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Original Article

Decision-making under conditions of explicit risk and uncertainty in autistic and typically developing adolescents and young adults

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Adolescence has been characterized as a period of risky and possibly suboptimal decision-making, yet the development of decision-making in autistic adolescents is not well understood. To investigate decision-making in autism, we evaluated performance on 2 computerized tasks capturing decision-making under explicit risk and uncertainty in autistic and non-autistic adolescents/young adults ages 12–22 years. Participants completed the Game of Dice Task (32 IQ-matched participant pairs) to assess decision-making under explicit risk and the modified Iowa Gambling Task (35 IQ-matched pairs) to assess decision-making under uncertainty. Autistic participants overall made riskier decisions than non-autistic participants on the Game of Dice Task, and the odds of making riskier decisions varied by age and IQ. In contrast, the autistic group showed comparable levels of learning over trial blocks to the non-autistic group on the modified Iowa Gambling Task. For both tasks, younger autistic participants performed poorer than their non-autistic counterparts, while group differences diminished in older ages. This age-related pattern suggests positive development during adolescence on risk assessment and decision-making in autism but also implies differential developmental trajectories between groups. These findings also suggest differential performance by the risk type, with additional complex influences of IQ and fluid cognition, which warrants further investigations.

Key words: adolescence; autism; decision making; development; young adulthood.

Introduction

Adolescence is considered a time of great promise alongside significant vulnerability in cognitive development. During adolescence, distributed brain networks become more refined and integrated because of strong cortical plasticity (Steinberg and Morris 2001; Gogtay et al. 2004; Lee et al. 2014). These changes foster more flexible thinking and behavior that support the maturation of complex social cognition and decision-making to facilitate the acquisition of the adaptive skills required for independent living in adulthood (Arnett 2000; Roisman et al. 2004). Adolescence, however, has also been described as a period of risky and possibly suboptimal decision-making characterized by increased engagement in social- and health-related risk-taking behaviors, such as drinking alcohol, smoking, and getting in the car with a drunk driver (Duell et al. 2018). Past studies have shown impairments in executive function and reward/affect processing in autism that are considered critical elements in decision-making (Brand et al. 2006). Thus, autistic persons may experience additional challenges in developing decision-making skills that could hinder achieving independence in adulthood.

Risky decision-making has been studied in laboratory settings for explicit risk and uncertainty. Under explicit risk, the odds and payouts of a particular decision are known and stable, and thus, the risks of individual decisions can be relatively easily calculated. The Game of Dice Task (GDT) is commonly used to study this type of decision-making in adolescents in typically developing and neurodivergent populations (Brand et al. 2005; Drechsler et al. 2008; Schiebener et al. 2015; Donati et al. 2019). Winning is determined by whether the rolled die matches the 1, 2, 3, or 4 sides that the participant chooses at the beginning of each trial. The perception of risk and benefits during this task is associated with real-life risk-taking behaviors in adolescents (Maslowsky et al. 2011). Executive function is considered a crucial determinant of decision-making in this task across a wide age range, including adolescence (Brand et al. 2006; Schiebener et al. 2015; Schiebener and Brand 2015), as are reasoning and probability processing (Schiebener et al. 2011).

Past research has shown that some autistic persons have difficulty estimating the probability of events (Sinha et al. 2014) or are more strongly influenced by current than past events (Pellicano and Burr 2012). This could cause them to experience difficulty performing the GDT. Zhang et al. (2015) conducted the only study of GDT performance in autism. They documented that autistic participants (mean age of 18 years) bet more on 2 sides (risky bet) and less on 4 sides (safe bet) compared with non-autistic participants. In both groups, performance on the GDT was significantly correlated with executive function measures.

Another type of decision-making, one involving uncertainty, is often studied with the Iowa Gambling Task (IGT) (Bechara et al. 1994). The individual learns about possible outcomes via feedback on previous trials without explicit risk information. In the standard IGT, participants select from 1 of 4 decks of cards

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to play on each trial. Two decks are "good" and produce overall monetary gains, while the 2 other decks are "bad" with a net cumulative loss. Performance is measured by the number of trials in which good decks are selected compared with those in which bad decks are chosen. Unlike the GDT, the net payouts of each deck are too complex to calculate (Bechara et al. 1994).

Decision-making on the IGT is typically referred to as affective as it relies heavily on processing previous rewards and losses. Participants who do not demonstrate explicit knowledge of good/bad decks still may develop anticipatory affective responses, such as skin conductance responses, before selecting a bad deck (Bechara et al. 1997). While the standard IGT has been used widely, the task has been criticized for potential confounds related to differences in exploration and shifting between decks and computing each deck's payout schedules. Cauffman et al. (2010) used a modified version of the IGT (mIGT), where the computer preselected a deck on each trial to eliminate these confounds. The participant then decided whether to pass or play the deck. Percentages of playing good decks showed an inverted U-shaped trajectory in children, with a peak at ages 14–21, while percentages of playing bad decks linearly decreased with age, suggesting potentially dissociable neural substrates for approaching good decks and avoiding bad decks (Cauffman et al. 2010; Icenogle et al. 2017).

A recent meta-analytic review (Zeif and Yechiam 2020) examined studies using the standard IGT or child-adapted version (Crone and van der Molen 2004) in autistic participants with average or higher IQs. Of the 14 studies reviewed, 3 indicated better and 2 indicated impaired performance in autism, while the other 9 suggested no group differences. Variables, including age, IQ, and gender, did not contribute to differences between studies. There was a trend for autistic participants to switch more between decks compared with non-autistic participants (Johnson et al. 2006; Mussey et al. 2015). Thus, removing the confound related to switching decks may be particularly important when the IGT is applied in autism research. However, to date, the mIGT has not been used with autistic individuals.

The current study contrasted decision-making performance with 2 different types of risk using the GDT and mIGT. We hypothesized that adolescents and young adults with autism would make riskier decisions on the GDT based on past studies documenting difficulty with probability information and the findings from Zhang et al. (2015). Regarding decision-making with uncertainty, we employed mIGT to remove deck switching opportunities, which enabled us to more directly examine the approach and avoidance toward reward and loss than the standard IGT. We predicted that autistic participants would have difficulty learning to decline bad decks, given their established difficulties in cognitive control and response inhibition (Solomon et al. 2009; Geurts et al. 2014; Solomon et al. 2017). We also explored differences between groups in task performance in relation to development/age and full-scale IQ (FSIQ) to see if group differences are present to a larger extent at certain ages and if higher FSIQ confers advantages in decision-making.

Materials and methods

Participants

All participants were ages 12–22 years and had a Wechsler Abbreviated Scale of Intelligence-II (Wechsler 2011) FSIQ of ≥70. Autistic participants were evaluated by licensed clinicians and met autism criteria using both the Diagnostic and Statistical Manual of Mental Disorders (DSM)-5 and the Autism Diagnostic Observation Schedule 2 (Lord et al. 2000). Non-autistic participants had no Axis I psychopathology based on parent reports, no history of neurodevelopmental disorders, and no first-degree relatives with a diagnosis of autism. They also did not meet the autism spectrum criteria based on the Social Communication Questionnaire (Rutter et al. 2003). All participants completed the NIH Toolbox Cognition Battery. Details of the participant recruitment and screening are provided in the Supplementary Materials (Section 1.1 Participant Recruitment and Screening, 1.2 Clinical Measures). Consent to participate was obtained from the participant or their guardian using a procedure approved by the University of California Davis Institutional Review Board. In cases where the participant could not provide consent, assent was obtained.

Data from decision-making tasks were collected from 86 autistic and 86 non-autistic participants. To avoid interferences between 2 decision-making tasks, our primary analysis for the GDT data includes only participants who performed the GDT task first (41 autistic; 46 non-autistic), and for the mIGT data, only the participants who performed the mIGT task first (45 autistic; 40 non-autistic). The participants for each task were submitted to an automated greedy matching algorithm to identify a 1:1 IQ-matched sample (http://bioinformaticstools.mayo.edu/research/gmatch/), which allowed a maximum of 7-point FSIQ difference within pairs. The final matched samples included 32 pairs for the GDT and 35 pairs for the mIGT.

In addition to the primary analysis, we conducted a secondary analysis using all participants, regardless of which task they completed first, and examined the effects of the task order and its interaction with diagnosis. Similar to the aforementioned approach, we matched the autistic and non-autistic participants on FSIQ and the order in which they completed the tasks. Details of the secondary analysis are included in the Supplementary Materials.

GDT (Brand et al. 2005)

On each of the 18 trials, the participant chose 1, 2, 3, or 4 sides of the die. If the die was rolled and landed on 1 of the sides the participant selected, the participant gained money. Otherwise, the participant lost money (Fig. S1). Selecting more sides increased the chance of winning, and thus, selecting 1 or 2 sides of the die was referred to as "risky" bets, while selecting 3 or 4 sides was referred to as "safe" bets.

mIGT (Cauffman et al. 2010)

On each of the 120 trials, 1 of the 4 decks was preselected by the computer and indicated by a yellow arrow (Fig. S2A). The participant could then decide whether to play or pass the deck. If the deck was passed, the money earned did not change (Fig. S2B). If the deck was played, feedback on whether money was lost, gained, or remained the same was displayed (Fig. S2C). Participants were told that some decks were more profitable but were not told which ones were profitable. As fully described in Cauffman et al. (2010), decks 1 and 2 resulted in a net loss (bad decks), and decks 3 and 4 resulted in a net gain (good decks). Furthermore, decks 1 and 3 were characterized by small, frequent losses, while large, infrequent losses characterized decks 2 and 4. The trials were given in 6 blocks of 20 trials, each containing 5 trials per deck.

Statistical analysis

Data analyses used a generalized linear mixed-effects model framework (McCulloch et al. 2008) in which, for both tasks, we modeled the probability of an event using a log link and binomial variance function. For the GDT, we modeled the probability of making a risky bet (over 18 independent trials), and we assumed

Table 1. Participant characteristics for the GDT and mIGT.

	GDT		mIGT	
	Autistic (*n* = 32)	**Non-autistic (*n* = 32)**	**Autistic (*n* = 35)**	**Non-autistic (*n* = 35)**
Age (years), *mean (SD)*	17.1 *(2.8)*	17.3 *(3.4)*	17.2 *(3.3)*	17.1 *(1.3)*
Sex (F, M), *n*	6, 26	8, 24	4, 31	6, 29
Ethnicity (Hispanic, Non-Hispanic), *n*	7, 25	9, 23	8, 27	3, 32
Race (Non-White, White), *n*	8, 24	13, 19	12, 23	14, 21
Years of education[a] (mean of parents), *mean (SD)*	12.0 (2.3)	11.2 (2.7)	12.2 (1.9)	12.2 (2.4)
WASI-II FSIQ, *mean (SD)*	105.8 *(11.0)*	106.4 *(9.7)*	105.9 *(12.7)*	106.2 *(11.7)*
WASI-II Verbal Comprehension, *mean (SD)*	101.3 *(11.0)*	103.2 *(10.6)*	100.0 *(14.3)*	102.4 *(11.0)*
WASI-II Perceptual Reasoning, *mean (SD)*	109.5 *(14.5)*	107.9 *(10.7)*	111.1 *(15.4)*	108.9 *(15.5)*
Social Communication Questionnaire[b], *mean (SD)*	21.2 *(5.3)**	3.4 *(3.1)**	21.7 *(5.2)**	2.3 *(2.9)**
ADOS (calibrated severity score), *mean (SD)*	7.4 *(1.7)*	NA	8.0 *(1.4)*	NA

Abbreviations: SD = standard deviation; WASI = Weschler Abbreviated Scale of Intelligence; ADOS = Autism Diagnostic Observation Schedule. Group differences were assessed using 2-tailed 2-sample t-tests for normally distributed data and Mann–Whitney U tests when normality assumptions were violated. Only Social Communication Questionnaire scores were statistically different between groups (*$P < 0.001$ for both GDT and mIGT samples). [a]Data missing for 1 autistic participant in GDT sample and 1 non-autistic participant in the mGIT sample. [b]Data missing for 1 autistic participant in mIGT sample.

that the log odds of a risky bet are a linear combination of terms reflecting diagnosis group, age, and FSIQ and all their interactions. After fitting this reference model, we examined a series of nested models in which quadratic effects of age and FSIQ and their interactions with the group were tested and retained only if they contributed significantly to the model.

For the mIGT, we analyzed each deck separately. We modeled the probability of playing the deck in a block (over 5 trials) and treated the data as repeated measurements (over blocks). We first fitted a model in which the log odds of playing the card were a linear combination of terms reflecting group, trial block (block 1 as the reference), age, FSIQ, and interactions between group and other 3 factors (block, age, FSIQ), and between age and FSIQ. Quadratic effects of age and FSIQ and their interactions with group were also assessed. The interaction terms and quadratic terms for age and FSIQ were kept in the model only if they contributed significantly to the model. The models included a random effect for person-specific intercept to account for within-person correlations. Empirical (sandwich) variance estimators were used to make the analysis robust against misspecification of the covariance structure and to adjust for small-sample bias. For both tasks, age, and FSIQ were centered at the mean to aid interpretation and reduce multicollinearity. The group was coded as a 0/1 binary variable, with 1 indicating the autism group. For models in which significant interactions were present, we subsequently constructed linear contrasts to estimate group differences at various combinations of age and FSIQ values. Results are presented as odds ratios (ORs) and 95% confidence intervals (CIs).

For the secondary analysis, we employed a similar model-building strategy but added order (coded as a 0/1 binary variable, with 1 indicating that the respective task was administered second) and its interactions with the terms described above to the models.

All analyses were implemented using SAS Version 9.4 (SAS Institute Inc, Cary, North Carolina) with 2-sided critical P-values < 0.05.

Results

Participant characteristics

The demographic and clinical characteristics of the participants included in the 2 matched samples are presented in Table 1. The paired participant groups had similar age, FSIQ, and sex distributions.

GDT

Overall, the autistic group placed more risky bets than the non-autistic group (155 vs. 77), with the percentage of risky bets averaging 26.9% for the autistic participants and 13.9% for the non-autistic. In unadjusted analyses, the main effect of group was significant, with autistic participants showing higher odds for making risky bets than non-autistic participants (OR = 2.35, 95% CI: 1.74–3.19, $P < 0.001$). The final adjusted model for GDT (Table S1) revealed a significant group × age × FSIQ interaction ($P < 0.001$), and thus, the group differences depended both on age and FSIQ. For example, due to centering, the term for group ($P < 0.001$) represents the difference between autistic and non-autistic participants with average age and FSIQ. The interaction between group and age ($P < 0.001$) and group and FSIQ ($P < 0.001$) were also significant. To help understand these complex interactions, we calculated and plotted the OR for making risky bets for autistic compared with non-autistic participants over a range of FSIQ and age values (Fig. 1).

Figure 1 shows that, overall, autistic participants were significantly more likely to make risky bets than same-age and same-FSIQ non-autistic participants. This difference was particularly high in participants with Q1 and median FSIQ at younger ages and with Q3 FSIQ across all ages. This difference was diminished at older ages for Q1 and median FSIQ participants. When examining the effect of FSIQ at different ages, it became apparent that the FSIQ effects were strongest at younger ages, where autistic participants made riskier bets across the entire FSIQ range. Autistic participants with median or Q3 age *and* high FSIQ also tended to make more risky bets than non-autistic participants. Table 2, which reports OR for age and FSIQ in quartiles, indicates that autistic participants were significantly more likely to make risky bets in all combinations of age/FSIQ, except Q3 age and Q1 FSIQ, where non-autistic participants were significantly more likely to make risky bets than autistic participants.

We used the same modeling strategy to examine relationships between the GDT performance and Fluid Cognition for each group separately, using the Fluid Cognition Composite score and age as predictors. There was an interaction between Fluid Cognition and age for the non-autistic group. The estimate for age × Fluid Cognition was positive (estimate = 0.02, $P = 0.001$), indicating that higher Fluid Cognition scores predicted *riskier* decision-making

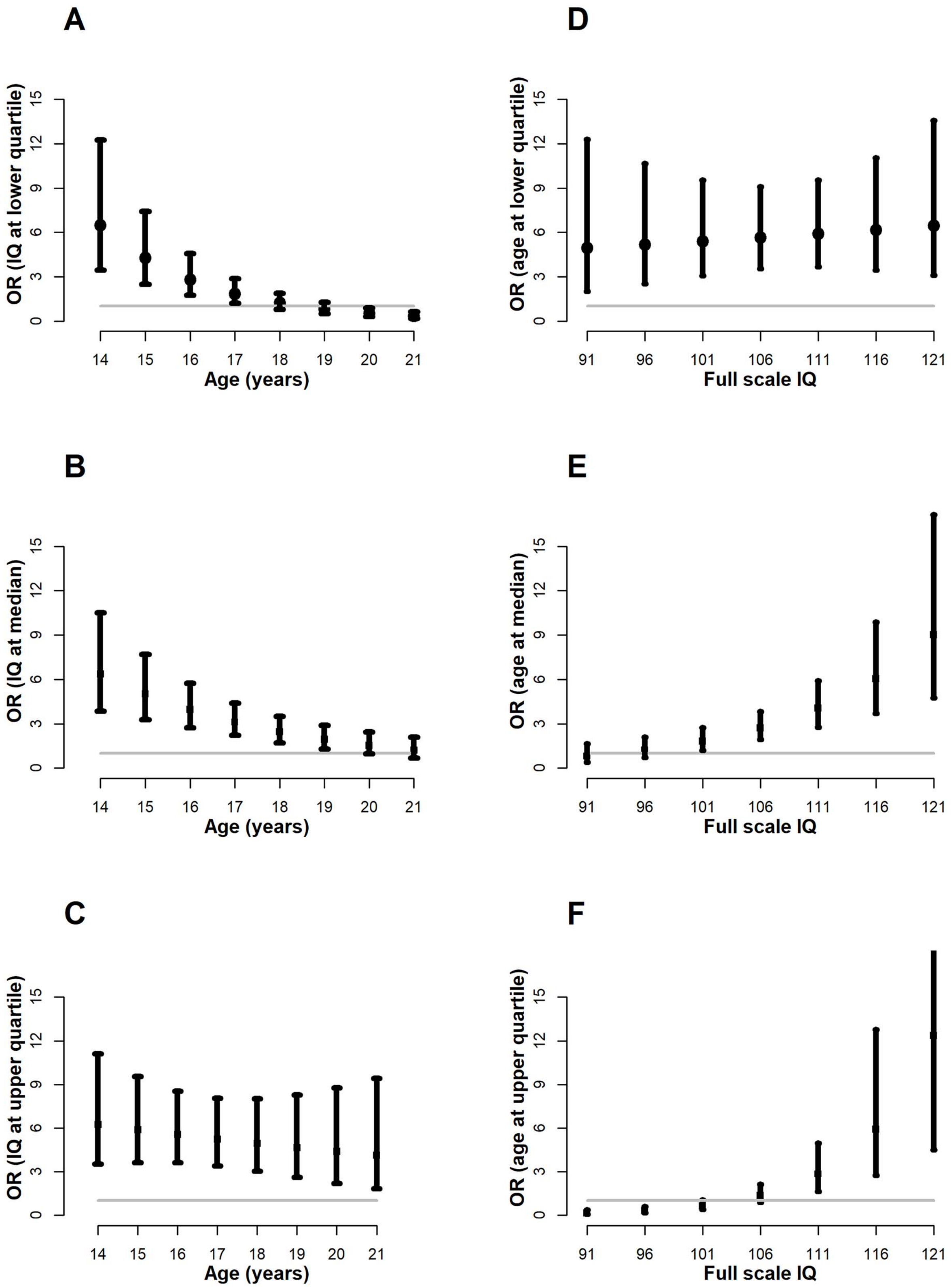

Fig. 1. Game of Dice task performance across age and FSIQ. The left panel shows the ORs and 95% CIs for making risky bets comparing autism vs. non-autistic at age 14–21 for lower quartile (Q1, 100) (A), median (107) (B), and upper quartile (Q3, 114) (C) of FSIQ. The right panel shows OR at FSIQ ranging from 91 to 121 for lower (Q1, 14.5 years) (D), median (17.3 years) (E), and upper quartile (Q3, 19.9 years) (F) of age. CIs that include 1 indicate that the odds for making risky bets do not differ between groups. *Abbreviations*: OR = odds ratio; CI = confidence interval; FSIQ = full-scale IQ.

Table 2. Estimated probabilities and ORs for making risky bets in Game of Dice across age and FSIQ.

	Autistic Probability	**Non-autistic Probability**	**Autistic vs. non-autistic**	
			OR (95% CI)	**P-value**
Age at Q1 (14.5 years)				
FSIQ at Q1 (100)	0.30	0.07	5.37 (3.03–10.02)	< 0.001
FSIQ at median (107)	0.34	0.08	5.71 (3.64–9.24)	< 0.001
FSIQ at Q3 (114)	0.40	0.10	6.07 (3.64–10.57)	< 0.001
Age at median (17.3 years)				
FSIQ at Q1 (100)	0.19	0.12	1.68 (1.10–2.61)	0.02
FSIQ at median (107)	0.27	0.11	2.94 (2.09–4.17)	< 0.001
FSIQ at Q3 (114)	0.36	0.10	5.15 (3.35–8.07)	< 0.001
Age at Q3 (19.9 years)				
FSIQ at Q1 (100)	0.12	0.19	0.56 (0.33–0.93)	0.02
FSIQ at median (107)	0.20	0.14	1.57 (1.00–2.50)	0.05
FSIQ at Q3 (114)	0.33	0.10	4.41 (2.26–8.83)	< 0.001

Abbreviations: OR = odds ratio; CI = confidence interval; FSIQ = full-scale IQ. CIs that include 1 indicate that the odds for making risky bets do not differ between groups.

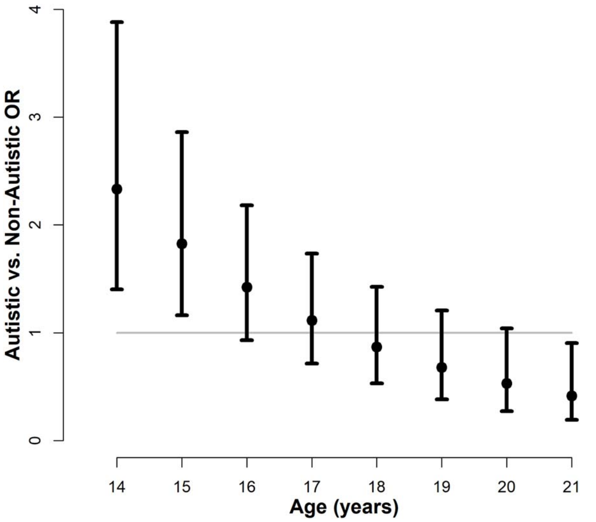

Fig. 2. Modified Iowa Gambling Task performance for deck 1. ORs for playing deck 1 are presented with 95% CIs for comparing autism vs. non-autistic at ages 14–21. FSIQ and block were held constant. CIs that include 1 indicate no group difference. *Abbreviations*: OR = odds ratio; CI = confidence interval; FSIQ = full-scale IQ.

on the GDT in older vs. younger non-autistic participants. For average-age non-autistic participants, GDT performance was not significantly related to fluid cognition (estimate = -0.02, $P = 0.30$). However, higher Fluid Cognition was associated with *riskier* decision-making (estimate = 0.04, $P < 0.001$) in the autism group.

mIGT

Table S2 presents the results of the linear mixed-effect logistic models for the 4 decks in mIGT. The interaction between the group and block did not reach statistical significance for any of the four decks. Therefore, it was removed from the reported models. Deck 1 was the only deck that consistently showed a difference in playing from block 1 (first 20 trials) compared to later blocks ($F(5, 344) = 3.40$, $P = 0.005$). Deck 1 is a disadvantageous deck characterized by small, frequent losses, and both groups were significantly less likely to play this deck in all subsequent blocks (blocks 2–6). There was no main effect of group for any of the decks, but the age x group interaction was significant for deck 1 (Fig. 2). At younger ages, autistic participants tended to play deck 1 more often than non-autistic participants, while the direction of the group difference was reversed at older ages. The average age x FSIQ interaction for deck 1 is detailed in the supplemental materials (Tables S3–S4).

The results of the secondary analyses are presented in the Supplementary Material (Section 3 Secondary Analysis Examining Task Order). Participant characteristics are summarized in Table S5. For both tasks, we found that task order interacted with group. When the task was administered first, the results replicated the primary analyses. However, when the task was administered second, the group differences diminished, primarily due to changes in the non-autistic group (Figs S3–S8, Tables S6–S8).

Discussion

The 2 decision-making tasks revealed distinct patterns of group differences depending on the type of associated risks. Autistic participants were more likely to make “risky” bets than non-autistic participants on the GDT, where they evaluated straightforward questions about probability on every trial. Younger autistic participants generally made riskier choices than their non-autistic counterparts, while the group differences diminished at older age. In contrast, there was no overall group difference in the performance in the mIGT, which is considered more difficult and involves learning and remembering various outcomes across 4 different decks. There was significant learning over trial blocks on disadvantageous deck 1 across groups. However, similar to the GDT, younger autistic participants were more likely to choose deck 1, while group differences reduced with age and eventually reversed among the oldest participants. The decreasing pattern of group differences over age on both tasks suggests differences in developmental trajectories of both forms of risky decision-making, which warrants further investigation.

The group difference was more robust on the seemingly easier, more straightforward GDT. The differential performance may suggest a generalized issue of motivation during an easier, potentially more boring task, but possibly a specific cognitive processing requirement related to the GDT. Past research suggested that autistic individuals may not process probability information well due to difficulty estimating underlying probabilities between series of events (Sinha et al. 2014) or greater influence by current information than what has been learned over time (Pellicano and Burr 2012). Brand et al. (2006) asserted that the GDT requires both executive and affective/reward systems, which must operate together in a flexible balance depending on the task and situation (Schiebener and Brand 2015). The requirement to flexibly apply executive control may pose a particular challenge for autistic persons given their established difficulties in executive control—particularly during adolescence when both affective and executive systems are developing (Steinberg 2008).

Our data showed complex influences of age, IQ, and fluid cognition on decision-making performance. While poor performance on risk-related decision-making tasks is often associated with impulsivity and poor judgment, Maslowsky et al. (2011) suggested that the decision-making process is much more multifaceted and that the performance on the GDT is affected by being a planned risk taker (more likely to plan ahead of time to engage in risky behavior) vs. an unplanned risk taker (more likely to decide to engage in risky behavior reactively). It is possible that some participants in the current study chose riskier bets because they were willing to take calculated risks. For instance, if the participant chose the safest option ($100 prize money, Fig. S1) on all 18 trials, the maximum amount of money won (with 18 wins) would be $1800. In contrast, with the riskiest option ($1000 prize), winning only 2 out of 18 trials would result in $2000. Some participants may have reasoned that winning 2 risky trials was sufficiently likely and be willing to tolerate the calculated risk of winning fewer than 2 trials. Thus, while some participants may have chosen more risky bets to reflect impulsivity or difficulty assessing probabilities, others may have chosen more risky bets with a willingness to take calculated risks. Future studies could change the payoff matrix by increasing the amount of prize money on safe bets to better contrast safer and riskier bets (thus, safer bets are more clearly advantageous). Performance patterns of those with high impulsivity or problem assessing probably are not likely to change. Still, those who are taking calculated risks are likely to adjust to the new payoff schedule.

The current work had several limitations. First, because of the task order effects, our primary analysis presented data from 2 independent samples that performed each decision-making task. Though the data patterns were very similar to the secondary analysis with larger samples, with regard to performance when each task was given first, it is still possible that the differential task performance reflects sample differences rather than the task requirements. Similarly, age was measured cross-sectionally, and the inference and generalization based on the age-related effects may be limited. Finally, impairments in decision-making have been observed in other clinical groups (Hartley and Phelps 2012; Wang et al. 2018) and thus may be better characterized as a transdiagnostic characteristic rather than at disorder levels. However, it is also possible that there is a potential contributing factor that is specific to autism, and this requires further research to clarify.

In conclusion, autistic participants tended to choose risker bets under explicit risk than their non-autistic counterparts but performed similarly on a task assessing risk under uncertainty. Younger autistic participants performed more poorly across both tasks but improved with age. Thus, one optimistic finding of our work is that there may be a positive development in decision-making in autistic adolescents. More work is needed to fully delineate the complex influence of age, intellectual abilities, and development on decision-making in autism.

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Author contributions

Marie K. Krug (Conceptualization, Data curation, Methodology, Writing-original draft, Writing-review & editing, Project administration), Yukari Takarae (Investigation, Writing-original draft, Writing—review & editing), Ana-Maria Iosif (Conceptualization, Data curation, Formal analysis, Methodology, Writing—original draft, Writing—review & editing), and Marjorie Solomon (Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing—original draft, Writing—review & editing).

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

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Conflict of interest statement: None declared.

Data availability

The GDT and mIGT were acquired from the Millisecond Test Library. (https://www.millisecond.com/). The raw, de-identified participant data and data analysis scripts are available at https://github.com/anamariaiosif/Gambling.

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