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Adults with autism tend to underestimate the hidden environmental structure: evidence from a visual associative learning task

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Abstract

The learning-style theory of Autism Spectrum Disorders (ASD) (Qian and Lipkin 2011) states that individuals with ASD differ from neurotypics in the way they learn and store information about the environment and its structure. ASD would rather adopt a *lookup-table* strategy (LUT: memorizing each experience), while neurotypics would favor an *interpolation* style (INT: extracting regularities to generalize). In a series of visual behavioral tasks, we tested this hypothesis in 20 neurotypical and 20 ASD adults. ASD participants had difficulties using the INT style when instructions were hidden but not when instructions were revealed. Rather than an inability to use rules, ASD would be characterized by a disinclination to generalize and infer such rules.

Keywords: autism; perception; categorization; learning; local and global processing

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INTRODUCTION

An atypical learning style was mentioned in the very first reports about autism (Asperger 1944; Kanner 1943). Léo Kanner had noticed that children with autism could not learn from adults in “*conventional ways*” (Kanner 1943). For instance, one child with autism had “*an unusual memory for faces and names, knew the names of a great number of houses*”, but “*seemed unable to generalize, transfer an expression to another similar object*” (Kanner 1943). Hans Asperger also described individuals with autism as being poor at “*mechanical learning*” (Asperger 1944; Frith 1991), referring to the learning style spontaneously used by typically developing children.

In Autism Spectrum Disorders (ASD), peculiarities of learning often suggested a failure to adapt rules and to generalize (Dawson et al. 2005; Plaisted 2001). Particularly, many studies have underlined an atypical category learning in ASD, usually slower and less accurate than in neurotypical (NT) participants (Alderson-Day and McGonigle-Chalmers 2011; Carmo et al. 2017; Church et al. 2010, 2015; Gastgeb et al. 2012; Gastgeb and Strauss 2012; Klinger and Dawson 2001; Soulières et al. 2007, 2011; Vladusich et al. 2010). The ability to extract regularities or common features between different stimuli in order to categorize them has often been investigated in ASD by using dot pattern categorization tasks. Studies using such tasks showed different degrees of impairment in children (Church et al. 2010) and adults (Gastgeb et al. 2012) with ASD, (although see Vladusich et al. 2010). Noticeably, individuals with ASD were more impaired than NT to categorize dot patterns that were most distorted from the category prototype (Froehlich et al. 2012). In ASD, studies showed an impaired ability to build up a mental representation of a category (Church et al. 2010; Klinger and Dawson 2001).

Importantly, these findings point towards learning impairments in ASD that affect low level perception, even in non-social contexts. It thus suggests that core atypical learning

mechanisms could be at the heart of ASD symptoms, including the social ones. And the later could simply be most prominent since social stimuli are multidimensional, complex, essential and ubiquitous in our daily lives. This strongly motivates the study of such mechanisms, independently of social contexts.

Several theories have attempted to explain which mechanisms fail to be used in ASD, yielding atypical perception and learning. The *Reduced generalization model* (Plaisted 2001) suggested that individuals with ASD would have difficulties to extract similarities between stimuli, hence to generalize. Not only should this affect perception, but also social comprehension. Indeed, spontaneously processing the main underlying regularities of social stimuli or social situations will help generalizing (e.g. facial expressions) or using social norms in a context-dependent manner. More recently, a *learning-style theory* of autism was introduced (Qian and Lipkin 2011), inspired by the observation that individuals with ASD show difficulties to learn based on training examples (Dawson and Mottron 2008). The authors oppose two learning styles: the *interpolation* (INT) and the *lookup-table* (LUT) one. They suggest that the INT learning-style would be preferentially used by NT individuals, while individuals with ASD would be more biased toward the LUT learning-style.

The INT learning style consists in extracting underlying regularities or hidden rules from the environmental structure, in order to generalize and categorize. Generalization would stem from the ability to interpolate across gaps between examples, in a context where examples could be encoded with broad tuning functions (i.e. with low precision). In contrast, the LUT learning style consists in storing each experience precisely without properly compressing information (e.g. learning an association of names and phone numbers). Storing examples with narrow tuning functions (i.e. with high precision) would prevent from making interpolations but would help distinguishing each example from one another. Fitting each example very precisely becomes a waste of resources in a noisy environment where details

are meaningless. In contrast, the INT learning style is context-dependent and particularly efficient in noisy environments, since encoding stimuli with broad tuning functions enables the categorization and interpretation of new stimuli. In other words, contrary to the LUT learning style, the INT one prevents from overfitting and would thus be more adapted to real-life situations where all kinds of noise have to be filtered out. This is essential to correctly interpret sensory stimuli, and subsequently to elaborate functions such as language (Fisher et al. 2014; Marcus et al. 2007) or appropriate social skills (Weston and Turiel 1980). Social stimuli are particularly noisy, flexible and context-dependent, and their multidimensional and complex underlying regularities need to be interpolated between situations. Hence, the INT style would be more optimal than the LUT style for processing social stimuli.

A wide variety of atypical behaviors in ASD could be explained by a reduced use of the INT style and a greater use of the LUT style (as compared to NT). For instance, some persons with ASD report that they tend to learn each situation almost by rote (LUT style) instead of generalizing (INT style). Temple Grandin explained: *“When I encounter a new social situation, I have to search my memory for a similar experience that I can use as a model for my next action. [...] For common social interactions with clients I use preprogrammed, prerehearsed responses”* (Grandin 1997). With the LUT style, accumulating a great number of examples would end up increasing the potential match between present and past situations, but is highly demanding and can be saturated. Since the LUT style is poorly adapted to the learning of socially relevant cues, if preponderant in ASD it may explain the difficulties in understanding social interactions, as well as the difficulties to transfer social training skills to realistic situations (Ozonoff and Miller 1995). A reduced use of the INT style in ASD would also be in line with findings on categorization and prototype formation suggesting impaired generalization (Church et al. 2010; Gastgeb et al. 2012; Suzanne Scherf et al. 2008; Vladusich et al. 2010). Yet, some results on categorization in ASD remain

inconsistent regarding the degree of impairment (e.g. Soulières et al. 2007; Vladusich et al. 2010), and the ability to categorize in real-life ecological situations (where individuals with ASD are not given instructions) might differ from the situations of experimental testing described in scientific reports.

In the present study, we designed and tested a new visual paradigm questioning whether ASD individuals would indeed spontaneously make less use of the INT style and more use of the LUT styles than NT. Our paradigm matched the recommendation by Qian and Lipkin (2011) suggesting that age- and IQ-matched NT and ASD participants needed to be “*trained on random (but fixed) association tasks and tasks with hidden, underlying rules*”, and that it was “*best to use non-social tasks (e.g., learning visual categorization of shapes) to avoid potential confounds from autistic and typical subjects’ different developmental and intervention histories*”.

Here, following Qian and Lipkin (2011), we hypothesized that contrary to NT participants, ASD participants would spontaneously favor a LUT over an INT learning strategy. Nevertheless, we also hypothesized that ASD participants would actually be able to understand and implement an INT strategy when explicitly instructed to do so, as the level of instructions can highly modify performance in ASD (Koldewyn et al. 2013; Van der Hallen et al. 2016). In other words, we hypothesized that in the case of limited guidance and minimal instructions, ASD participants would naturally favor a LUT learning strategy. However, we further hypothesized and tested that this difference with NT participants would diminish or even vanish in the case of explicit instructions about the strategy to be implemented.

Therefore, participants first performed a series of visual tasks where they received no instructions as to which learning strategy to implement. The hidden structure of the task relied on the INT learning style for rule-based tasks, whereas it relied on LUT learning style for memory-based tasks. Based on the above hypothesis, we expected the ASD participants to

perform (1) less accurately than NT in rule-based tasks, and (2) more accurately than NT in memory-based tasks. Upon completion of the series of learning tasks, participants completed questionnaires designed to elicit learning strategies used. We also expected that debriefing questionnaires would confirm that ASD participants were spontaneously biased toward the LUT style, whereas NT participants would be biased toward the INT style. Finally, participants were then asked to perform similar tasks but with clear instructions about the learning style to favor, in order to control for their ability to understand and implement each learning style. We here expected the behavior of ASD participants to resemble very much the one of NT participants and show that they were indeed able to implement one strategy or the other, as requested.

MATERIAL AND METHODS

Participants

Twenty-two participants with ASD and 23 NT participants took part in the study. Two participants with ASD and three NT participants were discarded from the analyses as they failed at performing the control task (see Results section). The two resulting groups consisted of 20 participants with ASD (mean age in years: 33.6 ± 10.0) and 20 NT participants (mean age in years: 30.8 ± 6.9). The two groups were matched for age, gender ratio and education level. Groups were also matched for intellectual quotient assessed by the Wechsler Adult Intelligence Scale (WAIS III or IV) on the verbal comprehension and perceptual reasoning subscores. Their characteristics are detailed in Table 1. Participants completed the autism-spectrum quotient (AQ) test (Baron-Cohen et al. 2001; Sonié et al. 2011). All participants scored above the cut-off threshold for ASD using the *Autism Diagnostic Observation Schedule* (Lord et al. 2000), but details of the scores could be obtained for 14/20 participants

only. Scores at the *Autism Diagnostic Interview* (Le Couteur et al. 2003) could be obtained for four participants only, due to the fact that many participants were diagnosed when they were adults. Based on these clinical assessments that concluded to a diagnosis of ASD also using criteria defined in the *Diagnostic and Statistical Manual of Mental Disorders DSM-IV* (American Psychiatric Association 2000) or DSM-V (American Psychiatric Association 2013), every participant then underwent an interview with an experienced psychiatrist highly specialized in autism diagnosis, research-certified in the ADI and the ADOS, and in charge of the regional Resources Center for Autism, before being enrolled in the study. All participants with ASD had a diagnosis of ASD without any intellectual deficiency or language acquisition delay. Participants had normal or corrected-to-normal vision. NT participants reported no history of neurological or psychiatric disorders. Approval was obtained from the local ethics committee (French South East IV Committee for the Protection of Persons). Participants gave their written consent beforehand.

----- *Please, insert Table 1 here* -----

Stimuli

We created visual stimuli that were unique and distinguishable enough to be memorized independently, but which could also be categorized based on common features. Importantly, these stimuli were new to all participants, so as to avoid any influence from prior knowledge. All stimuli were created using Matlab 2013a.

Each stimulus consisted of a geometric picture defined by lines and angles that formed a shape. It was made of nine points pseudo-randomly chosen on a horizontal ellipse and then connected with each other. The resulting pattern was filled with black color. Then, 104 of the ellipses were rotated by 15° [9:21], 32 by 90° [84:96], 104 by 135° [129:141], 32 by 255° [249-261] and 32 by 0° [-6:6] (Figure 1). These rotations enabled the formation of five categories of geometrical pictures: C_0 , C_{15} , C_{90} , C_{135} and C_{255} . We added a Gaussian noise to

the orientation within each category with a standard deviation of $\pm 6^\circ$ in order to assess whether this would affect performance.

----- *Please, insert Figure 1 here* -----

General procedure

Participants were sitting at 60cm from the computer screen and the displayed stimuli were 20cm long and 8cm wide. Participants responded with their dominant hand, using the two buttons of the computer mouse. The experiments were programmed using the software package Presentation (Neurobehavioral Systems).

Participants were told that they were going to perform a series of visual tasks in which the goal was to win as many points as possible. They were explained that each stimulus was predictive of the correct choice to be made (left or right) in order to be successful. In each trial, after button press, participants received feedback (“Won”: 1 point, “Lost”: 0 point). The feedback would give them the possibility to discover a strategy in order to win more points. They also knew that the link between the stimulus and the winning answer could be different from one task to another. Importantly and hidden from the participants, each stimulus-winning-response association was either consistent with a rule-based approach (INT) or with a memory-based approach (LUT). In the former, applying a memory-based (LUT) strategy would be suboptimal, while in the latter it would become the best (and only possible) strategy.

At each trial, one stimulus was displayed on a white screen for three seconds, and followed by two identical black discs indicating the two possible answers (Figure 1-A). Participants were given three seconds at most to select one of the two options. The disc on the side chosen by the participant was then colored in blue for 800ms to highlight their selection. Immediately after, a feedback was given to indicate whether their choice was correct or not (“Won” or “Lost” displayed on the screen for 2000ms). The inter-stimulus interval consisted of a white screen displayed for 500ms.

In each task, there were no more than five consecutive trials with the same winning response, and the same stimulus never appeared twice consecutively. Participants were asked to favor accuracy over speed. Participants completed six tasks and the whole experiment lasted for about one hour. The order of the tasks was the following: 1st (or 2nd): *Rule-based task*, 2nd (or 1st): *Memory-based task*, 3rd: *Mixed LUT-INT task*, 4th: *Recognition test*, 5th (or 6th): *Rule-based control task*, 6th (or 5th): *Memory-based control task*.

Main tasks without instructions

Rule-based task

This task assessed the spontaneous use of the INT learning-style. Participants were only told that the displayed stimulus was informative about the side of the winning response. The hidden associative rule was such that the correct response depended on stimulus orientation (Figure 1.B). Two categories of stimuli were presented: C_0 (32 different horizontal shapes) and C_{90} (32 different vertical shapes). The stimulus-winning-response association was counter-balanced over participants. For half of the participants, a correct left button press (respectively, right) was associated with horizontal stimuli (respectively, vertical) and the reverse rule applied for the other half. As each stimulus was never presented twice, this association could not be memorized. The *Rule-based task* consisted of 64 trials with 64 different visual stimuli, and lasted for six minutes on average.

Memory-based task

This task assessed the spontaneous use of the LUT learning-style. Participants were only told that there was a link between the stimulus displayed and the side of the winning response. To succeed, participants had to memorize a unique association between a stimulus and a response side (Figure 1.C). Eight stimuli from category C_{255} were pseudo-randomly presented eight times each. Four of them were associated with a left winning answer, whereas

the four others were associated with a right winning answer. Associations were counterbalanced over participants. The *Memory-based task* consisted of 64 trials with 8 different visual stimuli, and lasted for six minutes on average.

We counterbalanced the order of presentation of the *Rule-based task* and *Memory-based task* between participants.

Mixed LUT-INT task

This task tested the spontaneous use of both the LUT and INT learning strategies. Again, participants were told that there was a link between the stimulus displayed and the side of the winning response. They were also told that if they had discovered strategies during the two previous tasks (*Rule-based* and *Memory-based tasks*), these could be useful for this new task. To succeed, participants had to use the INT strategy for half of the stimuli (categorization), and the LUT strategy for the other half (memorization) (Figure 1.D). This task was divided into four sessions consisting of 64 trials each. In each session, 32 stimuli had to be classified according to their orientations (16 belonging to C_{15} , and 16 belonging to C_{135}) and 8 stimuli belonging to C_{255} were displayed four times each (i.e. 32 trials) and had to be memorized. The four sessions presented a total of 64 stimuli from C_{15} (each presented once), 64 stimuli from C_{135} (each presented once), and 8 stimuli from C_{255} (each presented 16 times). The *Mixed LUT-INT task* consisted of 256 trials in total, with 136 different visual stimuli. It lasted for about 24 minutes (interrupted by two-minute breaks in-between sessions).

Control tasks with full instructions

Rule-based control task

This task measured the participants' performance when explicitly told that stimuli presenting with the same orientation were associated with the same winning side, and that there were two classes of orientations. Prior to the task, participants were also shown two

stimulus examples illustrating the two different orientations. The design of this control task was the same as in the main *Rule-based task*. Two categories of stimuli were presented: 32 stimuli belonging to C_{15} (e.g., associated with a right winning response), and 32 belonging to C_{135} (e.g., associated with a left winning response). The side of the winning response was counter-balanced between participants. The *Rule-based control task* consisted of 64 trials with 64 different visual stimuli, and lasted for six minutes on average.

Memory-based control task

This task measured the participants' performance when explicitly told to memorize the stimulus-winning-response association. The design of this control task was the same as in the main *Memory-based task*. Eight stimuli belonging to C_{255} were pseudo-randomly presented eight times each (these were different from the ones presented in the previous tasks). Half of the stimuli were associated with a right winning answer, and the other half with the left winning answer. The side of the winning answer was counter-balanced between participants. The *Memory-based control task* consisted of 64 trials with 8 different visual stimuli, and lasted for six minutes on average.

Additional measures

Recognition test

This task tested whether participants did memorize some of the stimuli presented during the *Mixed LUT-INT task*, performed right beforehand. Note that this is different from having memorized the association between a given stimulus and the side of the winning response for that stimulus. Participants were presented with stimuli displayed during the *Mixed LUT-INT task* or never displayed before, and they had to indicate by a button press whether they had already seen them or not.

Sixteen stimuli from each of the three following categories were used: C₁₅, C₁₃₅ and C₂₅₅. Within each category, eight stimuli had been displayed during the *Mixed LUT-INT task*, while the eight others were new. Each stimulus appeared for three seconds, and participants had to press on the side of the screen indicating “*seen*” or “*never seen*” (this side was counterbalanced between participants). No feedback was provided, and the inter-stimulus trial lasted for 800ms. The *Recognition test* consisted of 48 trials with 48 different visual stimuli (24 had been previously shown), and lasted for about 4 minutes.

Post-experiment questionnaires

After the fourth task (before starting the control tasks), participants completed a questionnaire. They were asked to report the strategies they tried to use for each task. We classified answers to the question “Can you describe the strategy you used for each of the exercises?” within four categories: categorization based on the orientation, on another rule based on global stimulus features (e.g.: large vs. small colored surface), on a rule based on local stimulus features (e.g.: side of the smallest angle of the shape), or on memorization.

Statistical analyses

Between-group comparisons of the demographical data and scores at neuropsychological tests were performed using Student’s t-test. The accuracy corresponds to the percentage of correct answers over trials and was computed for each task separately. In the *Memory-based task*, *Rule-based task* and the two control tasks, accuracies and response times were compared between groups using Student t-tests. In the *Mixed LUT-INT task*, a three-way analysis of variance (ANOVA) was applied on accuracies to assess the effect of group (NT or ASD), stimulus type (INT or LUT) and sessions (1 to 4). Student’s t-tests were used for post-hoc comparisons. Correlations between accuracies and IQ scores were examined using Pearson analysis.

Chance levels were calculated as the upper limit of the confidence interval in binomial tests assessing 50% of success (with a confidence level of 0.95), i.e. 68.1% of correct answers for 32 trials, 62.8% for 64 trials, 59.0% for 128 trials and 56.3% for 256 trials. Proportions of participants scoring above chance level or reporting different strategies in the questionnaires were compared using proportion tests.

Statistical analyses were performed using R (<http://www.R-project.org>). The threshold for statistical significance was always set to $p < .05$.

RESULTS

No effect of orientation blurring within each stimulus categories could be observed on accuracy. Hence all the results reported below integrate over this dimension.

Participant selection criteria in the control tasks

The *Rule-based control* task was used to select participants for further analyses. We excluded the participants that were not able to categorize the stimuli according to their orientations when they were explicitly asked to. We considered this ability as a prerequisite to perform the implicit *Rule-based task* and *Mixed LUT-INT task*. Hence, participants who did not obtain more than two third of correct answers at this control task were excluded from our analyses. Three NT participants (mean accuracy: 56.8% \pm 14.0) and two ASD participants (mean accuracy: 53.9% \pm 3.3) were excluded. These participants reported that they did not manage to identify any global orientation in the displayed stimuli, apart from one of the ASD participant who reported that he recognized the orientation but could not help pressing the left button. The resulting groups consisted of 20 NT and 20 ASD participants whose characteristics are given in Table 1. Results reported below are all based on all ASD and NT participants (N=20 in each group).

----- Please, insert Table 2 here -----

Main tasks without instructions

Rule-based task

Results are presented in Table 2 and Figure 2-A. The NT group performed better than the ASD group ($p < .005$), with 81.9% (± 18.1) versus 62.8% (± 16.6) of correct answers. A higher proportion of NT than ASD participants scored above chance level (NT: 75% vs. ASD: 25%, $p < .05$). As another indicator of group difference in inferring and applying the rule, 85% of the NT participants answered correctly eight times in a row after only 16 trials (median). In contrast, only 30% of the ASD participants reached the same performance, but after 27 trials (median).

----- Please, insert Figure 2 here -----

Memory-based task

Results are presented in Table 2 and Figure 2-B. The NT and ASD groups obtained 59.0% (± 11.8) and 56.6% (± 14.0) of correct answers, respectively. No differences in accuracy were found between groups. Both groups scored at chance level on average. Participants scoring above chance level represented 40% of the NT group and 30% of the ASD group (no group difference).

Mixed LUT-INT task

Results are presented in Table 2 and Figure 3. We performed a nested ANOVA investigating the effect of group (NT and ASD), stimulus (INT and LUT) and session (1 to 4) on accuracy. There was a group effect ($F(38,1) = 7$, $p < .01$), with the NT group scoring higher than ASD (NT: 71.3% ± 11.2 vs. ASD: 62.3% ± 13.4 , $p < .05$). There was a stimulus effect ($F(38,1) = 43$, $p < 10^{-6}$), with a better recognition of INT stimuli than LUT stimuli (INT: 72.9% ± 18.1 vs. LUT: 60.7% ± 12.8 , $p < .001$). There was a session effect ($F(38,3) =$

17, $p < 10^{-6}$), with a significant increase from session 1 to session 3 ($p < .01$) and 4 ($p < .01$). Finally, there was an interaction between the factors group and stimuli ($F(38,1) = 20$, $p < 10^{-4}$), with the NT group scoring higher than ASD for INT stimuli (NT: 81.5% \pm 16.4 vs. ASD: 64.3% \pm 19.9, $p < .01$), but not for LUT stimuli. Within group, NT participants scored higher for INT than LUT stimuli ($p < .001$), whereas ASD participants showed no difference in accuracy between INT and LUT stimuli.

Participants scoring above chance level for INT stimuli were more numerous in NT than ASD (NT: 90% vs. ASD: 40%, $p < .001$) and were not different for LUT stimuli (NT: 55% vs. ASD: 50%). To determine which learning style was associated with the highest accuracy, we compared accuracy for INT versus LUT stimuli for each participant (Figure 3B). The proportion of participants with higher scores for INT than LUT stimuli was larger in NT than ASD (NT: 85% vs. ASD: 30%, $p < .001$). The proportion of participants with higher scores for LUT than INT stimuli was larger in ASD than NT (NT: 15%, ASD: 50%, $p < .05$). In the ASD group, 20% of the participants did not show any differences between scores for INT and LUT stimuli.

----- Please, insert Figure 3 here -----

Control tasks with full instructions

Rule-based control task

Results are presented in Table 2 and Figure 2-A. NT and ASD participants reached 98.4% (\pm 1.9) and 95.2% (\pm 6.3) of correct answers, respectively. In each group, 100% of participants scored above chance level. Although accuracy was very high in both groups, the NT group scored slightly higher than ASD ($p = .04$). After more detailed analyses of error repartition, this difference appeared to be mostly driven by differences during the first trials.

ASD participants committed twice more errors than NT participants between the 1st and 6th trial.

Memory-based control task

Results are presented in Table 2 and Figure 2-B. The percentages of correct answers were 66.6% (± 9.8) in NT and 61.9% (± 14.5) in ASD, and did not significantly differ between groups. Participants scoring above chance level were 60% in the NT group and 55% in the ASD group (no group difference).

Between task comparisons

Rule-based vs. Memory-based tasks

In the main tasks without instructions, the NT group showed greater accuracy in the *Rule-based task* than in the *Memory-based task* ($p < 10^{-5}$). In the ASD group, there was no significant difference between these two tasks.

In the control tasks with instructions, both groups were less accurate in the *Memory-based control task* than in the *Rule-based control task* ($p < 10^{-6}$ in both groups).

Without vs. with full instructions

In the *Rule-based tasks*, giving instructions resulted in a significant increase in accuracy by 16.5% (± 18.4) in NT ($p < .001$) and 32.3% (± 15.5) in ASD ($p < 10^{-6}$) (Table 2). In the *Memory-based tasks*, giving instructions resulted in a significant increase in accuracy by 7.6% (± 12.3) in NT ($p < .05$) and in a non-significant increase by 5.2% (± 16.1) in ASD.

Relationships with IQ scores

The perceptual reasoning score (including 3D visual search) was expected to correlate with accuracy in the *Rule-based task*. It proved to be the case for NT participants only ($r = .60, p < .01$).

The working memory score (including attention and concentration assessments) was expected to correlate with accuracy in the *Memory-based task*. It proved to be the case for NT participants only ($r = .49, p < .05$).

Additional measures

Recognition test

The overall accuracy in NT (60.9% \pm 8.2) and ASD (56.9% \pm 9.5) was not significantly different between groups. Groups did not differ in accuracy for LUT stimuli that needed to be memorized (NT: 70.9% \pm 13.9, ASD: 69.1% \pm 14.3), nor for INT stimuli that needed to be categorized (NT: 55.9% \pm 11.9, ASD: 50.8% \pm 14.4) (Figure 4A). Both groups remembered more accurately LUT stimuli than INT stimuli ($p < .001$ in both groups).

Post-experiment questionnaires

A higher proportion of NT than ASD participants reported searching for a rule in the *Rule-based task* (NT: 100% vs. ASD: 60%, $p < .01$), in the *Memory-based task* (NT: 95% vs. ASD: 50%, $p < .01$) and in the *Mixed LUT-INT task* (NT: 95% vs. ASD: 60%, $p < .05$) (Figure 4-B). In the *Memory-based task*, a higher proportion of ASD than NT participants tried to memorize the stimuli (ASD: 35% vs. NT: 5%, $p < .05$) (Figure 4-C).

Remarkably, the two ASD participants with the best accuracy for INT stimuli in the *Mixed LUT-INT task* reported an alternative rule to the one based on orientation. They classified the stimuli based on a single detail: given that the stimuli were angled, the highest point of the shape was on the right side of the screen for stimuli belonging to C₁₅ and on the left side of the screen for stimuli belonging on C₁₃₅. These two participants declared clicking on the side of this highest point to succeed. They were the only two participants who reported having found this rule.

----- Please, insert Figure 4 here -----

DISCUSSION

The goal of the present study was to investigate the spontaneous tendency of NT and ASD adults to use two kinds of learning styles: extracting regularities to interpolate between items (INT style) or memorizing lists of associations independently and precisely (LUT style). We had hypothesized that the ASD group would show a bias toward a decreased use of the INT style and an increased use of the LUT style, as compared to NT (Qian and Lipkin 2011). Two main results were in favor of this hypothesis: ASD participants were less inclined to spontaneously use the INT style and reported an increased tendency to use the LUT style. Importantly though, the ASD group was able to instantiate the INT style when instructed to do so.

Decreased use of the INT style and increased use of the LUT style in ASD

In ASD, the reduced use of the INT style was confirmed by lower scores in tasks without instructions and by their qualitative reports, while the tendency to favor the LUT style was confirmed by qualitative reports only. In the *Rule-based task* without instructions and in the *Mixed LUT-INT task*, ASD participants had difficulties extracting the underlying regularities between stimuli to find a rule. This could be explained by an increased focus on details of the stimuli preventing them from finding the global rule and by a reduced tendency to spontaneously look for rules. In addition, slower category learning in ASD (Bott et al. 2006; Gastgeb and Strauss 2012; Soulières et al. 2011) could explain the impairment of the ASD group in the *Rule-based task*. It could also explain the slightly reduced accuracy of the ASD group in the *Rule-based control task* (with instructions) during the first trials of the task. Interestingly, the study by Soulières et al. showed that ASD participants did not use any identifiable strategies in the early phases of training, but ended up using the same strategies as NT at the end of the training (Soulières et al. 2011).

Qian and Lipkin (2011) had hypothesized that individuals with ASD would perform better with the LUT style than NT. Yet, in the present study, the ASD group did not score higher than NT in tasks requiring the use of the LUT style. Group differences might have emerged if a longer period of learning had been proposed. Indeed, although qualitative reports from questionnaires revealed that a higher proportion of participants with ASD than NT tried to use the LUT style, the *Memory-based task* was apparently too difficult for most participants to elicit a group difference. Further use of a similar task should probably consider a longer exposure to the stimuli in order to be more sensitive to a putative group difference in memorizing individual stimulus-outcome associations.

Noteworthy, there were positive correlations between accuracy with the INT style and the perceptual reasoning score (IQ-PR), and between accuracy with the LUT style and the working memory score (IQ-WM) within the NT group, but not within the ASD group. This suggests that, in the NT group at least, the participants' abilities to find the orientation rule and to perform 3D visual search were related, and so were their abilities to memorize the association between stimuli and answers and their working memory scores. In the ASD group, their IQ scores could not be related to the intra-group variability in making use of the LUT or INT style.

Spontaneous versus instructed INT style

In the present study, ASD participants were able to interpolate and categorize, but made less spontaneous use of the INT learning-style, as compared to NT. Hence, the decreased performance of the ASD group in *Rule-based tasks* could be explained by the absence of explicit task instructions. Accordingly, other studies investigating perception in ASD showed that group differences appeared with implicit instructions only, but not with explicit instructions (Koldewyn et al. 2013; Van der Hallen et al. 2016). For instance, the effect of the level of instructions on performance was assessed in a study investigating global

and local processing abilities in children with ASD in a free-choice task versus an instructed task (Koldewyn et al. 2013). Their study revealed that children with ASD did not show a disability in global processing when they received explicit instructions, but showed disinclination in global processing in absence of explicit instructions. Likewise, a recent study involving visual search tasks showed that children with ASD did not differ from typically developing children when given explicit instructions, but had a lower accuracy when they were less aware of the targets to search for (Van der Hallen et al. 2016). Inconsistent results about local and global processing (Van der Hallen et al. 2015, for a meta-analysis) could be explained by different levels of task instructions. Similarly, explicit instructions can also significantly reduce the impairment of ASD participants found in non-instructed tasks assessing social cognition or executive functions (Baez et al. 2012; Baez and Ibanez 2014; Senju et al. 2009; White et al. 2009). In their studies, group differences were explained by difficulties to spontaneously integrate social and/or contextual information in ASD (Baez et al. 2012; Senju et al. 2009). Altogether, results from the literature and from the present study highlight the key role of instructions in assessing abilities in ASD, which could account for inconclusive results in ASD (e.g. on categorization). It also suggests that highly structured and explicit rules or instructions are necessary for individuals with ASD.

Precision tuning in the learning-style theory

The reduced automatic use of the INT style could be interpreted as a different precision tuning of the encoding of the training examples. In complex tasks involving several features, a broad precision tuning is optimal (INT style), whereas in easier tasks involving only one feature, a narrower precision tuning is optimal (Qian and Lipkin 2011). After receiving the instructions on the orientation rule, the ASD participants might have been able to categorize stimuli as they needed to encode only one feature. Accordingly, another study showed that when ASD and NT participants were attending to the same features of a stimulus,

people with ASD had similar performance as NT (Bott et al. 2006). Other visual tasks have investigated perceptual abilities in ASD in contexts where one or several features needed to be encoded. For instance, people with ASD showed enhanced perceptual abilities to detect orientation in a simple grid, but impaired abilities to detect orientation when noise was added to the grid (Bertone et al. 2005). This suggests that, in ASD, visual processing at a low-level can be enhanced, but that it might be impaired at a higher-level. In our tasks, a lower-level could correspond to tasks with instructions (where only the orientation needs to be encoded), and a higher-level could correspond to the non-instructed tasks (where several features, including noise, need to be encoded).

The learning-style theory of ASD is consistent with an older theory: the Adaptive Resonance Theory (Grossberg 1999). This theory stated that categorizing can be described as a top-down effect, decreasing differences within a category and increasing differences between categories. This top-down effect could adapt the precision tuning to allow categorization (i.e. with a broad precision tuning). In ASD, a decreased influence of top-down categorical knowledge on discrimination (Soulières et al. 2007) could explain the reduced use of the INT learning-style by ASD participants in our tasks.

From the learning-style theory to computational accounts of ASD

Recently, learning in ASD was approached within the Bayesian framework. In this framework, perception emerges from a weighted combination of sensory information and prior belief (Friston 2003). Priors typically capture the main features of the previously encountered stimuli and can be adjusted throughout learning. Priors are context-dependent and play a key role in categorization, generalization and prediction. The INT learning-style would allow broad priors. In contrast, the LUT learning-style favors the encoding of details and prevents from identifying commonalities between examples, which could be referred to as a set of precise *priors*.

Computational approaches have recently enabled to shed light on how people with ASD cope with different types of uncertainty, namely *sensory ambiguity*, *probabilistic uncertainty* and *environmental uncertainty* (Lawson et al. 2017; Palmer et al. 2017). These three dimensions of uncertainty can be identified in our tasks. First, *sensory uncertainty* was manipulated as stimulus orientations were following a normal distribution. Yet, we did not find any impact of such a sensory noise on the difference in performance between groups. Second, *probabilistic uncertainty* was null, since each stimulus was surely predicting the correct response. What remained to be determined by the participant was the actual predicting rule at play. Finally, *environmental uncertainty* was introduced between blocks by changing the learning strategy, and within the *Mixed LUT-INT task* by mixing the type of stimulus-response association. We did observe a difference between groups in dealing with this environmental uncertainty, in the sense that only NT participants reported raising their strategy to the use of two learning-styles in the case of the *Mixed LUT-INT task*. However, this may highlight another difference between ASD and NT participants than the one reported in Lawson et al. (2017). Indeed, while Lawson and colleagues studied associative learning, we investigated both the learning of a simple (deterministic) association and the ability to discover the predicting feature in the cueing stimulus. This aspect and the finding that ASD participants proved impaired compared to NT will have to be further investigated. This should be studied from a computational perspective, in order to possibly identify common mechanisms that would also explain recent findings by Lawson et al. (2017), as well as findings about perceptual learning in probabilistic environments (Robic et al. 2014).

Limitations

NT and ASD groups were matched for intellectual quotients, yet there was a high variability in the IQ scores of the ASD group (e.g. verbal comprehension index ranging from 83 to 149 across ASD participants). One limitation of the current study is the high level of difficulty of the *Memory-based*

tasks compared to the *Rule-based* ones, which yielded chance level performance on average in each group. This may have impaired our sensitivity to reveal group differences in memorization performance, expected to be in favor of ASD participants. The *Memory-based* tasks might have been too short for some participants to be able to learn the stimulus-outcome association.

Conclusion

We showed that people with ASD were less inclined to search for global underlying regularities, despite intact abilities to categorize. A reduced automatic and implicit learning of these regularities might impact daily life, and particularly, the understanding of social interactions (e.g., recognizing facial expressions requires being able to interpolate between facial expressions previously encountered). Studying the learning-styles in ASD can have concrete applications on learning strategies to use with children with ASD, and could explain, for instance, their difficulties to catch grammatical regularities and extract rules in general. Further studies investigating the spontaneous use of LUT and INT strategies in children with ASD may shed light on how these specificities unfold during the development.

Compliance with Ethical Standards

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Ethical approval: All procedures performed in this study were in accordance with the standards of the French ethical guidelines and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Approval was obtained from the local ethics committee (French South East IV Committee for the Protection of Persons). Participants gave their written consent beforehand.

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Tables

Table 1: Demographical and neuropsychological characteristics of the participants

	NT group	ASD group	p
Number	20	20	<i>ns</i>
Male / Female	15 / 5	16 / 4	<i>ns</i>
Age (years)	30.8 (\pm 6.9)	33.6 (\pm 10.0)	<i>ns</i>
Educational level (years)	4.6 (\pm 2.6)	3.4 (\pm 2.8)	<i>ns</i>
WAIS IV			
<i>Verbal comprehension</i>	124 (\pm 13)	123 (\pm 18)	<i>ns</i>
<i>Perceptual reasoning</i>	111 (\pm 14)	113 (\pm 17)	<i>ns</i>
<i>Working memory</i>	112 (\pm 11)	107 (\pm 20)	<i>ns</i>
<i>Processing speed</i>	111 (\pm 16)	105 (\pm 25)	<i>ns</i>
AQ score	12 (\pm 6)	35 (\pm 8)	$< 10^{-6}$

Values correspond to the group mean (\pm standard deviation). The p-values obtained from the t-test comparing the two groups are shown in the right column (*ns*: no significant difference). Educational level: number of years of study after Baccalaureate. AQ: Autism-spectrum quotient (maximum score of 50). Note that the standard deviation for the WAIS score was higher in the ASD than in the NT group.

Table 2: Group results of the behavioral tasks

Task			NT (n=20)	ASD (n=20)	<i>p</i>	
Without instructions	Rule-based	accuracy	81.9% (± 18.1)	62.8% (± 16.6)	**	
		% participants > chance	75%	25%	*	
	Memory-based	accuracy	59.0% (± 11.8)	56.6% (± 14.0)	<i>ns</i>	
		% participants > chance	40%	30%	<i>ns</i>	
	Mixed LUT-INT	accuracy (Total)	(INT)	71.3% (± 11.2)	62.3% (± 13.4)	*
			(LUT)	81.5% (± 16.4)	64.3% (± 19.9)	***
			(LUT)	61.1% (± 15.8)	60.4% (± 15.8)	<i>ns</i>
		% participants > chance (Total)	(INT)	100%	60%	**
			(LUT)	90%	40%	***
			(LUT)	55%	50%	<i>ns</i>
With instructions	Rule-based	accuracy	98.4% (± 1.9)	95.2% (± 6.3)	*	
		% participants > chance	100%	100%	<i>ns</i>	
	Memory-based	accuracy	66.6% (± 9.8)	61.9% (± 14.5)	<i>ns</i>	
		% participants > chance	60%	55%	<i>ns</i>	
Difference	Rule-based	accuracy	16.5% (± 18.4) ***	32.3% (± 15.5) ***	**	
	Memory-based	accuracy	7.6% (± 12.3) *	5.2% (± 16.1) *	<i>ns</i>	

Mean accuracy (\pm standard deviation) and percentage of participants scoring above chance level in each task in the NT and ASD groups. The “Difference” section provides the difference in accuracy between the tasks with instructions and the ones without. Reported *p*-values correspond to tests pertaining to accuracies or proportions of participants (* $p < .05$, ** $p < .01$, *** $p < .001$). The last column refers to between group comparisons.

Figures

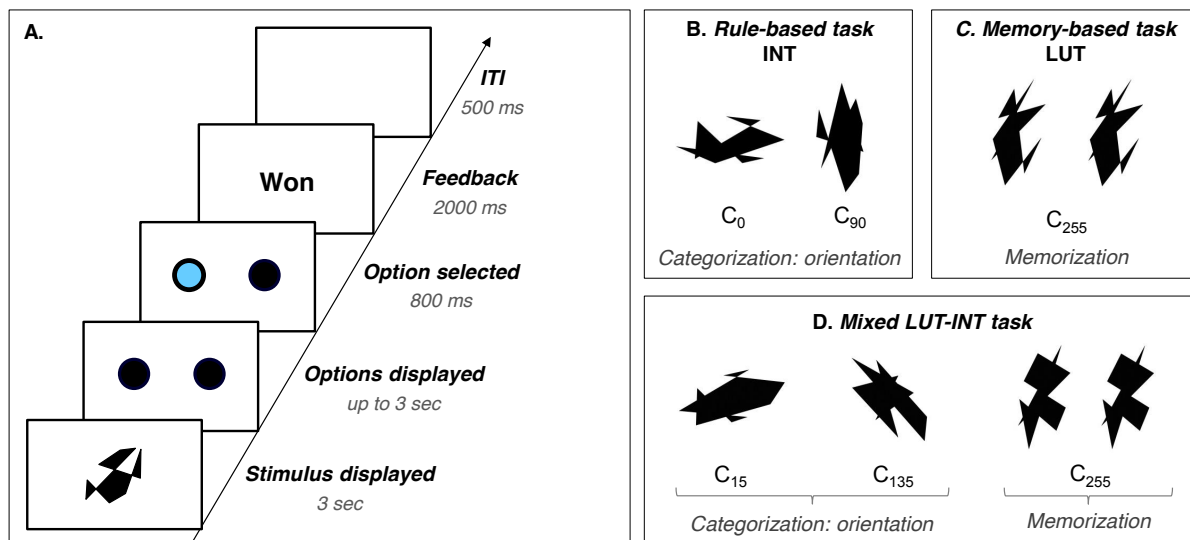


Figure 1: Typical trial (left) common to most of tasks (right)

- A. Example of trial presentation. This structure was the same in every task, except for the *Recognition test*. *ITI*: intertrial interval.
- B. The *Rule-based task* tested the spontaneous use of the INT strategy. Stimuli were oriented along 0° (category C_0) or 90° (category C_{90}) and each stimulus only appeared once. Stimuli had to be categorized according to their orientation.
- C. The *Memory-based task* tested the spontaneous use of the LUT strategy. Stimuli were all oriented along 255° (category C_{255}) and were repeated eight times each. The stimulus / winning response association had to be memorized.
- D. In the *Mixed LUT-INT task*, C_{15} and C_{135} stimuli had to be classified according to their orientation and were never repeated, whereas C_{255} stimuli had to be memorized and appeared 16 times each.

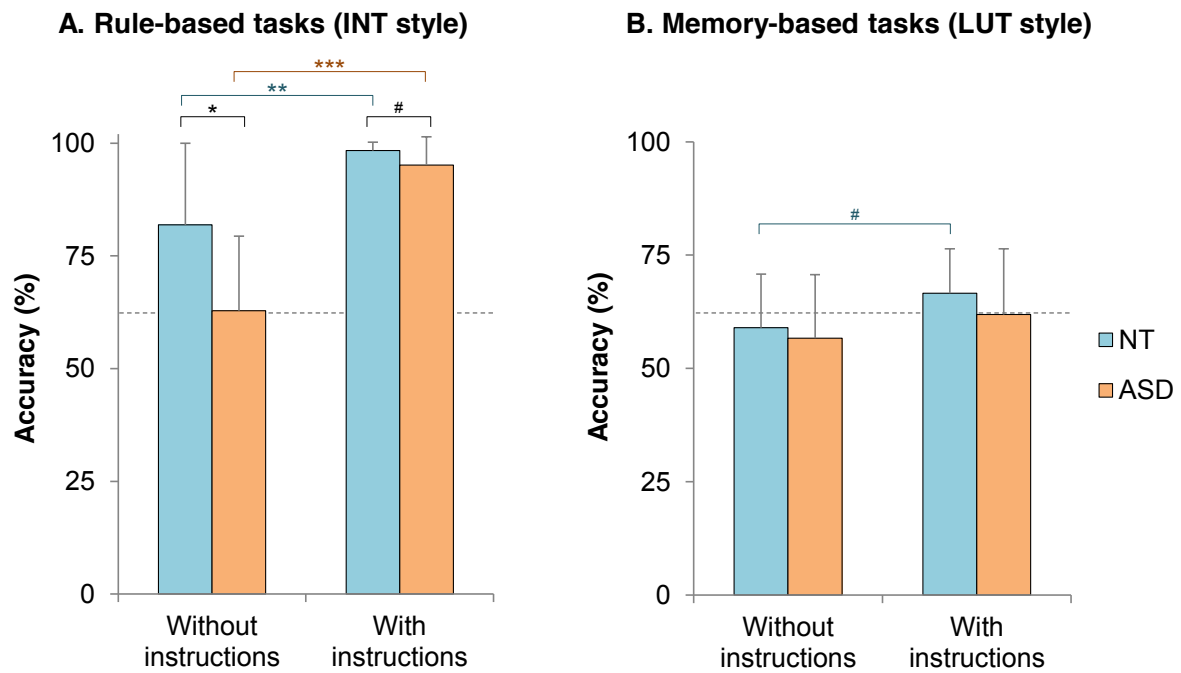


Figure 2: Accuracy in the Rule-based and Memory-based tasks

- A. Group mean accuracy observed in the *Rule-based task* without (left) and with instructions (right, control task).
- B. Group mean accuracy observed in the *Memory-based task* without (left) and with instructions (right, control task).

NT group: blue, ASD group: orange. Error bars correspond to standard deviations. The dash line indicates the chance level. $^{\#} p < .05$, $* p < .01$, $** p < .001$, $*** p < .0001$.

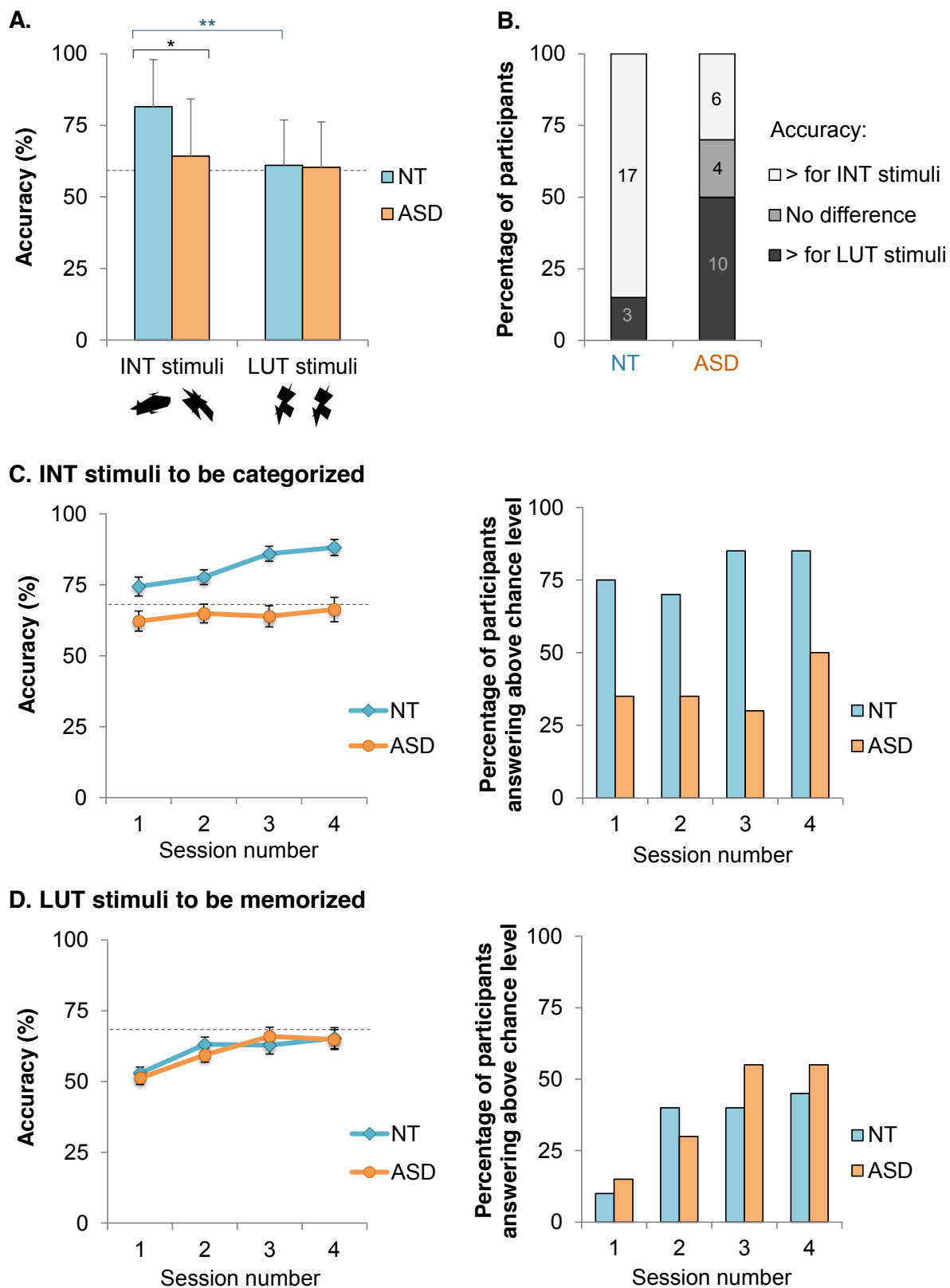


Figure 3: Accuracy in the Mixed LUT-INT task

A. Mean accuracy in the *Mixed LUT-INT task* for INT stimuli to be categorized (left) and LUT stimuli to be memorized (right).

- B. Percentages of participants with a higher accuracy for INT stimuli than LUT stimuli (clear grey), with a higher accuracy for LUT stimuli than INT stimuli (black), or with no difference in accuracy between INT and LUT stimuli (grey). Numbers correspond to the number of participants for each category.
- C. Results for INT stimuli across sessions: mean accuracy (left) and percentage of participants answering above chance level (right).
- D. Results for LUT stimuli across sessions: mean accuracy (left) and percentage of participants answering above chance level (right).

Error bars correspond to the standard deviation in A and to the standard error of the mean in C and D. The dash line corresponds to the chance level. * $p < .01$, ** $p < .001$.

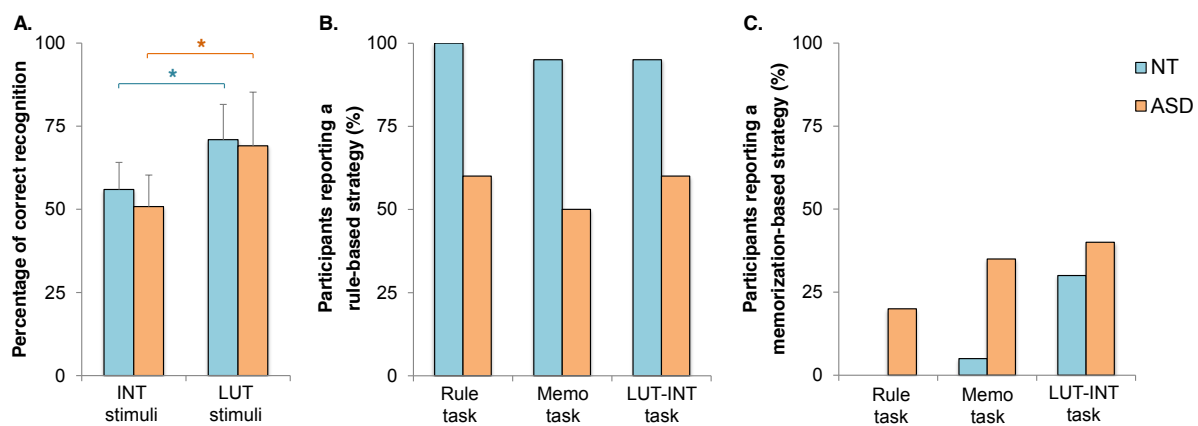


Figure 4: Recognition test and questionnaire results

A. Percentage of correct answer in the *Recognition test*, for INT stimuli (C_{15} and C_{135}) and LUT stimuli (C_{255}).

B-C. Percentage of participants who reported having used a rule-based strategy (B) or a memory-based strategy (C) to perform the *Rule-based task*, *Memory-based task*, and *Mixed LUT-INT task* (these tasks were performed without instructions). Participants could report both strategies for a unique task.

Error bars correspond to standard deviations. * $p < .01$