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Autism does not limit strategic thinking in the "beauty contest" game

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ABSTRACT

A popular hypothesis in developmental psychology is that individuals with autism spectrum disorder (ASD) have a specific impairment or developmental delay in their ability to reason about other people's mental processes, especially when this reasoning process is of a higher-order, recursive, or nested variety. One type of interpersonal interaction that involves this sort of complex reasoning about others' minds is an economic game, and because economic games have been extensively modeled in behavioral economics, they provide a unique testbed for a quantitative and precise analysis of cognitive functioning in ASD. This study specifically asked whether ASD is associated with strategic depth in the economic game known as The Beauty Contest, in which all players submit a number from 0 to 100, and the winner is the player who submits the number closest to 2/3 of the mean of all numbers submitted. Unexpectedly, the distribution of responses among adult participants with ASD reflected a level of strategic reasoning at least as deep as that of their neurotypical peers, with the same proportion of participants with ASD being characterized as "higher order" strategic players. Thus, whatever mentalistic reasoning abilities are necessary for typical performance in the context of this economic game appear to be largely intact, and therefore unlikely to be fundamental to persistent social dysfunction in ASD.

1. Introduction

Successful social interaction requires one to understand and predict the actions of others, often by making inferences about their hidden mental processes. This is the practical application of one's theory of mind (ToM) or "mentalizing" ability. ToM involves the representation of another person's mental states (e.g., beliefs, goals, intentions), to enrich one's internal model (or subjective *theory*) of how another person's mind works, and how this hidden inner world indirectly connects to observable actions and behaviors.

Social interactions can sometimes be competitive in nature—" games" in which the right decision inherently depends on the adopted strategies of the other "players." When certain assumptions have been made about the structure of a game (i.e., the number of players in the game, the nature of the possible "moves," and the payoffs each player will receive depending on various outcomes of the game), game theory prescribes the normatively rational strategy with which to play it. Although not all games have multiple players, many canonical economic games do (e.g., the prisoner's dilemma and the stag hunt), and the game theoretic analyses of these games can provide insight into the choices agents make in interpersonal situations.

To the extent an agent treats other players as having minds, and makes decisions on the basis of how the mental states of others relate to their actions, strategic thinking in these situations bears a resemblance to traditional psychological characterizations of ToM (cf. Abell, Happé, & Frith, 2000; Dennett, 1987; Leslie, 1994). Both faculties involve reasoning about the thought processes of other people, often in a recursive or nested manner (e.g., "I think that he thinks that I think…"; Hedden & Zhang, 2002).

In a strategic scenario, game theory prescribes the optimal action, based on the rules of the game and the set of possible outcomes. But in practice, an advantage can sometimes be gained if one brings additional assumptions to bear on the interaction—for example, assumptions about just *how* sophisticated one's adversaries are. In the analysis of these situations, the study of economics and ToM truly synthesize into a field known alternatively as "behavioral game theory," "game theory of mind," or "social decision making" (see Camerer, 2008; Gariépy, Chang, & Platt, 2013; Hedden & Zhang, 2002; Lee, 2008; Yoshida, Dolan, & Friston, 2008). Whereas orthodox game theory assumes the rationality of all players, behavioral game theory treats the level of rationality of the players as a variable to be estimated by each player in the game—and, ultimately, the researcher who is studying their behavior. Because estimating the inner workings of other

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people's minds indeed defines ToM, the connection between these two disciplines is clear, though often tacit (Baker, Saxe, & Tenenbaum, 2009; Pantelis et al., 2016). This study further explores the insights behavioral game theory can offer to the understanding of ToM, in both typical and atypical development.

1.1. Autism and theory of mind

Autism spectrum disorder (ASD) is, by its very clinical definition, characterized by a disruption of the faculties recruited for successful social interaction (American Psychiatric Association, 2000, 2013). A longstanding hypothesis in developmental psychology is that the root of this dysfunction is an impairment or developmental delay in ToM—especially the higher-order, complex variety (Baron-Cohen, 1989; Baron-Cohen, Leslie, & Frith, 1985). By adulthood, higher-functioning adults often improve to typical performance on canonical tests of ToM (e.g., the classic "Sally-Anne" false belief task), at least when presented with an explicit task in a laboratory setting (Schneider, Slaughter, Bayliss, & Dux, 2013; Senju, Southgate, White, & Frith, 2009). Other experimental paradigms are sensitive to apparently persistent—albeit sometimes latent—deficits in this domain (Castelli, Frith, Happé, & Frith, 2002; Moran et al., 2011).

To preface a point of later discussion, not all agree that any of these just-mentioned experimental tasks are true demonstrations of ToM, strictly construed. It has been argued that typical performance in the vast majority of tasks presumed to require the attribution of mental states in another (such as beliefs and desires) can also be achieved by application of learned (or innate) behaviorist-style input-output rules that map the observed situation of another to the predicted action (Heyes, 2014; Penn & Povinelli, 2007; Perner, 2010; Perner & Ruffman, 2005). We will revisit this topic in the *Discussion* with specific respect to the task we present in this study.

That said, reasoning about other people's thought processes to predict their actions lies at the heart of both ToM and strategic thinking, and this has naturally led interdisciplinary researchers to wonder how people with ASD approach economic games (Ewing, Caulfield, Read, & Rhodes, 2015; Kashner, 2014; Kishida, King-Casas, & Montague, 2010; Sally & Hill, 2006; Tayama et al., 2012; Yoshida et al., 2010). However, experimental data on this topic are surprisingly scarce. This study continues down this path of inquiry with the analysis of an economic game called The Beauty Contest.

1.2. The beauty contest

Each player submits a whole number from 0 to 100. The winner is the player who submits the number closest to 2/3 of the mean of all numbers submitted (Nagel, 1995; the fraction used varies from study to study, but 2/3 is popular because using this fraction allows one to successfully decouple a strategy of answering at the middle of the scale [in this case, 50] from one in which one takes the fraction used times the max of the scale [in this case, ~67]). The Nash equilibrium (i.e., game theoretic solution) for this game is the result of a repeated undercutting process that ultimately prescribes that the rational actor should select 0—as should all of the other players.[1] Everyone wins.

Empirically, however, choosing the normative solution of 0 only allows for a moral victory. Sampling from a variety of populations—from U.S. high school students to economics PhDs (Camerer, Ho, & Chong, 2004)—the mean response is typically between 25 and 35, making the winning response ~20. To actually win the game in practice, one must estimate just *how* close opponents' strategies will be to the "rational" choice of 0—or get very lucky.

When approaching this game, players may adopt strategies in which they explicitly reason about the *beliefs that other players have about other players' beliefs*, and the strategies the other players will employ based on those beliefs. Multiple behavioral game theoretic approaches have explicitly modeled this game in this fashion, additionally allowing that although some players will reason in this mentalistic manner, others will forego this approach in favor of a simpler strategy.

1.3. Mentalistic and non-mentalistic strategies in the beauty contest

The various strategies one may bring to the Beauty Contest require one to think mentalistically about the other players in the game to varying extents. Some answer randomly ("0th order" players) or assume that others will do so ("1st order" players). Others employ "higher-order" strategies that involve *beliefs* about other people's *beliefs*, and their *policies* or *strategies* in connecting these beliefs to actions. To the extent that players produce responses consistent with these higher-order strategies, we argue that they are more likely to be engaging something closely akin to ToM (see also Goodie, Doshi, & Young, 2012).

This account of a typical distribution of strategies employed by players in the Beauty Contest—with its explicit appeals to a ToM framework, in which some players explicitly take into account presumptions about others' beliefs and their policies for acting on those beliefs—can be straightforwardly and intuitively converted into a quantitative model (Camerer et al., 2004; Nagel, 1995). The intuitive elegance of these models and their ability to fit actual human behavior in the Beauty Contest (both qualitatively and quantitatively), often with as few as one free parameter, has been one of the clearest successes of the behavioral game theoretic approach as an explanatory and predictive psychological theory, and provides evidence for their validity.

1.4. Quantitative modeling approach

Nagel (1995) and Camerer et al. (2004) model the typical distribution of responses in the beauty contest as reflecting variability in the number of "cognitive steps" people are willing or able to take. The number of steps taken by the individual defines the "order" of the strategy. 0th order players answer randomly (or by some arbitrary criterion). 1st order players assume everyone else will submit random numbers (on average, 50), and therefore submit an answer of $(2/3) * 50 \approx 33$. 2nd order players assume they are playing against a mixture of 0th and 1st order players, and higher order players are defined recursively from there.

The Camerer et al. (2004) model assumes that a kth order player has an accurate belief about the proportions of players taking on lower-order strategies, but does not believe any of the other players will adopt kth and higher-order strategies. The Nagel (1995) model assumes that kth order players believe all other players will adopt a $k-1$ order strategy (see also Coricelli & Nagel, 2009).

Under the Camerer et al. (2004) model, strategies are distributed according to the Poisson distribution, defined by a single λ parameter (equivalent to both the mean and variance of the orders of strategy adopted by the players). Their model is fully specified by this one parameter, and can fit the present study's data well qualitatively, namely predicting peaks in the response distribution at the appropriate places. However, for better quantitative fits (as measured by the likelihood of beauty contest responses under the model) we instead employ a variation on Nagel (1995).

As in Nagel (1995), our model assumes that kth order players believe all other players will adopt a $k-1$ order strategy. The

[1] Technically, if players are only allowed to submit integer values (as in this paper), all players submitting 1 is also a Nash equilibrium for this game (Bosch-Domènech, Montalvo, Nagel, & Satorra, 2002).

model we adopt posits that player responses are sampled from a mixture of Gaussians (centered respectively at 50, 33, 22, 15, etc., ± an additional noise parameter) each representing a discrete order of strategy. Orders of strategy are assumed to be Poisson-distributed among the players (an assumption shared by the Camerer et al., 2004 model).

Thus, the relative probability of a given number response—$p(R)$—given a model specified with parameters λ and σ is defined as:

$$p(R) \propto \sum_{k=0}^{\infty} gauss(R) poiss(k) \quad (1)$$

where k is the order of strategy, $poiss(k)$ is the probability of a kth order strategy given a Poisson distribution with an assigned λ parameter, and $gauss(R)$ is the probability of a given number response R given a Gaussian distribution with a mean of $50 * (2/3)^k$ and a standard deviation of σ.

This treatment models both the central tendencies of a group (mean, modes) and the individual differences within it. Each participant follows some order of strategy (from 0th on up). Under most plausible parameterizations of the model, there are many 0th, 1st and 2nd order players, fewer 3rd order players, and very few 4th order players and above. λ represents the average number of cognitive steps taken by the players in the sample. The selection of a lower number in the beauty contest is associated with greater depth of strategic thinking (i.e., higher λ), but the winning player will truncate this cognitive process long before arriving at the infinite limit (i.e., the Nash equilibrium of zero).

There is an important qualitative distinction between 0th/1st order thinkers, who apparently do not fully appreciate the strategic nature of the game, and thinkers who go beyond 1st order depth, and then must make a second decision about how low they should go. 0th order and 1st order players do not necessarily appeal to the belief states of the other players; 0th order players answer randomly, and 1st order players make a prediction about what others will *do* (i.e., answer randomly) but not necessarily what they *believe*. However, the strategies of 2nd order and higher players appeal directly to others' beliefs, with reasoning along these lines: "I think that the other players *believe* that the rest of us will adopt a certain strategy (a strategy which may, in turn, account for the *beliefs* we have about the strategies of others, and so on). The rational strategy corresponding to their *belief* will be to take 2/3 of what they expect from us, so I will in turn go one step beyond, and select a response that is 2/3 of what I predict they will choose."

Thus, we first argue—on the basis of past successes in modeling this approach mentalistically—that a greater proportion of players selecting lower numbers (especially those closely corresponding to 2nd or higher order strategies) is indicative of a greater propensity to recruit ToM in this game. To the extent that populations differ in this proportion, we argue that they recruit ToM to differing extents when they participate in the Beauty Contest. After our experimental participants produce their responses in this one-shot game, we additionally ask a small number of follow-up questions to provide some additional insight into the nature of their decision making. Our primary analysis, however, is to use quantitative modeling to discern whether individuals with and without ASD (or with higher or lower levels of subclinical autistic personality traits) produce different distributions of responses in the Beauty Contest.

2. Experiment 1

Experiment 1 aimed to: (1) replicate the qualitative pattern of results reported in past studies of the beauty contest, while validating the modeling approach with respect to a large sample, (2) derive the winning (correct) response for participants in Experiment 2, and (3) examine how depth of strategic reasoning in the beauty contest relates to subclinical autistic personality traits, as measured by the Autism-Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001).

2.1. Method

250 undergraduate psychology students at Indiana University played the beauty contest remotely via an online questionnaire, in exchange for course credit. The sample was predominantly female (164 female, 83 male, 3 unknown). Though a prospective power analysis was not particularly straightforward given the planned modeling approach, a sample of this size is typically large enough to detect even small-to-moderate effect sizes (e.g., Cohen's $d > 0.35$, Spearman's rho > 0.18) with 80% power when using traditional parametric tests. After 250 players completed the study, the contest was terminated and winners were informed.

Participants were instructed that the winners of the game would split a $100 Amazon gift card. The winner(s) would be the player(s) who selected the number closest to 2/3 of the mean number selected by the entire group of 250 participants. Because the basic arithmetic skills of our participants were not of particular interest in this study, participants were instructed that they should feel free to use pen and paper, or a calculator, to assist them at any time.

First, the participant was presented with an illustrative example of the beauty contest, as played by three hypothetical players ("Alice, Bob, and Charles") who each chose a random number (3 random numbers were generated for each participant, so as not to systematically bias responses via possible anchoring effects). The participant was then asked: "To the nearest integer (whole number), what would the mean (average) of these choices be? And what would be 2/3 of this mean?" These questions were each answered using a sliding scale from 0 to 100. The participant was then asked whether Alice, Bob, or Charles had won the hypothetical game, and answered via radio button.

After this illustrative example, the participant was invited to play the game against the other 249 participants, selecting an integer value using a sliding scale from 0 to 100. At the next screen (participants could not go back to change responses once they were entered, and thus, no subsequent question could retroactively influence the participant's initial recorded response in the beauty contest), the participant was asked to briefly explain how he or she decided on this number, and did so by entering text into a box.

Next, participants were asked if their answer would have been different if they were told that the other participants all had "a psychological condition which makes it very difficult for them to take on the perspective of others." If they answered yes, they could provide their hypothetically different answer (again using the sliding scale). Participants were also asked whether their answer would have been different if the other participants were all math majors, or if the other participants were all English majors. These three follow-up questions were included to possibly provide insight into individual participants' thought processes in this one-shot game. However, participants' intuitions with respect to the latter two questions varied greatly, making their idiosyncratic responses difficult to interpret. We therefore only report analyses related to the first follow-up question.

Finally, each participant was invited to complete the AQ questionnaire, and 221 of the participants completed the questionnaire in its entirety. The remaining participants left one or more items blank, and were omitted from analyses related to AQ.

2.2. Results

The mean response of the 250 players in the beauty contest was 36.4; thus, the winning number was 24. Four participants selected this number and split the prize.

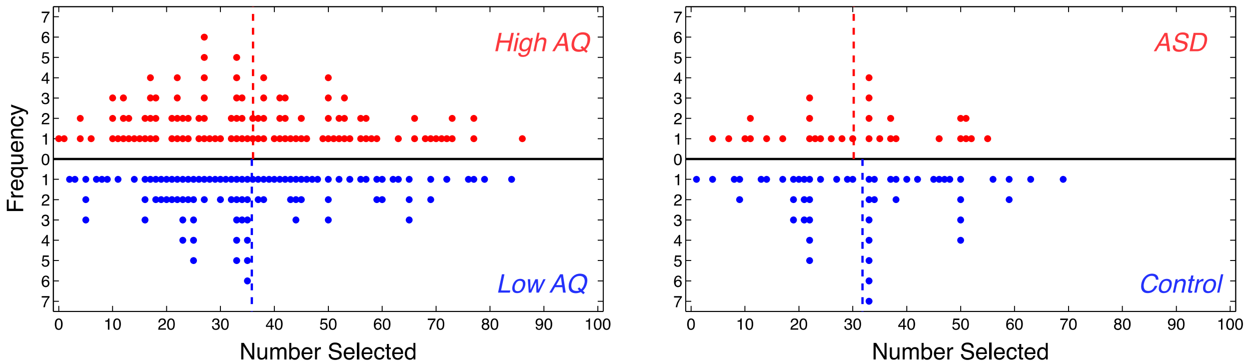

Fig. 1. Histograms of player responses in the beauty contest. *Left:* Experiment 1. The distribution of numbers selected by participants with a high (top, in red) or low (bottom, in blue) Autism-Spectrum Quotient (AQ). *Right*: Experiment 2. The distribution of numbers selected by participants with ASD (top, in red) and controls (bottom, in blue). Group mean responses are represented with dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Modeling revealed a best-fitting λ parameter of 1.20 (and a best-fitting σ parameter of 18). This model fit implies that 66.3% of players were either 0th order (i.e., random) or 1st order (i.e., assuming other players responded randomly and answering ~33) players. Participants' responses to a follow-up question ("Would the answer you provided have been different if we told you that the other participants all had a psychological condition which makes it very difficult for them to take on the perspective of others?") were helpful in assessing whether this was an accurate characterization of the sample.

Whereas for higher-order thinkers (i.e., 2nd or higher), the answer to this question should be a fairly obvious "yes", 0th and 1st order thinkers likely answer "no" to what is probably a puzzling question. Empirically, 74.4% of players answered "no," a similar proportion to the 66.3% of participants posited by the model to be 0th or 1st order players.

Consistent with this account, the distribution of initial responses among those who later answered "yes" reflected a much deeper level of strategic sophistication (M = 29.6; λ = 2.15) compared to those who answered "no" (M = 38.8; λ = 0.94; Fig. S1 in Supplementary Material contains histograms of the two groups). A Bayesian analysis revealed very strong evidence of a group difference in depth of strategic reasoning, with respect to λ (Bayes Factor = 69.37).[2] And, those who answered "yes" typically revised their response to be much higher given the hypothetical scenario (M = 41.0, $t[63] = 4.15$, $p < 0.001$).

It is therefore evident that certain participants understood the strategic nature of this game better than others. What factors contributed to these individual differences? The data reveal that AQ was irrelevant to performance on this task (Fig. 1, left). In this sample, AQ was almost totally uncorrelated with the number selected ($r[219] = -0.009$, $p = 0.891$; recall that selection of a lower number is associated with a greater depth of strategic reasoning). A median split of the sample (AQ greater or less than 15, and throwing out the 12 participants precisely at this median) revealed that high- and low-AQ groups produced remarkably similar distributions of responses in the beauty contest (high-AQ: n = 108, M = 36.0, λ = 1.25; low-AQ: n = 101, M = 35.8, λ = 1.24). A Bayesian analysis indicated moderate evidence in favor of the null hypothesis of no group difference in λ (BF = 0.25).

[2] Bayesian analyses in this paper directly compare the null hypothesis that both groups' strategies were distributed according to the same λ parameter, with the alternative hypothesis of a group difference in λ. For the alternative hypothesis, the prior distribution for λ was assumed to be uniform over the interval [0, 3]. For all group comparisons, the additional σ parameter necessary to specify the model was always assumed to be the same for both groups being compared, and was fit to the two groups' pooled responses. BF > 1 indicates evidence against the null hypothesis, and 0 < BF < 1 indicates evidence for the null hypothesis.

3. Experiment 2

3.1. Method

Another beauty contest was staged between November 2014 and March 2016. The winning response—24—was known ahead of time, and was defined with respect to the sample that participated in Exp. 1.

To more directly address the question of whether ASD is systematically related to depth of strategic reasoning, 30 high-functioning adults with ASD were invited to participate in the beauty contest. Two additional participants with ASD were invited to participate, but declined. All but one of these individuals was also assessed with the Wechsler Abbreviated Scale of Intelligence (WASI), to obtain an estimated full-scale intelligence quotient (FSIQ), verbal comprehension IQ (VIQ) and perceptual reasoning IQ (PIQ). All participants with ASD who were assessed with the WASI were confirmed to be of average to above average intelligence (all FSIQ > 80, *M* = 116.4).

These adults with ASD were recruited from the Bloomington, Indiana area. Participants responded to flyers posted around the community, responded to advertisements posted on Craigslist, or were referred by word of mouth; several had already participated in previous studies conducted in the laboratory. All 30 ASD participants reported previously receiving clinical diagnoses of autism, Asperger's Syndrome, or Pervasive Developmental Disability—Not Otherwise Specified (PDD-NOS). A DSM-IV-TR diagnosis was confirmed using the Autism Diagnostic Observation Schedule-2 (ADOS-2) Module 4 (Lord et al., 2000) and a review of background information and neuropsychological assessments (including IQ testing, Autism Spectrum Quotient [AQ], Beck Depression Inventory, State-Trait Anxiety Inventory, and self-reported clinical history), together with clinical judgment. All ADOS administrations and scoring were performed by research reliable administrators. The suggested ADOS cutoff score is 7; however, in light of empirical evidence that the ADOS Module 4 has very similar specificities at thresholds of 6 and 7 when administered to high-functioning adults (Bastiaansen et al., 2011), we included participants with an ADOS score of 6 if all other available information supported an ASD diagnosis (n = 3).

Control participants without a diagnosis of ASD were recruited from the Bloomington community over the same time period. Each of 67 participants participated in the beauty contest before or after participation in other experiments being performed in the

Table 1
Characteristics of ASD and control samples.

	ASD	Controls	p-value
N	30	51	
Male/Female	24/6	41/10	0.966[b]
Age	26.1 (8.5)	26.9 (6.4)	0.640[a]
FSIQ	116.4 (11.7)	114.3 (12.6)	0.474[a]
VIQ	117.9 (13.4)	114.2 (12.2)	0.219[a]
PIQ	110.3 (13.0)	111.0 (14.1)	0.839[a]
AQ	30.0 (8.7)	15.6 (4.5)	<0.001[a]
Number Selection	30.2 (14.8)	31.8 (15.9)	0.65[c]
Best Fitting λ	1.54	1.43	0.77[c]
Proportion > 1st Order	0.433	0.431	0.986[b]

For Age, FSIQ, VIQ, PIQ, AQ, and Number Selection, the mean value is shown with standard deviation in parentheses.
P-values with respect to group differences are derived from:
[a] Two-tailed unpaired-sample *t*-tests.
[b] Chi-square tests.
[c] Approximations of non-parametric permutation tests.

laboratory. To create better balance across groups with respect to male/female ratio (which is male-skewed in the ASD sample), we eliminated 16 female participants from the control sample. This subset of female participants was selected such that its elimination would create the best possible resultant balance between the ASD and control samples with respect to both mean VIQ and PIQ (IQ had also been higher in the ASD sample than in the original NT sample). This left a sample of 51 controls, 49 of whom were also assessed with the WASI.

This sampling procedure yielded two groups (ASD and control) with very similar demographic characteristics (with respect to gender breakdown, age, FSIQ, VIQ, and PIQ; see Table 1). Paring the original samples down into two clean samples of well-matched participants was necessary in order to be confident that any observed group difference in performance could be attributed to autistic symptomatology.

Participants were presented (in the laboratory, via a computerized questionnaire) with a slightly-reworded version of Exp. 1's beauty contest: Rather than being told they would be *one of* 250 undergraduate psychology students to take part in the game, they were instructed they would be playing *against* 250 undergraduate psychology students. Additionally, because the AQ was administered to each participant as part of the laboratory's standard battery of questionnaires, participants in Exp. 2 did not complete the AQ after completing the beauty contest.

Participants were compensated for their time at a rate of $15/h. Winners of the beauty contest (those who correctly selected the number 24) would additionally split a $100 Amazon gift card. Two participants (one from the ASD sample and one control) won the contest, and were awarded the prize.

3.2. Results

The distributions of responses for the control and ASD groups were qualitatively similar (Fig. 1, right). Among controls, the mean response was 31.8 and the best-fitting λ was 1.43. Among participants with ASD, the mean response was 30.2 and the best-fitting λ was 1.54. These data provided moderate evidence in favor of the null hypothesis that the two groups were sampled from distributions with the same λ parameter (BF = 0.31), consistent with a hypothesis that adults with ASD did not have a deficit in strategic reasoning compared to their neurotypical peers—at least with respect to this beauty contest game. It is also worth noting that the ASD group's mean response indicated performance that was significantly above $\lambda = 1$ (p = 0.011 by Monte Carlo simulation)—i.e., the mean ASD participant was a strategic thinker using higher-order strategies.

Because there is an important qualitative distinction to be made between those who apparently do not appreciate the strategic nature of this game (0th and 1st order players) and those who do (and then incur another decisional process in truncating the number of subsequent steps of iterated reasoning), we also examine these data with respect to the proportion of each sample that were (most likely) 2nd order players or above (i.e., players who selected a number < 28, as per the criterion put forth by Coricelli & Nagel, 2009). Nearly identical proportions of both groups (~43%; see Table 1) could be considered higher-order players—moderate evidence in favor of a null hypothesis of no group difference (BF = 0.16).[3]

Across all participants, we replicated a result from Exp. 1, in which we examined participants' responses conditional upon whether they later answered "yes" to the follow-up question (i.e., what if the other players "had a psychological condition"?). The initial responses of those who later answered "yes" again revealed deeper strategic sophistication (n = 22; M = 24.8; $\lambda = 2.27$) compared to those who answered "no" (n = 59; M = 33.6; $\lambda = 1.22$; BF = 8.6). This was true across both groups (Controls: $M_{yes} = 25.6$, $M_{no} = 34.9$; ASD: $M_{yes} = 22.0$, $M_{no} = 31.8$), though we do not have sufficient statistical power to make a finer-grained comparison of subtle group differences in this response pattern.

Were there any discernable, systematic differences in how the two groups approached the task? One variable that could have potentially influenced participants' responses had to do with the simple example of the beauty contest game presented to each participant, in which fictional players (Alice, Bob, and Charles) each selected a number as an illustrative hypothetical. Because whichever responses these fictional characters made could have potentially caused anchoring effects (Tversky & Kahneman, 1974), these hypothetical responses were randomized for each participant's session. Neither controls nor participants with ASD showed significant anchoring with respect to the correlation between the mean of these randomized numbers and the number ultimately selected by the participant (Controls: $r[49] = -0.091$, $p = 0.524$; ASD: $r[28] = 0.281$, $p = 0.132$). IQ also was not significantly correlated with number selection, neither for the control (r[47] = −0.173, p = 0.235) nor ASD groups (r[27] = 0.076, p = 0.694).[4] In summary, we found no measurable difference in the manner with which these two groups approached the beauty contest.

4. Discussion

A savvy approach to the beauty contest involves both an intuitive grasp of the essential strategic nature of the game, and the ability to accurately estimate the extent to which other players will exploit this strategic intuition. 0th or 1st order players do not take into account that whatever reasoning process they employ may also be shared by the other players—an insight that would demand a deeper "dive" into the strategic reasoning process to arrive at a reasonable selection. Reasoning a step further or more—grasping this mutual rationality to at least a minimal extent—is a deeper

[3] This Bayes factor was calculated with code developed for and described in Mazurek et al. (2015), under the assumption of a uniform prior over the possible group differences in proportion of higher-order players.

[4] In the original, unmatched sample of 67 controls (63 of which were assessed with the WASI), there was indeed a significant relationship between IQ and number selection, with higher IQ individuals selecting significantly lower numbers (r[61] = −0.306, p = 0.015). Such a result was consistent with previous findings relating cognitive abilities with performance on the beauty contest (Brañas-Garza, García-Muñoz, & González, 2012; Gill & Prowse, in press). However, this correlation was no longer present in the more constrained range of IQs present in the matched sample (i.e., after throwing out a handful of participants toward the lower end of the IQ spectrum).

thinking process that bears a strong familial resemblance to "theory of mind" or "mentalizing."

Experiment 2 demonstrated that, on average, adults with ASD employ at least the same depth of strategic thinking as controls. This result corroborated Experiment 1, which demonstrated that AQ—a measure of subclinical autistic traits—also has no relationship with performance in the beauty contest.

We should here be careful in drawing strong conclusions that performance in this game is a true reflection of ToM ability, if one strictly defines this ability as requiring the attribution of mental states in others. Several authors (Heyes, 2014; Penn & Povinelli, 2007; Perner, 2010; Perner & Ruffman, 2005) have warned that although competence in certain putative tests of ToM (indeed, even canonical false belief tasks) may suggest that the subject is successfully attributing mental states to another agent, this performance is also consistent with that subject applying simpler "behavior rules" to the prediction of others' behaviors. These behavior rules are if-then statements that map observable situations to predicted actions, without appealing to intervening mental states. If one were to apply such a behavior rule in the interpretation and prediction of others' actions, then this reasoning process does not necessarily require any sort of mental state attribution. We argue that the 0th or 1st order players in our game (i.e., those who either answer randomly or select a response of ~33) indeed need not appeal to mental states, *per se*, to derive their answers.

From one theoretical perspective (Yoshida et al., 2008; Zhang, Hedden, & Chia, 2012), a more fully-developed capacity for ToM requires the cognitive ability to perform *recursion* on the rules presumed to govern the behavior of other agents. This recursive ability is closely related to the capacity for *metarepresentation* that Leslie (1987, 1994a, 1994b) has argued critically subserves ToM (though recursion and metarepresentation are not strictly equivalent concepts; see Stone & Gerrans, 2006). In the case of the beauty contest, one type of player could have an expectation that the other players will behave in a certain reflexive, non-mentalistic manner. But the recursion—the *belief* or *expectation* that other players *believe* or *expect* that other players will behave in a certain manner, even if the behavior embedded at the basis of this recursive process is non-mentalistic—may be an important distinction. This is why we argue that higher-order strategies (those corresponding to responses of ~22, for example) connect strongly to important aspects of ToM.

However, Perner (2010) proposes a different criterion for determining whether competence on a task is a true demonstration of ToM: Povinelli's Challenge (Povinelli & Vonk, 2004). The proposed criterion is whether the mentalistic reasoning process posited can be collapsed into more concise rules that do not appeal to mental states anywhere in the applied inference procedure. In terms of the beauty contest specifically, consider a player who responds "22", a strategy we consider to be as good a demonstration of ToM as any. One could argue that this response could also be explained as this player expecting that other players will behave according to a behavior rule dictating that when other people are approached with this number game, they will provide an average response of "33." But what kind of behavior rule would lead the observed player to answer "33" in this game?

One could learn such a rule from experience, but in this one-shot game, from where would the player have gleaned such experience? It is more likely that the player appeals to the intuition that others expect random play from their competitors, and this would be the "behavior rule" applied in this alternate account. However, it is indeed difficult to phrase such an intuitive rule without appealing to the mentalistic concept of "belief" or some close synonym. As one attempt: "The player answers '22' because he believes that when other people play a game of this nature, they will answer as if others are invoking a rule that others are likely to answer randomly, thus answering '33'." Yet, construction of this behavior rule requires a bit of semantic finesse; one must be willing to accept that the observed player can "answer as if" something is true without this constituting a belief state.

Further, if the responses of 2nd order (and higher) players were the result of the application of a behavior rule without appeal to their competitors' mental states, then why did these players also tend to systematically change their responses when given modified expectations about the presumed cognitive capacities of these competitors?[5] Such flexibility does not lend itself to behaviorist intuition, unless the behavior rule is flexible enough to account for differing mental capacities in the imagined target—but somehow without attributing a mind to that hypothetical person.

We leave it at the discretion of the reader which definitions and tests for ToM are most compelling, and to what extent the various strategies participants bring to the beauty contest capture these alternative theoretical intuitions. At minimum, however, deep strategies in the beauty contest involve recursive reasoning about other people, and these deeper strategies are equally prevalent in adults with and without ASD.

Further unpacking the cognitive abilities recruited in this game, there may be multiple factors that contribute to a player's decision to truncate his or her strategic reasoning process (for example, settling on "22" instead of continuing to iterate further through higher-order strategies to arrive at a lower number selection). On one hand, it is possible that the participant is fundamentally unable to iterate further down this strategic path due to cognitive limitations. On the other, the participant may be quite able to continue stepping through this iterative process, but chooses not to because of the (quite accurate) presumption that few of the other players will. Although this study was careful to match the control and ASD groups in terms of basic cognitive functioning, it remains possible that the underlying faculties recruited by either group in the beauty contest were subtly different, even though the two groups produced substantially similar distributions of responses. This is a hypothesis that would need to be tested in future experiments, and perhaps in conjunction with neuroimaging techniques (Coricelli & Nagel, 2009; Saxe, 2006).

Notwithstanding this speculation, the data presented in this study were unexpected given a hypothesis that individuals with ASD are impaired in complex, mentalistic reasoning about others' thoughts and actions. This experimental result therefore contributes to an increasingly nuanced profile of cognitive differences characteristic of ASD. Although this study found no discernable difference in the manner with which adults responded in the beauty contest, Yoshida et al. (2010) indeed found a deficit in autistic adults' ability to represent the level of strategic sophistication in others with respect to the Stag Hunt game. In other studies, Sally and Hill (2006) found only subtle differences in performance in the Prisoners' Dilemma, Dictator, and Ultimatum games among autistic children, and Tayama et al. (2012) found that young adults with ASD may actually outperform controls in a modified Prisoner's Dilemma, and choose to cooperate at a similar rate. Even in the sterile, stripped-down experimental contexts afforded by economic games, a coherent picture has not yet emerged regarding how ASD relates to associated cognitive processes—let alone how these faculties may evolve across the development of the condition. Continued exploration of how individuals with ASD perform in economic games will serve to more narrowly define the set of social impairments that persist into adulthood for these individuals.

[5] Recall that in a follow-up question, we asked participants if their answer would have been different if they were told that the other participants all had "a psychological condition which makes it very difficult for them to take on the perspective of others."

Although myriad experimental tasks putatively tap into ToM, ToM is not a single, irreducible ability. In this we can agree with Perner (2010), who encouraged cognitive scientists to break open the black box of ToM. In that spirit, this study furthered the endeavor to deconstruct ToM into more fundamental pieces, so that it can be reconstructed into a more tractable framework that can be better connected to corresponding neurobiological bases (Schaafsma, Pfaff, Spunt, & Adolphs, 2015). Recursion is one such subfunction, and one which is elegantly recruited in the beauty contest. The reasoning applied to the beauty contest is potentially complex and mentalistic, but this is also an explicit, abstract task for which participants are extrinsically motivated (through monetary reward). There is increasing evidence that the most persistent social deficits in ASD instead may relate to the interaction of mentalizing abilities with attentional and perceptual processes (e.g., Bush & Kennedy, 2015 for a review; Neumann, Spezio, Piven, & Adolphs, 2006; Senju et al., 2009), which in typical functioning allows the social apparatus to spontaneously and dynamically operate in real-world settings.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.12.015.

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