images, a GLMM for correct answers was fitted using a binomial distribution with a "logit" family link. Group (Autistic, Typical), Condition (Perception, Imagery) variables and their interaction were considered as fixed effects in the model. We accounted for participant and stimulus variability by adding a random intercept for participants (id) and a condition by participants random slope to the model. We found a significant main effect of Condition ( $\chi^2(1) = 19.89, p < .001$ ) but no main effect of Group ( $\chi^2(1) = 0.49, p = .482$ ) and no Group\*Condition interaction ( $\chi^2(1) = 0.08, p = .931$ ). Hence there was no group difference concerning the correct answers. However, participants, regardless of the group, gave fewer correct answers in the Imagery condition than in the Perception condition.

Concerning the response times for the generation of mental images, consistent with previous research (e.g., Kosslyn, 1988; Kosslyn et al., 1997), we examined the response times only for trials where the "X" probe would have been covered by the letter ("true" trials). From these data, trials with incorrect responses were eliminated. Trials with latencies less than 300 ms or greater than 8000 ms were also eliminated. Finally, outliers, defined as trials with response latencies greater than  $\pm 2$  standard deviations from the mean response latency for that participant, were eliminated. A GLMM was fitted using an Inverse Gaussian distribution with an "identity" family link for response times. Group (Autistic, Typical), Condition (Perception, Imagery), Location (Early, Late) variables and their interactions were considered as fixed effects in the model. We accounted for participant and stimulus variability by adding a random intercept for participants (id) and a location by participants random slope to the model. We found no main effect of Group ( $\chi^2(1) = 3.55, p = .059$ ) nor any Group\*Condition interaction ( $\chi^2(1) = 15.75, p = .181$ ), Group\*Location interaction ( $\chi^2(1) = 0.13, p = .719$ )



or Group\*Condition\*Location interaction ( $\chi^2(1) = 0.39, p = .534$ ). However, we found a main effect of Condition ( $\chi^2(1) = 1671.56, p < .001$ ) and, replicating Kosslyn et al. (1988), there was also a significant main effect of probe Location ( $\chi^2(1) = 19.81, p < .001$ ) and a Location\*Condition interaction ( $\chi^2(1) = 17.41, p < .001$ ) (Kosslyn, 1988). There was no group difference concerning the speed of response. However, participants, regardless of the group, were slower to respond in the Imagery condition than in the Perception condition. Furthermore, in the Imagery condition, participants were slower to respond when the "X" probe was at the "Late" location of the letter than when it was at the "Early" location of the letter (see Figure 6).

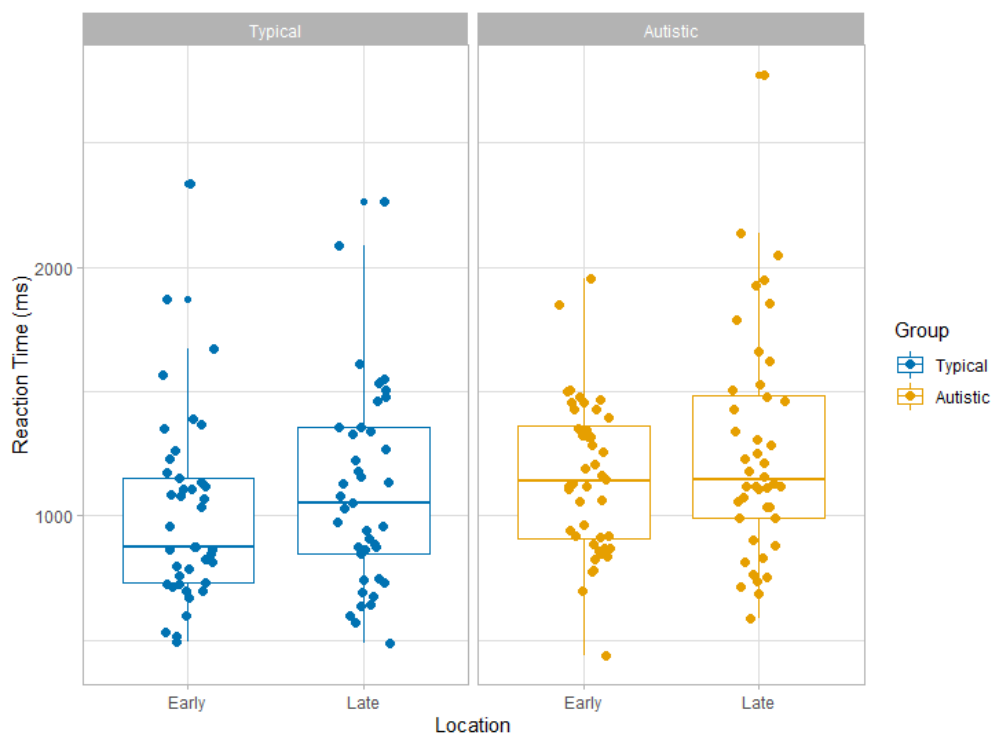


Figure 6. Reaction time of the Image generation task, for early and late location conditions, for the Typical group and the Autistic group.

### Second stage: maintenance of mental images

For the maximum number of boxes correctly recalled at least twice on the visual pattern test, we found a significant group difference, with the Autistic group having a greater visual span than the Typical group [*Mean* Typical = 10.24, *SD* = 1.65, *Mean* Autistic = 10.91, *SD* = 1.16,  $t(83) = -2.16, p = .034, d = -0.47$ ] (see Figure 7).



with latencies less than 300 ms or greater than 8000 ms were eliminated (Borst & Kosslyn, 2010). Finally, outliers, defined as trials with response latencies greater than  $\pm 2$  standard deviations from the mean response latency for that participant, were eliminated. A GLMM was fitted using an Inverse Gaussian distribution with an "identity" family link for response times. Group (Autistic, Typical), Distance (Short, Long), Angle (Small, Large) variables and their interactions were considered as fixed effects in the model. We accounted for participant and stimulus variability by adding a random intercept for participants (id). We found no main effect of Group ( $\chi^2(1) = 3.62, p = .057$ ), Group\*Distance interaction ( $\chi^2(1) = 3.98, p = .056$ ), Group\*Angle interaction ( $\chi^2(1) = 0.81, p = .369$ ) or Group\*Distance\*Angle interaction ( $\chi^2(1) = 3.59, p = .058$ ). However, we found a main effect of Distance ( $\chi^2(1) = 5.05, p = .025$ ) but no significant effect of Angle ( $\chi^2(1) = 1.82, p = .177$ ) and no Distance\*Angle interaction ( $\chi^2(1) = 0.41, p = .524$ ). All participants showed a slower response when the distance between the arrow and the target dot was greater and when the angle between the “missed” arrow and the target dot was smaller (see Figure 8).

As exploratory analysis showed a tendency for the group\*distance interaction to be significant, we focused only on the effect of distance on the reaction times of autistic participants. Interestingly, we did not find an effect of distance on their reaction times ( $p = .489$ ). They took the same time to respond whether the arrow was far from or near the target dot.

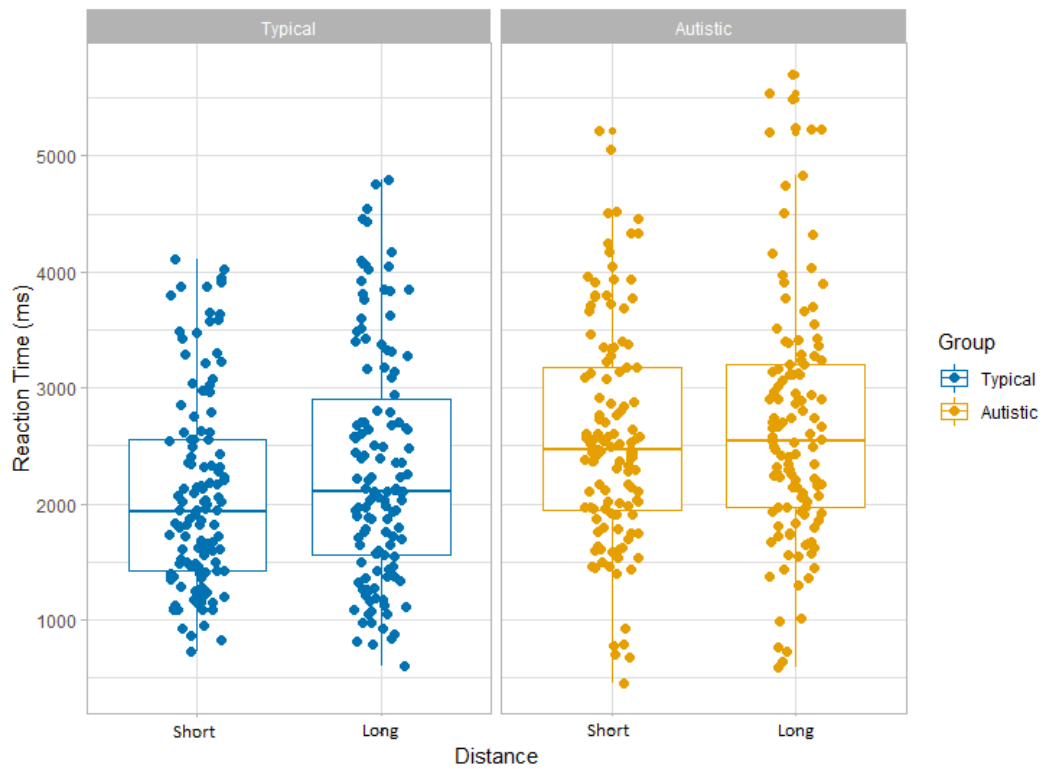


Figure 8. Reaction time of the Image scanning test, for the short distance and long distance conditions, for the Typical group and the Autistic group.

#### Fourth stage: manipulation of mental images

We found no significant group difference for the total of correct answers on the mental rotation test [ $Mean$  Typical = 18.36,  $SD$  = 8.53,  $Mean$  Autistic = 19.02,  $SD$  = 8.26,  $t(84) = -0.37$ ,  $p = .714$ ,  $d = -0.08$ ] (see Figure 9).

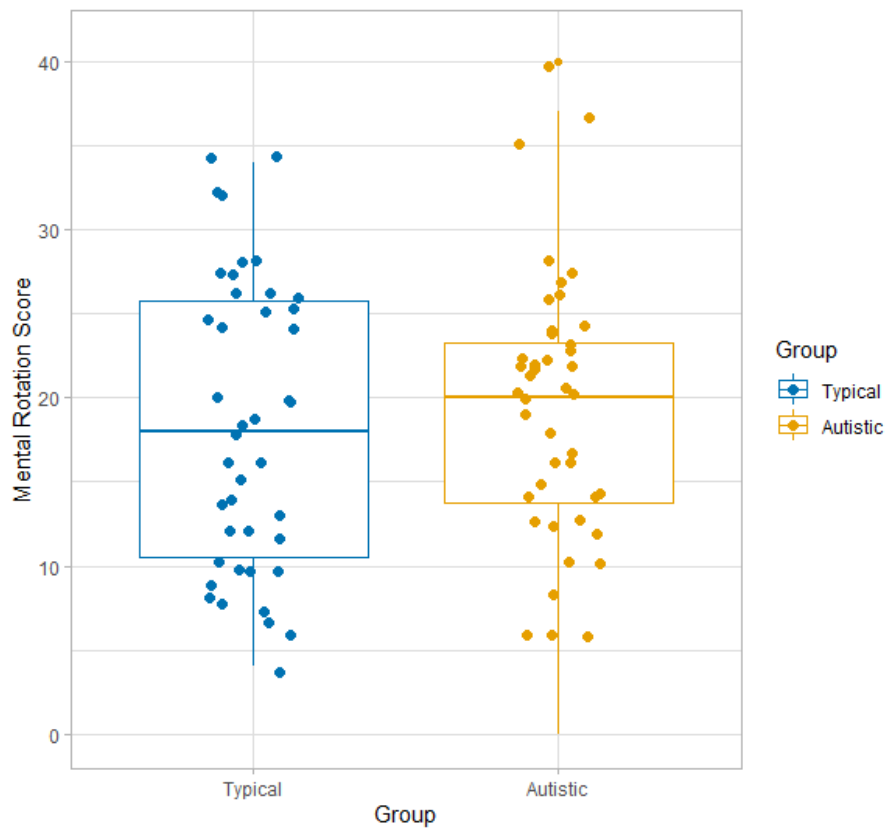


Figure 9. Mean Mental rotation score, for the Typical group and the Autistic group.

### Correlations between stages

We tested the correlations between correct answers for the Image generation task (mean of total correct answers for both early and late locations in the Imagery condition), Visual pattern test, Image scanning test (average of the number of correct answers for the long and short distance conditions) and Mental rotation test. The correlations among measures of mental imagery, for all participants, are presented in Figure 10.

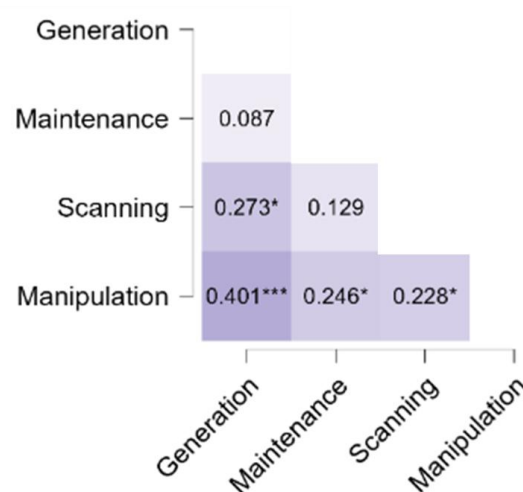


Figure 10. Correlation heat map between the different mental imagery scores, with Pearson r correlation coefficients (\*  $p < .05$ , \*\*  $p < .01$ , \*\*\*  $p < .001$ ).

Regarding the first stage of mental images, we found that the Image generation scores were significantly positively correlated with the Image Scanning scores ( $p = .013$ ) and the Mental rotation scores ( $p < .001$ ). For the second stage of mental images, the only significant correlation we found with the Visual pattern scores was a positive one with the Mental rotation scores ( $p = .022$ ). As for the last two stages, we found a positive correlation between the Image scanning scores and the Mental rotation scores ( $p = .038$ ). Hence, all the stages were correlated with each other, except for maintenance which was correlated only with manipulation.

Furthermore, all stages of mental imagery were correlated with the Raven's Matrices scores, i.e. with visual reasoning performances. Lastly, we found correlation patterns that were similar between typical and autistic individuals (see supplementary data).

## Discussion

We evaluated autistic individuals' performances in the four stages of mental imagery with four experimental tasks, in order to have a more detailed characterization of this mental process in autism. Globally, we observed intact, sometimes superior, mental imagery performances in the autistic group. For the generation stage of mental imagery, we found the typical effect of the probe location in both groups, as well as similar performance for autistic and typical participants. For the maintenance of mental images, we found a greater visual span in autistic than in typical individuals. Concerning the scanning of mental images, we

found some atypicalities in our autistic group with no effect of the difficulty. Contrary to expectations, we did not find any group difference for the mental rotation test. In the following, we will discuss each result separately.

In the image generation task, we found that participants responded faster in the Early location condition compared to the Late location condition. This confirms the findings of previous research, suggesting that the mental image of the letter is indeed generated segment by segment and not as a whole (Kosslyn, 1988). Participants with autism were equivalent to controls for both reaction times and correct responses in image generation. The patterns of generation of mental images appeared to be similar between autistic and typical individuals.

Results from the maintenance task evidenced a greater ability to maintain mental images in autistic individuals. As working memory is involved in the maintenance of mental images, a significant capacity to maintain such images therefore raises the question of short-term memory. As visual mental imagery and visual short term memory may rely upon a common “depictive representation system”, the active maintenance of mental images requires the central executive component of visual working memory (Pearson et al., 2013). Working memory in autism could be impaired by challenged executive attentional resources known in autism but it can also be enhanced by domain-specific representations reinforced by more efficient visual perceptual encoding (Hamilton et al., 2018). Indeed, it has been found that visuospatial working memory is compromised in autism (Kercood et al., 2014; Wang et al., 2017). However, in the majority of studies, it is the spatial working memory that is evaluated (Hamilton et al., 2018). Spatial working memory could be challenged in autistic individuals, while visual working memory could be more efficient with more detailed visual representation. In line with this hypothesis, one study evidenced a significant positive relationship between autistic traits and visual working memory performance in children (Hamilton et al., 2018). As the Visual Pattern Test is limited in spatio-sequential properties, it has been described as a relatively pure measure of the visual component of working memory (without spatial properties) (Della Sala et al., 1999), which may explain the better performance of autistic participants in this task.

Concerning the third mental imagery stage, the scanning of mental images, many studies using the image scanning test have reported a linear increase in response times with increasing scanning distances (Borst et al., 2006; Borst & Kosslyn, 2008; Pinker, 1984). Our results are in line with these previous findings, suggesting that participants indeed created a mental image of the pattern of dots and then scanned the distance between the arrows and the

dots. Furthermore, the way mental representations are processed reflects the spatial structure of the representations used in the tasks. Regarding the inspection of mental images, autistic individuals were just as accurate and fast as typical participants. More interestingly, we did not find any effect of distance on their accuracy and response times. Their response times did not increase with the level of difficulty unlike what was observed in typical participants. This can be explained by a more detailed mental imagery and thus by the fact that they manage to answer tasks of increasing difficulty with the same ease. Indeed, Enhanced Perceptual Functioning (EPF) in autism entails enhanced role, performance and autonomy of perception (Mottron et al., 2006; Samson et al., 2011; Mottron & Gagnon, 2023). EPF might consequently lead to a more "accurate" and detailed visual mental representation in autism. Another possible explanation is that the maintenance of mental images is greater in autistic individuals so it may be easier to inspect a better maintained image than a blurry one.

Last, considering the manipulation of mental images, autistic individuals performed as well as typical participants. Thus, we can conclude that the manipulation of mental images is intact in autism. Although several studies have shown superior performances of autistic compared to typically developed individuals on mental rotation tasks (Falter et al., 2008; Hamilton et al., 2009; Pearson et al., 2016; Soulières et al., 2011), our study failed to replicate this result. A question arises as to the time limit for carrying out the test. Several studies report that autistic individuals encounter difficulties in timed tasks, due to difficulties with initiation and psychomotor speed with a slow and accurate response style (Hill & Bird, 2006; Johnston et al., 2011). Unlike the previously cited studies, the version of the Mental rotation test used in our study involved a time limit (e.g. complete as many items as possible within 3 minutes). This may explain why we did not replicate those previous results. It is possible that autistic individuals are more accurate than typical individuals, but answer fewer items within the time limit.

We were also interested in the correlation between the four stages of mental images. As expected, we found that inspection and manipulation were correlated together and are linked to the generation of mental images. Oddly, for the second stage, we only found a link between the maintenance of mental images and manipulation. This was unexpected given that a proper maintenance of the images is necessary for their manipulation, but also for their visual scanning. This may be due to the fact that the Visual pattern test, an indirect measure of the maintenance of mental images, is not "pure", and also involved other cognitive processes than



mental imagery, such as visual working memory as already mentioned. Lastly, the correlation patterns were similar between typically developed and autistic participants.

One limitation of our study is the small number of participants. There was also a gender bias with more female participants in the Autistic group than expected according to the sex ratio in autism (Rodgaard et al., 2019; Zeidan et al., 2022). In addition, due to the complexity of the protocol, all participants had an average, or above average, intellectual functioning level. Therefore, our sample is not entirely representative of the autism spectrum. Besides, one possible explanation for the fact that we did not find group differences for some mental imagery tasks, is the significant heterogeneity of cognitive profiles that is well known in autism (Nader et al., 2015). It is indeed possible that only a “subprofile” of autistic individuals develops increased mental imagery abilities. For example, autistic individuals who experienced delayed language acquisition may develop significant visual capacities and use mental imagery as an alternative mechanism to verbal thinking. It would therefore be interesting to study mental imagery abilities specifically in autistic individuals with delayed language acquisition to verify whether there is a link between language and visual capacities.

The results of this study, which is the first to explore the different stages of mental imagery in autism, indicate preserved to greater visual mental imagery abilities in this population. Maintenance of mental images is greater in autistic individuals. Particularities in the inspection of mental images in autism can be related to the atypical perceptual functioning present in this population, including the bias towards a more local processing of information and a lesser top-down effect. It would also be interesting to study, at a higher level, how these mental imagery abilities are related to the cognitive functioning of autistic individuals.

### **Conflict of interest**

The authors have no conflict of interest to declare.

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## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## References

- Albaret, J. M., & Aubert, E. (1996). Etalonnage 15-19 ans du test de rotation mentale de Vandenberg. *Evolutions psychomotrices*, 206-209.
- American Psychiatric Association. (2013). Diagnostic and statistical manual of mental disorders (5th ed.). <https://doi.org/10.1176/appi.books.9780890425596>
- Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59(4), 390–412. <https://doi.org/10.1016/j.jml.2007.12.005>
- Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. *Journal of autism and developmental disorders*, 31(1), 5–17. <https://doi.org/10.1023/a:1005653411471>
- Beacher, F. D. C. C., Radulescu, E., Minati, L., Baron-Cohen, S., Lombardo, M. V., Lai, M.-C., Walker, A., Howard, D., Gray, M. A., Harrison, N. A., & Critchley, H. D. (2012). Sex Differences and Autism: Brain Function during Verbal Fluency and Mental Rotation. *PLoS ONE*, 7(6), e38355. <https://doi.org/10.1371/journal.pone.0038355>
- Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain*, 128(10), 2430–2441. <https://doi.org/10.1093/brain/awh561>
- Borst, G., & Kosslyn, S. M. (2008). Visual mental imagery and visual perception: Structural equivalence revealed by scanning processes. *Memory & Cognition*, 36(4), 849–862. <https://doi.org/10.3758/MC.36.4.849>

- Borst, G., & Kosslyn, S. M. (2010). Individual Differences in Spatial Mental Imagery. *Quarterly Journal of Experimental Psychology*, 63(10), 2031–2050.  
<https://doi.org/10.1080/17470211003802459>
- Borst, G., Kosslyn, S. M., & Denis, M. (2006). Different cognitive processes in two image-scanning paradigms. *Memory & Cognition*, 34, 475–490.  
<https://doi.org/10.3758/BF03193572>
- Caron, M.-J. (2006). Cognitive mechanisms, specificity and neural underpinnings of visuospatial peaks in autism. *Brain*, 129(7), 1789–1802.  
<https://doi.org/10.1093/brain/awl072>
- Cocude, M., Charlot, V., & Denis, M. (1997). Latency and duration of visual mental images in normal and depressed subjects. *Journal of Mental Imagery*, 21, 127–142.
- Conson, M., Mazzarella, E., Froli, A., Esposito, D., Marino, N., Trojano, L., Massagli, A., Gison, G., Aprea, N., & Grossi, D. (2013). Motor Imagery in Asperger Syndrome: Testing Action Simulation by the Hand Laterality Task. *PLoS ONE*, 8(7), e70734.  
<https://doi.org/10.1371/journal.pone.0070734>
- Dawson, M., Soulières, I., Ann Gernsbacher, M., & Mottron, L. (2007). The Level and Nature of Autistic Intelligence. *Psychological Science*, 18(8), 657–662.  
<https://doi.org/10.1111/j.1467-9280.2007.01954.x>
- Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwinding visuo-spatial memory. *Neuropsychologia*, 37(10), 1189–1199.  
[https://doi.org/10.1016/S0028-3932\(98\)00159-6](https://doi.org/10.1016/S0028-3932(98)00159-6)
- Duret, P., Samson, F., Pinsard, B., Barbeau, E. B., Boré, A., Soulières, I., & Mottron, L. (2018). Gyrification changes are related to cognitive strengths in autism. *NeuroImage: Clinical*, 20, 415–423. <https://doi.org/10.1016/j.nicl.2018.04.036>
- Eriksson, J. M., Andersen, L. M., & Bejerot, S. (2013). RAADS-14 Screen: Validity of a screening tool for autism spectrum disorder in an adult psychiatric population. *Molecular Autism*, 4(1), 49. <https://doi.org/10.1186/2040-2392-4-49>
- Falter, C. M., Plaisted, K. C., & Davis, G. (2008). Visuo-spatial Processing in Autism—Testing the Predictions of Extreme Male Brain Theory. *Journal of Autism and Developmental Disorders*, 38(3), 507–515. <https://doi.org/10.1007/s10803-007-0419-8>
- Finke, R. A., & Pinker, S. (1983). Directional scanning of remembered visual patterns. *Journal of experimental psychology. Learning, memory, and cognition*, 9(3), 398–410. <https://doi.org/10.1037//0278-7393.9.3.398>

- Finke, R. A., & Pinker, S. (1982). Spontaneous imagery scanning in mental extrapolation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8, 142–147. <https://doi.org/10.1037/0278-7393.8.2.142>
- Grandin, T. (2009). How does visual thinking work in the mind of a person with autism? A personal account. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1522), 1437–1442. <https://doi.org/10.1098/rstb.2008.0297>
- Hamilton, A. F. de C., Brindley, R., & Frith, U. (2009). Visual perspective taking impairment in children with autistic spectrum disorder. *Cognition*, 113(1), 37–44. <https://doi.org/10.1016/j.cognition.2009.07.007>
- Hamilton, C. J., Mammarella, I. C., & Giofrè, D. (2018). Autistic-like traits in children are associated with enhanced performance in a qualitative visual working memory task: Child ALTs associated with enhanced visual memory. *Autism Research*, 11(11), 1494–1499. <https://doi.org/10.1002/aur.2028>
- Hill, E. L., & Bird, C. M. (2006). Executive processes in Asperger syndrome: Patterns of performance in a multiple case series. *Neuropsychologia*, 44(14), 2822–2835. <https://doi.org/10.1016/j.neuropsychologia.2006.06.007>
- Hooven, C. (2004). The relationship of male testosterone to components of mental rotation. *Neuropsychologia*, 42(6), 782–790. <https://doi.org/10.1016/j.neuropsychologia.2003.11.012>
- Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, 59(4), 434–446. <https://doi.org/10.1016/j.jml.2007.11.007>
- Johnston, R. J., Otake, Y., Sood, P., Vogt, N., Behnia, R., Vasilias, D., McDonald, E., Xie, B., Koenig, S., Wolf, R., Cook, T., Gebelein, B., Kussell, E., Nakagoshi, H., & Desplan, C. (2011). Interlocked Feedforward Loops Typical Cell-Type-Specific Rhodopsin Expression in the Drosophila Eye. *Cell*, 145(6), 956–968. <https://doi.org/10.1016/j.cell.2011.05.003>
- Kercood, S., Grskovic, J. A., Banda, D., & Begeske, J. (2014). Working memory and autism: A review of literature. *Research in Autism Spectrum Disorders*, 8(10), 1316–1332. <https://doi.org/10.1016/j.rautistic.2014.06.011>
- Koenig, O., Kosslyn, S. M., & Wolff, P. (1991). Mental imagery and dyslexia: a deficit in processing multipart visual objects?. *Brain and language*, 41(3), 381–394. [https://doi.org/10.1016/0093-934x\(91\)90162-t](https://doi.org/10.1016/0093-934x(91)90162-t)

- Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Cambridge, MA: MIT Press.
- Kosslyn S. M. (1988). Aspects of a cognitive neuroscience of mental imagery. *Science (New York, N.Y.)*, 240(4859), 1621–1626. <https://doi.org/10.1126/science.3289115>
- Kosslyn, S. M., Daly, P. F., McPeck, R. M., Alpert, N. M., Kennedy, D. N., & Caviness, V. S. (1993). Using Locations to Store Shape: An Indirect Effect of a Lesion. *Cerebral Cortex*, 3(6), 567–582. <https://doi.org/10.1093/cercor/3.6.567>
- Kosslyn, S. M., Thompson, W. L., & Ganis, G. (2006). *The case for mental imagery*. New York: Oxford University Press, Inc.
- Kosslyn, S. M., Thompson, W. L., & Alpert, N. M. (1997). Neural Systems Shared by Visual Imagery and Visual Perception: A Positron Emission Tomography Study. *NeuroImage*, 6(4), 320–334. <https://doi.org/10.1006/nimg.1997.0295>
- Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., Bishop, S. L., ... & Gutrie, W. (2015). *ADOS-2. Manual (Part I): Modules*, 1-4.
- 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(5), 659–685. <https://doi.org/10.1007/BF02172145>
- Morrison, A. S., Amir, N., & Taylor, C. T. (2011). A Behavioral Index of Imagery Ability in Social Anxiety. *Cognitive Therapy and Research*, 35(4), 326–332. <https://doi.org/10.1007/s10608-009-9274-6>
- Mottron, L. (2019). Detrimental “Sensitivity” framework misses the positive performance, role and autonomy of autistic perception. *Cognitive neuroscience*, 10(3), 168-169. <https://doi.org/10.1080/17588928.2019.1596073>
- Mottron, L., & Burack, J. A. (2001). Enhanced perceptual functioning in the development of autism. In J. A. Burack, T. Charman, N. Yirmiya, & P. R. Zelazo (Eds.), *The development of autism: Perspectives from theory and research* (pp. 131–148). Lawrence Erlbaum Associates Publishers.
- Mottron, L., Dawson, M., Soulières, I., Hubert, B., & Burack, J. (2006). Enhanced Perceptual Functioning in Autism: An Update, and Eight Principles of Autistic Perception. *Journal of Autism and Developmental Disorders*, 36(1), 27–43. <https://doi.org/10.1007/s10803-005-0040-7>

- Mottron, L., & Gagnon, D. (2023). Prototypical autism: New diagnostic criteria and asymmetrical bifurcation model. *Acta Psychologica*, 237, 103938. [https://doi: 10.1016/j.actpsy.2023.103938](https://doi.org/10.1016/j.actpsy.2023.103938)
- Muth, A., Hönekopp, J., & Falter, C. M. (2014). Visuo-Spatial Performance in Autism: A Meta-analysis. *Journal of Autism and Developmental Disorders*, 44(12), 3245–3263. <https://doi.org/10.1007/s10803-014-2188-5>
- Nader, A.-M., Jelenic, P., & Soulières, I. (2015). Discrepancy between WISC-III and WISC-IV Cognitive Profile in Autism Spectrum: What Does It Reveal about Autistic Cognition? *PLOS ONE*, 10(12), e0144645. <https://doi.org/10.1371/journal.pone.0144645>
- Pearson, A., Marsh, L., Ropar, D., & Hamilton, A. (2016). Cognitive Mechanisms underlying visual perspective taking in typical and ASC children: Cognitive mechanisms of perspective taking. *Autism Research*, 9(1), 121–130. <https://doi.org/10.1002/aur.1501>
- Pearson, D. G., Deeprase, C., Wallace-Hadrill, S. M. A., Heyes, S. B., & Holmes, E. A. (2013). Assessing mental imagery in clinical psychology: A review of imagery measures and a guiding framework. *Clinical Psychology Review*, 33(1), 1–23. <https://doi.org/10.1016/j.cpr.2012.09.001>
- Pearson, J., Naselaris, T., Holmes, E. A., & Kosslyn, S. M. (2015). Mental Imagery: Functional Mechanisms and Clinical Applications. *Trends in Cognitive Sciences*, 19(10), 590–602. <https://doi.org/10.1016/j.tics.2015.08.003>
- Pinker, S. (1984). *Language learnability and language development*. (pp. xi, 435). Harvard University Press.
- Podgorny, P., & Shepard, R. N. (1978). Functional representations common to visual perception and imagination. *Journal of experimental psychology. Human perception and performance*, 4(1), 21–35. <https://doi.org/10.1037//0096-1523.4.1.21>
- Raven, J., & Raven, J. (2003). Raven Progressive Matrices. In *Handbook of nonverbal assessment*. (pp. 223–237). Kluwer Academic/Plenum Publishers. [https://doi.org/10.1007/978-1-4615-0153-4\\_11](https://doi.org/10.1007/978-1-4615-0153-4_11)
- Rhode, M., Burnap, P., & Jones, K. (2018). Early-stage malware prediction using recurrent neural networks. *Computers & Security*, 77, 578–594. <https://doi.org/10.1016/j.cose.2018.05.010>
- Ritvo, R. A., Ritvo, E. R., Guthrie, D., Ritvo, M. J., Hufnagel, D. H., McMahon, W., Tonge, B., Mataix-Cols, D., Jassi, A., Attwood, T., & Eloff, J. (2011). The Ritvo Autism Asperger Diagnostic Scale-Revised (RAADS-R): A Scale to Assist the Diagnosis of

- Autism Spectrum Disorder in Adults: An International Validation Study. *Journal of Autism and Developmental Disorders*, 41(8), 1076–1089.  
<https://doi.org/10.1007/s10803-010-1133-5>
- Rødgaard, E. M., Jensen, K., Miskowiak, K. W., & Mottron, L. (2022). Representativeness of autistic samples in studies recruiting through social media. *Autism Research*, 15(8), 1447–1456. <https://doi.org/10.1002/aur.2777>
- Rutter, M., Le Couteur, A., & Lord, C. (2003). Autism diagnostic interview-revised. *Los Angeles, CA: Western Psychological Services*, 29, 30.
- Samson, F., Hyde, K. L., Bertone, A., Soulières, I., Mendrek, A., Ahad, P., Mottron, L., & Zeffiro, T. A. (2011). Atypical processing of auditory temporal complexity in autistics. *Neuropsychologia*, 49(3), 546–555.  
<https://doi.org/10.1016/j.neuropsychologia.2010.12.033>
- Silk, T. J., Rinehart, N., Bradshaw, J. L., Tonge, B., Egan, G., O’Boyle, M. W., & Cunnington, R. (2006). Visuospatial Processing and the Function of Prefrontal-Parietal Networks in Autism Spectrum Disorders: A Functional MRI Study. *Am J Psychiatry*, 4.
- Soulières, I., Dawson, M., Samson, F., Barbeau, E. B., Sahyoun, C. P., Strangman, G. E., Zeffiro, T. A., & Mottron, L. (2009). Enhanced visual processing contributes to matrix reasoning in autism. *Human Brain Mapping*, 30(12), 4082–4107.  
<https://doi.org/10.1002/hbm.20831>
- Soulières, I., Zeffiro, T. A., Girard, M. L., & Mottron, L. (2011). Enhanced mental image mapping in autism. *Neuropsychologia*, 49(5), 848–857.  
<https://doi.org/10.1016/j.neuropsychologia.2011.01.027>
- Stevenson, J. L., & Nonack, M. B. (2018). Gender differences in mental rotation strategy depend on degree of autistic traits: Mental Rotation Strategy. *Autism Research*, 11(7), 1024–1037. <https://doi.org/10.1002/aur.1958>
- Vandenberg, S. G., & Kuse, A. R. (1978). Mental Rotations, a Group Test of Three-Dimensional Spatial Visualization. *Perceptual and Motor Skills*, 47(2), 599–604.  
<https://doi.org/10.2466/pms.1978.47.2.599>
- Wang, Y., Zhang, Y., Liu, L., Cui, J., Wang, J., Shum, D. H. K., van Amelsvoort, T., & Chan, R. C. K. (2017). A Meta-Analysis of Working Memory Impairments in Autism Spectrum Disorders. *Neuropsychology Review*, 27(1), 46–61.  
<https://doi.org/10.1007/s11065-016-9336-y>

- Zarrinpar, A., Deldin, P., & Kosslyn, S. M. (2006). Effects of depression on sensory/motor vs. Central processing in visual mental imagery. *Cognition & Emotion*, 20(6), 737–758. <https://doi.org/10.1080/02699930500405600>
- Zeidan, J., Fombonne, E., Scolah, J., Ibrahim, A., Durkin, M. S., Saxena, S., Yusuf, A., Shih, A., & Elsabbagh, M. (2022). Global prevalence of autism: A systematic review update. *Autism Research*, 15(5), 778–790. <https://doi.org/10.1002/aur.2696>.