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Research Report

Communicative misalignment in Autism Spectrum Disorder

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ABSTRACT

Communication deficits are a defining feature of Autism Spectrum Disorder (ASD), manifest during social interactions. Previous studies investigating communicative deficits have largely focused on the perceptual biases, social motivation, cognitive flexibility, or mentalizing abilities of isolated individuals. By embedding autistic individuals in live nonverbal interactions, we characterized a novel cause for their communication deficits. Adults with ASD matched neurotypical individuals in their ability and propensity to generate and modify intelligible behaviors for a communicative partner. However, they struggled to align the meaning of those behaviors with their partner when meaning required referencing their recent communicative history. This communicative misalignment explains why autistic individuals are vulnerable in everyday interactions, which entail fleeting ambiguities, but succeed in social cognition tests involving stereotyped contextual cues. These findings illustrate the cognitive and clinical importance of considering social interaction as a communicative alignment challenge, and how ineffective human communication is without this key interactional ingredient.

1. Introduction

Autism Spectrum Disorder (ASD) is diagnosed on the basis of communicative deficits observed in everyday social interactions (American Psychiatric Association, 2013; Frith, 2003; Klin, McPartland, & Volkmar, 2013. The deficits are most evident in situations where the speaker's intention and a sentence's literal meaning strongly diverge, such as in the case of irony and sarcasm (Tesink et al., 2009; Zalla et al., 2014), and have been argued to be a product of a primary

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impairment in representing mental states (Baron-Cohen, Leslie, & Frith, 1985; Happé, 1993). However, empirical studies of this impairment have produced mixed results, including compelling observations of intact social perception and reasoning in individuals with ASD (Bowler, 1992; Cusack, Williams, & Neri, 2015; Pantelis & Kennedy, 2017; Sally & Hill, 2006). Other accounts suggest that the communication deficits arise from core difficulties with social motivation, social attention, or cognitive flexibility (Chambon et al., 2017; Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012; Geurts, Corbett, & Solomon, 2009). Yet other accounts emphasize biases in processing biological and multimodal linguistic cues used during face-to-face interactions (Constantino et al., 2017; Cook, Saygin, Swain, & Blakemore, 2009; Hobson, Ouston, & Lee, 1988; Hutchins & Brien, 2016; Nackaerts et al., 2012; Silverman, Bennetto, Campana, & Tanenhaus, 2010). These considerations highlight severe limitations in our understanding of communication in ASD, and consequently a lack of principled interventions for improving communication between autistic and neurotypical individuals.

Here we examined the possibility that individuals with ASD have difficulties in using the conceptual space defined by an ongoing interaction to resolve the pervasive ambiguity of human communicative signals (Goodman & Frank, 2016; Levinson, 1983; Stolk, Verhagen, & Toni, 2016). Human communication is often framed in terms of signal transmission, presupposing that communicators already share the same set of encoding-decoding rules, e.g., a common language (Akmajian, Farmer, Bickmore, Demers, & Harnish, 2017; Eco, 1976; Jakobson, 1971). Yet even commonly used words do not contain fixed meanings that are reliably shared across communicators (Grice, 1975; Rumelhart, 1979; Sperber & Wilson, 1996). Their meaning is flexibly coordinated through an online interpersonal alignment process by which people in dialogue seek and provide evidence that they understand one another (Brennan, Galati, & Kuhlen, 2010; Fusaroli & Tylén, 2016; Garrod & Anderson, 1987; Misyak, Melkonyan, Zeitoun, & Chater, 2014; Stolk et al., 2016). This dynamic alignment process provides a conceptual frame of reference necessary for interpreting intrinsically ambiguous communicative signals (Stolk et al., 2016). The present study quantitatively tested whether individuals with ASD have difficulties in dynamically aligning conceptualizations of their behaviors with a communicative partner.

This test was implemented in a novel communicative setting in which cognitively able adults with ASD interacted with another individual via a digital game board (Fig. 1A). This two-player computer game captures the open-ended and interpersonal nature of everyday communication by challenging players to generate, negotiate, and align the meaning of their non-verbal communicative behaviors (de Ruiter et al., 2010). The design of the computer game remediates several factors hypothesized to account for communicative impairments in ASD. For instance, the game prevents recourse to pre-existing shared communicative representations, such as those offered by some linguistic and gestural emblems (Groen, Zwiers, van der Gaag, & Buitelaar, 2008), and avoids verbal and face-to-face contact between players. This nullifies the effects of individual differences in processing biological and multimodal linguistic cues (Constantino et al., 2017; Cook et al., 2009; Hobson et al., 1988; Hutchins & Brien, 2016; Nackaerts et al., 2012; Silverman et al., 2010). Furthermore, the game manipulates the ambiguity of the communicative signals by introducing problems that are more easily solved in light of previous interactions. This feature mimics daily conversation, which consists of ambiguous words and behaviors that can only be discerned by individuals who know their context of use in an ongoing interaction. Under these controlled yet genuinely interactive experimental circumstances, it becomes feasible to quantitatively test whether communicative deficits in individuals with ASD arise specifically from difficulties establishing dynamic conceptual alignment of ambiguous signals with another person.

2. Materials and methods

2.1. Participants

Fifty-two adult participants were recruited to take part in this study (M ± SD 23.9 ± 6.5 yrs of age, 20 females, 22 individuals with ASD). ASD participants were recruited from a database of research volunteers maintained by the authors. Typical participants were recruited from local participant pools populated by students of the University of London and members of the general public, and were selected to match the ASD sample on age, gender, and IQ (see below). Participants were assigned pairwise to either the ASD group (7 pairs, each containing two individuals with ASD), the Typical group (11 pairs, each containing two individuals with no clinical diagnosis), or the Mixed group (8 pairs, each including one individual with ASD and one individual with no clinical diagnosis). The Mixed group served as a control for behavioral changes related to the clinical status of the communicative partners in the full ASD and Typical groups. All study procedures received ethical approval by the local institution's ethics committee and all participants provided informed consent in line with the declaration of Helsinki. Analysis took place after completion of data collection.

Individuals with and without ASD did not differ in terms of age [24.7 ± 6.5 *vs* 23.2 ± 6.6, t (50) = .79, p = .44, d = .23, 95% CI = (−.33 .78), BF = 2.76 in favor of the null hypothesis of no difference] or gender [6/22 *vs* 14/30 females, $X^2(1,52)$ = 2.02, p = .16, d = .19, 95% CI = (-.06 .45), BF = 1.16 in favor of the null hypothesis]. They also did not differ in terms of IQ [102.1 ± 19.4 *vs* 109.4 ± 14.1, t (50) = −1.59, p = .12, d = −.46, 95% CI = (−1.01 .10), BF = 1.28 in favor of the null hypothesis], measured by the Wechsler Abbreviated Scale of Intelligence [WASI-II (Wechsler, 2011)] in neurotypical individuals, and the Wechsler Adult Intelligence Scale [WAIS-IV (Wechsler, 2008)] in those with ASD. Autistic traits were assessed in all individuals using the Autism-Spectrum Quotient [AQ (Baron-Cohen, Hoekstra, Knickmeyer, & Wheelwright, 2006)], and were more prevalent in individuals with ASD than in neurotypical participants [32.6 ± 8.4 *vs* 16.0 ± 8.0, t (50) = 7.23, p < .001, d = 2.07, 95% CI = (1.39 2.75)]. All individuals with ASD were diagnosed by an independent clinician, and completed the Autism Diagnostic Observation Schedule [ADOS-2 (Lord et al., 2012)]. Six of the ASD participants met the ADOS criteria for Autism, while nine met the criteria for Autism

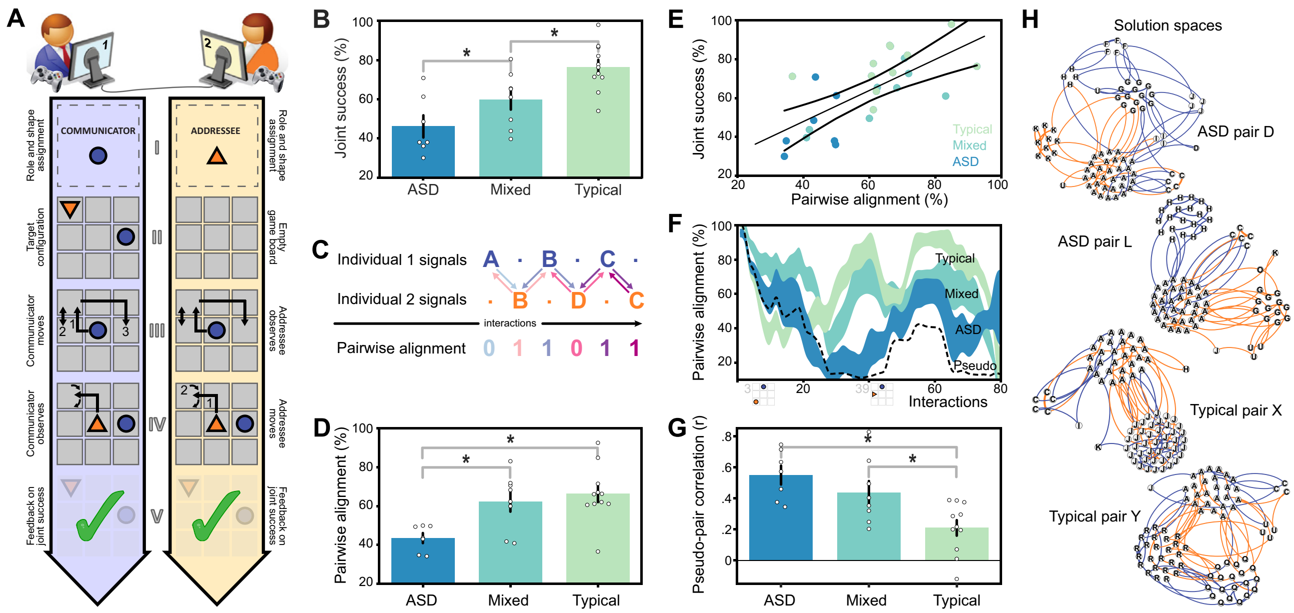

Fig. 1 — Communication impairment and misalignment in ASD. (A) The joint goal of Communicator and Addressee is to reproduce a target configuration of their two given shapes on a digital game board, shown only to the Communicator (event II). Given that the Addressee cannot see the target configuration, a successful interaction requires the Communicator and Addressee to construct and comprehend how the behavior of the Communicator's shape indicates the target location and orientation of the Addressee's shape (a 'communicative signal', event III). (B) Pairs containing one or more individuals diagnosed with ASD (ASD and Mixed pairs) jointly solved fewer communicative problems than pairs containing two individuals with no clinical diagnosis (Typical pairs). (C and D) Pairwise alignment measured the percentage of interaction-by-interaction overlap in signals produced by pair members, and revealed less frequent dynamic alignment of communicative signal use in ASD pairs than in the other pair types. Pairs were considered aligned at a given interaction if the type of communicative signal used in that interaction was identical to the signal in the interactions directly preceding or following it, when the other member of the pair was the Communicator. Letter indices correspond to a descriptive list of observed signals (Supplemental Table S2). (E) Pairwise alignment predicted communicative success across pairs. Lines show linear fit and mean 95% confidence intervals. (F and G) Pairwise alignment was also calculated for pseudo-pairs, constituted of members from different pairs. Given that pseudo-pair members lack any interpersonal coordination, their distribution of trial-by-trial alignment (dashed black line) provided a quantitative index of problem ambiguity, where low ambiguity indicated high pseudo-pair alignment because those configurations evoked consistent solutions across different pairs, cf. interactions 3 and 39. The bar graph indicates that ASD and Mixed pairs' alignment tended to follow the distribution of pairwise alignment found in the pseudo-pairs, whereas Typical pairs achieved alignment even when the problem space afforded multiple solutions. Lines' spread indicates ±1 SEM. A version of the line graph with trials ordered from lowest to highest ambiguity can be seen in Supplemental Figure S1. (H) Network visualizations of four pairs' trajectories through their idiosyncratic solution spaces. The nodes represent the signals constructed by the Communicator of each interaction and are clustered to show signals that were used repeatedly. The colored edges connect each individual's consecutively produced signals as Communicators (blue for individual 1, orange for individual 2). ASD pairs showed more individual exploration than Typical pairs of their solution space, as indicated by relatively large clusters of individually-visited solutions (clusters of nodes that were connected only by edges of a single color) and small clusters of jointly-visited solutions.

Spectrum. Seven individuals with ASD did not meet ADOS criteria despite their clinical diagnosis, but were diagnosed by an independent clinician and reported a similar degree of autistic traits on the AQ as the individuals who did meet the ADOS criteria (31.5 ± 10.2, 32.1 ± 9.7, and 33.9 ± 5.7 for the Autism, Autism Spectrum, and the None group, respectively). Independent samples *t*-tests did not indicate differences in AQ scores between these three groups (all $p > .62$, all $BF > 1.88$ in favor of the null hypothesis). Supplemental Table S1 represents an overview of AQ scores and ADOS classifications for all individuals diagnosed with ASD.

2.2. *Task*

We used the same two-player communication game employed in a previous experiment (Stolk, Verhagen, et al., 2013). The game involves pairs of participants interacting on a digital game board with a 3 × 3 grid layout, which was visually presented on each participant's computer screen (Fig. 1A). Each pair communicated in real-time over the course of 80 interactions, alternating between the roles of Communicator and Addressee across successive interactions. During each interaction, their goal was to reproduce a target configuration of two geometric shapes on the game board. Each member of the pair controlled the movement of one of these shapes. The target configuration was shown to the Communicator only and thus a successful interaction required the Communicator to convey to the Addressee the target location and orientation of the Addressee's shape, while also ensuring that the final location and orientation of their own shape was as specified by the target configuration. In this game, the only means available to the Communicator for communicating with the Addressee is by moving the Communicator's own shape around the grid using horizontal and vertical translations, and 90° clockwise rotations controlled by button presses on a handheld game controller (four face buttons and one shoulder button, respectively). The only means available to the Addressee for completing the configuration is by inferring the target location and orientation of his or her own shape on the basis of the movements of the Communicator, and positioning it accordingly using a second handheld game controller.

At interaction onset, each player is assigned their role (Communicator or Addressee) and shape (event I in Fig. 1A), followed by presentation of the target configuration to the Communicator (event II). Both Communicator and Addressee know that the Communicator has unlimited time available for planning the movements of the Communicator's shape, but only 10 sec to execute them (event III). As soon as the Communicator presses the start/stop button, the target configuration disappears from the Communicator's screen and the Communicator's shape appears in the center of the grid on both participants' screens, signaling readiness to move. All movements are then visible on both the Communicator's and Addressee's screens. After 10 sec, or earlier if the Communicator presses the start/stop button for a second time, the Communicator's shape cannot move further and the Addressee's shape appears in the center of the grid, indicating control by the Addressee over the Addressee's own shape. Similarly, the Addressee has no time constraints on planning the movements of their shape, but only 10 sec to position it in a location and orientation deemed correct on the basis of the movements of the Communicator (event IV). Finally, after 10 sec, or earlier if the Addressee presses the start/stop button again, the same feedback is presented to both players in the form of a green check mark or red cross, indicating whether or not the participants had successfully reproduced the target configuration (event V). The 80 target configurations were presented in the same predetermined order to all 26 participant pairs.

There are no a priori correct communication strategies in this game nor can the Addressee solve the task by simply reproducing the movements of the Communicator's shape. Rather, the Addressee needs to disambiguate communicative and instrumental components of the Communicator's movements, and identify the relationship between the Communicator's movements and the message they intend to convey. Several pieces of evidence indicate that the players jointly and dynamically establish an agreement, also known as a ‘conceptual pact’ (Brennan & Clark, 1996), concerning the meaning of their behaviors. For instance, the same communicative behavior can be used by different pairs to convey different meanings. The same behavior can even have different meanings in different interactions of the same pair when the communicative agreement is jointly revised, and across various pairs [for examples see movies in (Stolk, Noordzij, Verhagen, et al., 2014; Stolk, Verhagen, et al., 2013)]. To drive participants to continuously (re)negotiate the meaning of their communicative behaviors rather than to exploit already-established communicative conventions, we increased task difficulty across successive interactions. This was achieved by introducing deliberate mismatches between the geometrical characteristics of the pairs' shapes, and by introducing target orientations incompatible with the Communicator's shape. For instance, if a Communicator was able to successfully communicate the target orientation of the Addressee's shape by rotating their own shape, this strategy would be negated when the Communicator's shape changed to a circle and the Addressee's to a triangle. The Communicator would then have to find a new way to indicate the target orientation of the Addressee's shape, because rotations of the circle shape would not be visible. A further level of difficulty could be introduced by maintaining the same circle-triangle shape combination, but having the Addressee's triangle point outside the grid. If the Communicator had previously used a signal that involved repeatedly stepping in and out of the Addressee's target location in the direction of the target orientation (as seen in Fig. 1A), an interaction where the Addressee's triangle pointed outside of the grid would be impossible to solve using that signal. Therefore, the Communicator would have to devise a new behavior to solve this new problem type.

Prior to task performance, participants completed an individual training session in order to familiarize themselves with the handheld game controller, ensuring that each could manipulate their shape quickly and accurately. Given that atypical movements kinematics have been reported in ASD (Cook, Blakemore, & Press, 2013), we extended the allotted movement time for Communicator and Addressee from 5 to 10 sec in this study, which was found to be sufficient for participants with ASD to execute their planned movements. Participants also jointly completed 20 practice interactions to familiarize themselves with the communicative setting and the sequence of events occurring during an interaction. To minimize any effect stemming from potential individual differences in working memory capacity, we allowed Communicators to refer to a hard copy of the target configuration throughout the interaction. The order of trials was consistent across participant pairs. The experiment was programmed using Presentation (Neurobehavioral Systems, Albany, CA, USA) software on a Windows XP personal computer, and lasted approximately 40 min.

2.3. Analysis

Participants’ behaviors, communicative success, and alignment of communicative signal use were analyzed offline using custom MATLAB (Mathworks, Natick, MA, USA), Python (Python Software Foundation, DE, USA) and Java code (Oracle, CA, USA), the SPSS (IBM, Armonk, NY, USA) and JASP (JASP Team, jasp-stats.org) statistical software packages, and the Gephi (Gephi Consortium, gephi.org) network visualization software package. Communicative success was calculated as the percentage of spatial configurations successfully reproduced by each pair over the course of their interactions.

Pairwise alignment was calculated as the percentage of interaction-by-interaction overlap in signals used by pair members in the Communicator role for communicating the target location and orientation of the Addressee's shape. The pair members were considered aligned at a given interaction if the type of communicative signal used in that interaction was conceptually identical (irrespective of movement speed and trial-specific trajectories) to the signal in the interactions preceding or following it, when the other member of the pair was the Communicator (Fig. 1C). The bidirectional sensitivity of the measure captures conceptual alignment even in instances where new communicative signals are introduced, and avoids ascribing transient task difficulty-related to signal changes to misalignment. Furthermore, unlike the inherently joint measure of communicative success, alignment can be calculated between members of different pairs. As outlined below, these pseudo-pair combinations provided a quantitative index of a problem's ambiguity, for testing whether autistic and neurotypical pairs differed in their ability to achieve alignment as a function of problem ambiguity.

An experimenter familiar with the communicative task (author H.W.) performed an interaction-by-interaction classification of the communicative signals using a custom-made replayer tool, while remaining blind to the clinical status of each participant. The signals varied from common pauses for distinguishing a target location from other visited locations, to idiosyncratic drawing, rotation, or 'wiggling' behaviors (stepping out from and back into a location, e.g., the double-arrowed number 2 action in Fig. 1A) for conveying the target location and orientation of the Addressee's shape. A list of signals and their descriptions was constructed on the basis of previously identified behaviors from using this game (Blokpoel et al., 2012; Stolk, Noordzij, Verhagen, et al., 2014; Volman, Noordzij, & Toni, 2012). In cases where no pre-existing description was considered sufficiently accurate for an observed behavior, a new description was created for that communicative behavior. A total of 18 unique signals were observed, see Supplemental Table S2. It should be emphasized that in this game it cannot be determined on the basis of a single interaction alone whether, for instance, a wiggling behavior is intended to emphatically indicate the direction in which the Addressee's shape needs to point, or whether the number of wiggles corresponds to the number of clockwise rotations required for the Addressee's shape to reach the target orientation. Moreover, the communicative signals not only need to be disambiguated from other signals but also from instrumental elements of a Communicator's behavior which are necessary to achieve the Communicator's own target location and orientation. We controlled for subjectivity in the interpretation of the inherently ambiguous communicative behaviors in two ways. First, we asked a second rater to perform an interaction-by-interaction classification of the same dataset using the descriptions of behaviors observed by the first rater. We based our analyses on the classifications of the second rater given that the second rater was unaware of the details of this study. Second, we report statistical inferences based on the measure of pairwise alignment. Pairwise alignment is less prone to rater-specific interpretation and labeling of communicative signals, given that it considers the parity of signals across each pair's interactions as classified by the same rater. To validate the final signal classifications and resulting alignment values, we compared these measures between the two raters. The raters' individual signal classifications overlapped by 82% (intraclass correlation = .97, Kappa = .78). The subsequent alignment values for each pair overlapped by 84% (intraclass correlation = .81, Kappa = .68).

The main analysis tested for between-group differences in joint communicative success and pairwise alignment of communicative signals, over and above individual differences in general cognitive function. The fixed effect of Group (ASD, Mixed, Typical) was assessed with two univariate ANCOVAs using pairs' communicative success and pairwise alignment as dependent variables, respectively (Fisher, 1925). The covariate in these analyses considered the inter-pair variance in general cognitive function accounted for by the IQ in each pair (Reber, Walkenfeld, & Hernstadt, 1991). We selected between the mean and minimum IQ in a pair to describe this relationship, with the latter providing a better fit to communicative success [$F\ (1,24) = 16.17$, $p = .001$, $R^2adj = .38$] than the former [$F\ (1,24) = 4.72$, $p = .04$, $R^2adj = .16$]. We report values adjusted for IQ where appropriate to resolve the variability in the pairwise measures. The sources of the between pair differences in communicative success and pairwise alignment were further qualified with post-hoc comparisons using Fisher's least significant difference (LSD). The predictive strength of pairwise alignment on communicative success was determined using linear regression analysis. We report effect size estimates (partial η^2 and Cohen's d) and 95% confidence intervals for each ANOVA and post-hoc comparison to facilitate cumulative science (Lakens, 2013). We report Bayes Factors (BF) for statistical tests evaluating evidence in favor of the null hypothesis. Bayes Factors express the relative likelihood of the data under the models at hand.

A follow-up analysis tested for between-group differences in the dynamic relationship between pairwise alignment and problem ambiguity. The fixed effect of Group (ASD, Mixed, Typical) was assessed with a univariate ANOVA of Pearson's correlations between the two dependent variables and further qualified using post-hoc comparisons as in the main analysis. Problem ambiguity was measured as 1 minus the average pairwise alignment in pseudo-pairs, which is calculated in the same way as in the original pairs (Fig. 1C), and indicates consistent signal use across at least two consecutive trials by two members who are originally from different pairs, e.g., between individual 1 of pair A and individual 2 of pair B. This pairing produces a total of 650 possible pseudo-pair combinations between members of all 26 pairs. Averaging the alignment across all pseudo-pairs for each trial results in the trial-by-trial chance-distribution seen in Fig. 1F. In this distribution, a trial has low ambiguity because pseudo-pairs were frequently aligned in their signal use for that problem, indicating consistent signal use across individuals regardless of communicative history. For instance, target configurations that did not require Addressees to rotate their shapes to reach a target orientation (e.g., circle-circle combinations presented in early interactions, as seen in Fig. 1F, trial 3) tended to evoke consistent solutions across pairs. On these trials, Communicators needed to distinguish Addressees' target locations from other locations visited on the game board in their movement, which several Communicators achieved by using a brief movement pause on the Addressees' target location (signal A). Conversely, high ambiguity trials were solved more easily with signals that had been negotiated and coordinated through pairs' unique communicative histories. For instance, problems involving mismatches between the shapes' geometrical characteristics and that require Addressees to rotate (e.g., circle-triangle combinations, in later interactions such as trial 39, shown in Fig. 1F) were often solved with different signals by different pairs (cf. signals E through S in Supplemental Table S2). Therefore, pseudo-pairs had lower alignment during these trials.

A network analysis provided further insight into how Typical and ASD pairs navigated their solution space over the course of 80 interactions. To visualize the distribution of individually and jointly visited solutions in each pair, networks consisting of two sets of edges (indicated by color, one for each member) followed the two pair members' signals at each trial. The blue edges represented player 1, and connected the nodes for odd trials (1, 3, 5, 7, and so on). The orange edges represented player 2, and connected the nodes for even trials (2, 4, 6, 8, and so on). All 80 trials, represented as nodes and connected by their Communicators' corresponding edges, were then clustered by signal type to visualize each player's solution space in respect to the other. A Fruchterman Reingold algorithm (Fruchterman & Reingold, 1991), implemented in Gephi, minimized the energy of the system by moving the nodes and changing the forces between them. This provided a two-dimensional layout of the pairwise trajectories through the pairs' solution spaces. Hamming distance, a metric used to measure differences in networks (Hamming, 1950), was calculated between pair members' solution spaces to show how much the members differed in their solution sets.

2.4. *Additional analyses*

Five additional analyses were used to assess the specificity of communicative success and pairwise alignment, beginning with two control analyses. First, we tested whether ASD-related differences in these variables were driven by generic motor-related differences between individuals in each group, using a multivariate ANOVA with a between-participants factor of Group (ASD, Typical) and the dependent variables of planning time, movement time, number of moves and time spent on target and other locations of the game board. Second, we tested whether the reduced pairwise alignment in ASD could be a consequence of this sample population generating a reduced number of intelligible solutions to the novel communicative problems, owing, for example, to perseveration being common in ASD (Geurts et al., 2009; Hill, 2004). To test this possibility, we calculated the number of distinguishable signals that were used in the interactions by each participant in the Communicator role, and tested for between-group differences using an independent samples *t*-test. We additionally examined whether individuals with ASD differed in the type of communicative signals they generated, using a Chi-squared test to assess the between-group overlap in signals used as a fraction of the total number of signals observed across both groups. An additional Kullback-Leibler divergence test was used to measure the difference between the two groups' signal frequency distributions. Third, we assessed whether the reduced conceptual alignment in ASD could be a consequence of this sample population not being able or motivated to change their communicative signal following a misunderstanding during the last time they were the Communicator, by testing for between-group differences in signal changes (in interaction i) following an error (interaction i - 2) using an independent samples *t*-test. Fourth, we assessed whether between-group differences in communicative success and pairwise alignment could be attributed to differences in a motivation to communicate. To this end, we used a repeated-measures ANOVA to test for between-group differences (ASD, Typical) in the communicative emphasis participants in the Communicator role spontaneously placed on the Addressee's target location relative to other visited locations (Target, Non-target). These two analyses were adopted from other similar studies (Stolk, D'Imperio, di Pellegrino, & Toni, 2015; Stolk, Hunnius, Bekkering, & Toni, 2013; Stolk, Verhagen, et al., 2013). Fifth, we assessed whether communication impairment in ASD resulted selectively from an inability to align production and not interpretation of a behavior to a partner. For this exploratory analysis, we used a repeated-measures ANOVA to test for between-group differences (ASD, Typical) in communicative success in the role of Communicator and Addressee.

3. Results

3.1. *Communication impairment*

To quantify communicative abilities, we asked participant pairs to communicate over the course of 80 interactions, alternating between the roles of Communicator and Addressee. In any given interaction, the Communicator and Addressee must recreate a spatial configuration of two assigned shapes on the digital game board. The target configuration is only shown to the Communicator (event II in Fig. 1A), who must use his or her own assigned shape to relay to the Addressee his or her target location (event III, hereafter referred to as a ‘communicative signal’). The Communicator must then reach his or her own target position. The Addressee, who has not seen the target configuration, must then infer his or her target position based on the Communicator's communicative signal and move accordingly (event IV). After the Addressee has moved, the same feedback is presented to both players to indicate communicative success, i.e., whether or not they jointly reproduced the target configuration (event V). Fifty-two adult participants were recruited to take part in this study: 22 individuals with ASD and 30 neurotypical individuals, matched on gender, age, and IQ. Participants were assigned pairwise to either the ASD group (7 pairs), the Typical group (11 pairs), or the Mixed group (8 pairs, each including one individual with ASD and one individual with no clinical diagnosis). Confirming the study's predictions, the three groups differed in their overall communicative success [$F(2,22) = 11.40$, $p < .001$, partial $\eta^2 = .51$]. As seen in Fig. 1B, this effect was driven by pairs containing one or more individuals with ASD (ASD and Mixed pairs) successfully solving fewer communicative problems than Typical pairs [Typical versus ASD, $p < .001$, $d = 2.41$, 95% CI = (1.18 3.65); Typical versus Mixed, $p = .048$, $d = 1.06$, 95% CI = (.09 2.04); Mixed versus ASD, $p = .047$, $d = 1.27$, 95% CI = (.16 2.38)], providing quantitative evidence for communication impairment as a core diagnostic feature of ASD (American Psychiatric Association, 2013).

3.2. Communicative misalignment

The task is primarily designed to quantify and manipulate interpersonal alignment in communication. Similar to how idiosyncratic shared constructs emerge from everyday dialogue (Brennan & Clark, 1996), this task allows pairs to converge on unique meanings for the same behavior. For instance, some pairs solve the communicative problem illustrated in Fig. 1A by stepping in and out multiple times from the Addressee's target location, to indicate the direction in which the Addressee's shape needs to point. Other pairs use the exact same communicative signal to indicate the number of rotations the Addressee needs to apply to his/her shape to obtain the desired orientation (Supplemental Table S2 provides a list of identified signals). These examples also illustrate how the meaning of the ambiguous signals produced in this game cannot be determined from a single interaction. A pair has converged on a shared meaning for a signal only if both individuals manage to comprehend and reproduce that signal successfully. Therefore, pairs were considered aligned during a given interaction if its Communicator used a communicative signal that was conceptually identical to the signal used in the interactions directly preceding or following it, when the other member of the pair was the Communicator (Fig. 1C). This trial-by-trial alignment is analogous to two communicators using an ambiguous word or gesture that only they would know the exact meaning of. Their ability to produce and understand this behavior is proof of their pair-specific conceptual agreement.

To manipulate alignment over the course of the task, target configurations with multiple possible solutions were introduced in a consistent and deliberate order. This experimental manipulation makes it possible to calculate a trial-by-trial chance-distribution of pseudo-pairs' communicative alignment, containing for each trial the average pairwise alignment of communicative signals between members of different pairs (dashed black line in Fig. 1F). Given that pseudo-pair members lack any interpersonal coordination, their distribution of trial-by-trial alignment allows us to quantitatively differentiate between configurations which evoke consistent solutions across pairs and configurations solved with different signals by different pairs (cf. interactions 3 and 39 in Fig. 1F). We took these differences in the solution space to indicate problem ambiguity, where high ambiguity equated to a larger set of empirically observed signals used to solve that problem. We predicted problem ambiguity to strongly modulate alignment in pairs containing one or more individuals with ASD, consistent with their inability to establish conceptual alignment.

The main finding of this study quantitatively illustrates that reduced conceptual alignment explains communicative impairment in ASD. Comparison of signals used across contiguous interactions showed differing alignment across the three groups [F (2,22) = 9.07, $p = .001$, partial $\eta^2 = .45$]. As shown in Fig. 1D and Movies S1 and S2, full ASD pairs aligned their communicative signals across contiguous interactions less frequently than the other pair types [Typical versus ASD, $p < .001$, $d = 2.11$, 95% CI = (.94 3.29); Mixed versus ASD, $p = .003$, $d = 2.03$, 95% CI = (.78 3.28); Typical versus Mixed, $p = .99$, $d = .01$, 95% CI = (−.90 .92)]. This analysis leads to two independent observations about conceptual alignment. First, a correlation analysis showed a strong relationship between alignment and success across all pairs, confirming conceptual misalignment as a predictor of communicative impairment [F (1,24) = 32.79, $p < .001$, $R^2adj = .56$, $r = .76$, 95% CI = (.53 .89)], see Fig. 1E. Second, full- and mixed-ASD pairs largely followed the distribution of communicative alignment found in pseudo-pairs, during both unambiguous and ambiguous problems (Fig. 1F and G). This observation indicates that the interaction dynamics of full- and mixed-ASD pairs were comparable to those of pairs of individuals with no previous communication. In contrast, Typical pairs achieved higher alignment than pseudo-pairs even during ambiguous problems, indicating that individuals in Typical pairs capitalized on their communicative history. These between-group differences are supported by a statistical analysis testing for the effect of problem ambiguity on pairwise alignment [F (2,23) = 8.51, $p = .002$, partial $\eta^2 = .43$; Typical versus ASD, $p = .001$, $d = 2.02$, 95% CI = (.86 3.17); Typical versus Mixed, $p = .012$, $d = 1.34$, 95% CI = (.33 2.34); Mixed versus ASD, $p = .24$, $d = .68$, 95% CI = (−.36 1.73)].

Supplementary video related to this article can be found at https://doi.org/10.1016/j.cortex.2019.01.003.

The group-based observations are also supported by descriptive analyses of pairwise trajectories through their idiosyncratic solution spaces, where pair members' signals at every interaction are represented as nodes in a network (Fig. 1H). These networks allowed us to follow individual pair members' behaviors in relation to one another, and visualize patterns of exploration and alignment through the solution space. It can be seen that in Typical pairs, both individuals frequently used the same signal (e.g., signals J and C in pair X; signals R and Q in pair Y), while occasionally exploring other solutions (e.g., signals K, H, and I in pair X; signal J in pair Y). However, those options were not pursued further if the other pair member did not adopt those signals. The large size of shared clusters, and the point-like structure of the individually-visited solutions, confirm that Typical pairs develop strong conceptual agreements across the 80 interactions. In contrast, ASD pairs show more individually-visited solutions and small clusters of jointly-visited solutions, the exception being large clusters of signal A that was used predominantly during problems requiring no rotation by the Addressee (e.g., circle-circle problem configurations). As seen through the spread of behaviors by each member, these pairs were able to explore signals, but unlike Typical pairs, struggled to converge on shared signals. This is supported by an analysis comparing the dissimilarity between signal sets produced by members of ASD and neurotypical pairs [Hamming distance: .67 ± .04 *vs* .50 ± .04, M ± SEM, t (16) = 2.84,

$p = .012$, $d = 1.46$, 95% CI = (.40 2.52)]. Thus, members of ASD pairs produced signals that were largely independent from those of their partners, and failed to reach conceptual alignment.

3.3. *Preserved cognitive abilities and communicative propensities*

The experimental setting and additional empirical observations exclude several proposed causes for the communicative impairment observed in individuals with ASD. First, planning time, movement time, number of moves, time spent on target and other locations of the game board were consistently matched between neurotypical and individuals with ASD [Fig. 2A, F (5,46) = 2.00, $p = .10$, partial $\eta^2 = .18$]. This finding indicates that the communicative impairment is not a consequence of the sensorimotor demands of the task, nor of misapprehension of its communicative demands. Second, individuals with and without ASD exhibited a comparable heterogeneity of communicative behaviors throughout their interactions [Figs. 2A and 5.41 ± .35 *vs* 5.07 ± .24 distinguishable signals in each participant, M ± SEM, t (50) = .84, $p = .40$, $d = .29$, 95% CI = (−.27 .84), $BF = 2.66$ in favor of the null hypothesis; 13 out of 18 identical signals across both groups, X^2 (1,18) = 7.1, $p = .008$, $d = .44$, 95% CI = (.15 .74); Kullback-Leibler divergence of signal frequency distributions = .016], indicating that the communicative misalignment was not due to perseveration commonly associated with ASD. Moreover, individuals in both groups were similarly inclined to re-use signals that were previously understood by their partner (Fig. 2A, Kullback-Leibler divergence of success rate distributions = .029), showing that misalignment persisted despite an intact ability to remember and learn from successful interactions. Furthermore, individuals with ASD were also similarly inclined to change their signal following a communicative failure [Fig. 2B, t (50) = 1.28, $p = .21$, $d = .37$, 95% CI = (−.19 .92), $BF = 1.83$ in favor of the null hypothesis], excluding the possibility that reduced success or misalignment was due to a failure to detect or react to a misunderstanding with their partner. Third, similar to neurotypical individuals, individuals with ASD spontaneously spent more time on communicatively relevant locations of the game board [Fig. 2C, main effect of location F (1,50) = 188.88, $p < .001$, partial $\eta^2 = .79$; no main effect of group or interaction involving ASD and location, both $p > .15$], indicating that they were willing to invest resources in switching between communicative and instrumental portions of their actions to mark a communicatively relevant location for the benefit of their partner. Finally, communicative success was lowest when individuals with ASD were Addressees [interaction effect of group and role, F (1,50) = 11.31, $p = .001$, partial $\eta^2 = .18$; no main effect of role, $p = .61$; Typical versus ASD Communicator success, t

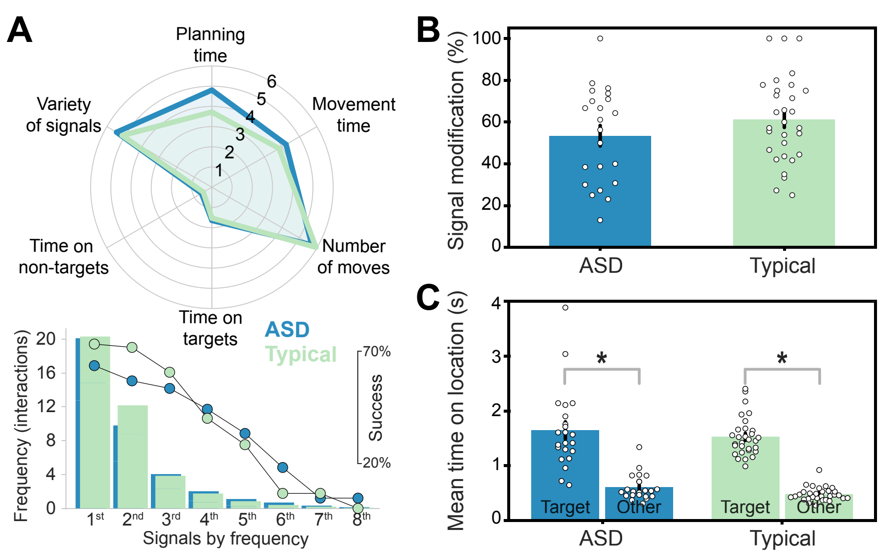

Fig. 2 – Preserved cognitive abilities and communicative propensities in ASD. (A) Planning time, movement time, the number of moves, time spent on target and other locations of the game board were consistently matched between neurotypical and autistic individuals. Individuals with and without ASD also exhibited a comparable heterogeneity of communicative signals throughout the task, and were similarly inclined to re-use signals that were previously understood by their partner as indicated by the comparable slopes of the frequency and success distributions. Times are measured in seconds. (B) Individuals with and without ASD showed a similar propensity for modifying their behavior as Communicators if not understood previously. (C) Similar to neurotypical individuals, individuals with ASD spontaneously spent more time on communicatively relevant locations of the game board as Communicators, discriminating them from other visited locations for the benefit of their communicative partner.

(50) = 1.80, $p = .08$, $d = .52$, 95% CI = (−.04 1.07); Typical versus ASD Addressee success, $t(50) = 3.26$, $p = .002$, $d = .94$, 95% CI = (.36 1.51)]. Taken together with their misalignment, this finding suggest that individuals with ASD struggled to both produce and comprehend behaviors in light of the context of interaction.

4. Discussion

The findings reported in this study demarcate a key cognitive challenge intrinsic to human interpersonal communication that individuals with ASD struggle to overcome, despite having otherwise indistinguishable performance from neurotypical adults across several task metrics. This study shows that communicative impairments in ASD are not simply a consequence of neglect of communicative demands during interaction nor of altered sensory processing, motor performance, interaction memory, social motivation or attention, or cognitive perseveration. As the communicative demands of the current task prohibit recourse to known biological and linguistic cues, ASD communicative impairment was also unaffected by altered processing of those stimuli (Constantino et al., 2017; Cook et al., 2009; Hobson et al., 1988; Hutchins & Brien, 2016; Nackaerts et al., 2012; Silverman et al., 2010). Furthermore, individuals with ASD showed comparable ability and motivation to neurotypical individuals in producing intelligible communicative behaviors. They even modulated the use of these behaviors based on their partners' responses, questioning suggestions of universally diminished social motivation or impaired cognitive flexibility in ASD (Chevallier et al., 2012; Geurts et al., 2009).

Yet, individuals with ASD struggled to align the conceptualizations of their communicative signals with those of their interaction partners when the problem space afforded multiple solutions. This impairment could be isolated because the novel communicative setting prevented access to pre-existing contextual cues that cognitively-able individuals with ASD can capitalize on to resolve ambiguity (Au-Yeung, Kaakinen, Liversedge, & Benson, 2015; Birmingham, Stanley, Nair, & Adolphs, 2015; Branigan, Tosi, & Gillespie-Smith, 2016; Brewer, Biotti, Bird, & Cook, 2017; Hahn, Snedeker, & Rabagliati, 2015; Nadig, Seth, & Sasson, 2015; Pijnacker, Hagoort, Buitelaar, Teunisse, & Geurts, 2009). Under these experimentally-generated conditions, built to recreate the fleeting ambiguities of everyday interaction, communication requires more than pruning a decision tree of possible signals or iteratively optimizing behavioral outcomes (Botvinick & Weinstein, 2014; Donoso, Collins, & Koechlin, 2014; Keysers & Perrett, 2004). Despite their ability to consistently produce, modify, and remember interpretable communicative behaviors, i.e., behaviors that were also part of the neurotypical solution space, autistic individuals were less likely to select signals in light of their partner's behaviors. This resulted in greater misalignment, especially when full- and mixed-ASD pairs were presented with ambiguous problems. In contrast, neurotypical individuals navigated through epochs of communicative ambiguity by considering and aligning to their partner's recent signals. The observed differences in task performance between neurotypical and full- and mixed-ASD pairs arose specifically from this reduced ability to produce and comprehend communicative behaviors informed by their recent communicative history. This observation explains why autistic individuals are vulnerable to the transient and interaction-specific ambiguities in everyday social situations, and provides novel boundaries to the general notion that ASD is linked to altered mentalizing abilities (Baron-Cohen et al., 1985; Happé, 1993; Schaafsma, Pfaff, Spunt, & Adolphs, 2015). Although adults with ASD can communicate on the basis of presumed knowledge about a generic partner, they fail to dynamically update that conceptual knowledge according to the ongoing interaction with a specific individual. Precise characterization of dynamic conceptual updating might provide a new window into understanding autistic communication, and how signals derive their meaning from the communicative context in which they are embedded.

Failures in using the conceptual space implied by the ongoing interaction are likely to have two important consequences. First, those failures might affect the recognition of the relevance of a communicative signal for jointly coordinating the shared conceptual space. Second, those failures might affect the resolution of the ambiguity intrinsic in those signals. It remains to be seen whether other social deficits observed in ASD (and controlled for in this study), such as abnormalities in eye contact, facial expressions, speech, and turn-taking (Madipakkam, Rothkirch, Dziobek, & Sterzer, 2017; Shriberg et al., 2001; Tager-Flusberg & Anderson, 1991), could in fact be downstream consequences of difficulties in predicting and monitoring mutual understanding (Stolk et al., 2016). It will also be of interest to know whether and how conceptual alignment deficits interact with cognitive traits and environmental factors to give rise to the considerable behavioral and developmental variability observed in ASD, opening the way for principled interventions to improve communication between autistic and neurotypical individuals (Edey et al., 2016; Fusaroli, Weed, Fein, & Naigles, 2018; Greenberg, Warrier, Allison, & Baron-Cohen, 2018; Perry, Levy-Gigi, Richter-Levin, & Shamay-Tsoory, 2015; Stolk, Hunnius, et al., 2013; Stolk, Noordzij, Volman, et al., 2014). This work illustrates that to answer these key questions, it is both feasible and pertinent to study autistic individuals engaged in social interactions with others. This is the natural context in which communication is learned, where it is used, and where individuals with ASD experience difficulties.

5. Conclusion

This study provides a novel and precise characterization of communicative deficits in ASD, one of its core diagnostic features (American Psychiatric Association, 2013). The results suggest that individuals with ASD and neurotypical individuals would be equally able and motivated to communicate if human communication could be reduced to an information transfer problem in a signal encoding–decoding framework (Shannon, 1948). Yet, the ASD communicative deficits observed here indicate that human communication is best characterized as a solution to a conceptual alignment challenge, organized to predict and monitor mutual understanding (Stolk et al., 2016). This study illustrates how the efficacy of the evolutionarily anomalous human communicative system is severely limited without this key interactional ingredient.

Author contributions

R.B., G.B., I.T., and A.S. conceived and designed the study. R.B. and G.B. conducted the study and collected the data. H.W., I.T., and A.S. conducted the data analyses. H.W., I.T., and A.S. drafted the manuscript, and R.B. and G.B. provided critical revisions. All authors approved the final version of the manuscript.

Data and code availability

The data and analysis code are available from the corresponding author upon request.

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Supplementary data

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