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Decision-making under risk and ambiguity in adults with Tourette syndrome

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Abstract

Background. Tourette syndrome (TS) as well as its most common comorbidities are associated with a higher propensity for risky behaviour in everyday life. However, it is unclear whether this increased risk propensity in real-life contexts translates into a generally increased attitude towards risk. We aimed to assess decision-making under risk and ambiguity based on prospect theory by considering the effects of comorbidities and medication.

Methods. Fifty-four individuals with TS and 32 healthy controls performed risk and ambiguity decision-making tasks under both gains and losses conditions. Behavioural and computational parameters were evaluated using (i) univariate analysis to determine parameters difference taking independently; (ii) supervised multivariate analysis to evaluate whether our parameters could jointly account for between-group differences (iii) unsupervised multivariate analysis to explore the potential presence of sub-groups.

Results. Except for general 'noisier' (less consistent) decisions in TS, we showed no specific risk-taking behaviour in TS or any relation with tics severity or antipsychotic medication. However, the presence of comorbidities was associated with distortion of decision-making. Specifically, TS with obsessive–compulsive disorder comorbidity was associated with a higher risk-taking profile to increase gain and a higher risk-averse profile to decrease loss. TS with attention-deficit hyperactivity disorder comorbidity was associated with risk-seeking in the ambiguity context to reduce a potential loss.

Conclusions. Impaired valuation of risk and ambiguity was not related to TS *per se*. Our findings are important for clinical practice: the involvement of individuals with TS in real-life risky situations may actually rather result from other factors such as psychiatric comorbidities.

Introduction

Tourette syndrome (TS) is a neurodevelopmental syndrome characterised by tics as a core symptom, which is commonly associated with other psychiatric comorbidities such as attention-deficit hyperactivity disorder (ADHD), obsessive–compulsive disorder (OCD) and impulse control disorders (Frank, Piedad, Rickards, & Cavanna, 2011; Hirschtritt et al., 2015; Martino, Ganos, & Pringsheim, 2017) as well as increased alcohol/drug consumption (Virtanen et al., 2021).

Several studies have suggested associations between TS and increased propensity for risky behaviour in everyday life. For instance, even if comorbidities might have a significant impact, individuals with TS were reported to exhibit a higher frequency of vehicle accidents (Mataix-Cols et al., 2021) and traumatic brain injury (Chen, Su, Wang, Hsu, & Shen, 2019), overall leading to premature death (Fernández de la Cruz & Mataix-Cols, 2020; Meier, Dalsgaard, Mortensen, Leckman, & Plessen, 2017). It is still not clear whether the increased risk propensity of individuals with TS in real life translates into (or even stems from) a generally increased attitude towards risk and whether it is related to TS *per se* or comorbid conditions.

The layman notion of risk typically brings to mind uncertainty for adverse real-life outcomes, i.e. from undesirable and mildly inconvenient to dire and life-threatening. At a decision

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theory level, risk-taking is rather defined as a tendency to select risky outcomes over safer, sometimes more beneficial ones, in both positive and negative contexts (Byrnes, Miller, & Schafer, 1999; Howat-Rodrigues, Tokumaru, & Izar, 2018). Closely related to the notion of risk and uncertainty is the concept of ambiguity. While risk relates to situations where outcome distributions are known (e.g. a lottery or documented health hazards like COVID infection risks), ambiguity refers to situations where the likelihood of different outcomes cannot be expressed with any mathematical precision (Tobler & Weber, 2014).

The most dominant model of decision under risk is prospect theory (Kahneman & Tversky, 1979); a common extension of it in the domain of decision under ambiguity (Levy, Snell, Nelson, Rustichini, & Glimcher, 2010) allows for quantitative evaluations of behaviour in a variety of decisional contexts. Prospect theory models decision-making under risk with (among other things) three core assumptions. First, decision-makers are risk averse over moderate probability gains and seek risk over losses, an attitude captured by a decreasing marginal utility over gains and losses, making value functions convex in loss domain and concave in gain domain. Second, decision-makers are much more sensitive to losses than gains of equal magnitude, an attitude captured by a loss aversion parameter. Finally, decision-makers overweight small probabilities and underweight high probabilities. Overall, with a limited and principled set of parameters, this model can account for complex patterns of behaviour, such that the same individual could have a risk averse behaviour in context of gain (i.e. preferring a small gain obtained with certainty than a higher gain with a lower degree of certainty) and risk seeking in context of loss (i.e. preferring a high loss with an undetermined probability of occurrence to a lower loss with a certain probability of occurrence). The extension of prospect theory to ambiguity aversion also accounts for why decision-makers typically prefer known risks over unknown risks. Overall, this model-based approach of decision-making under risk and ambiguity allows a summary of the history of participants' choices as a small set of interpretable parameters (Huys, Maia, & Frank, 2016; Montague, Dolan, Friston, & Dayan, 2012).

In TS, previous experimental reports of decision-making in context of risk using different versions of gambling tasks showed no difference in performance compared to healthy controls (HC) (Crawford, Channon, & Robertson, 2005; Goudriaan, Oosterlaan, de Beurs, & van den Brink, 2005). However, because these reports did not always account for frequent comorbidities or treatment with antipsychotics, their effects on risk-attitude in TS remain unclear. Similarly, studies of decisional processes under the risk of frequent comorbid conditions with tics showed discrepant results. For instance, ADHD patients without tics exhibit a deficit in general decisional process rather than making riskier decisions compared to HC (Dekkers et al., 2021, 2020; Humphreys, Tottenham, & Lee, 2018). Interestingly, ADHD patients without tics presented performances similar to HC in a context of decision-making under ambiguity (Norman et al., 2018). OCD patients were also found to be similar to HC in a context of risk (Kim et al., 2015; Zhang et al., 2015), and inconsistently similar (Norman et al., 2018) or impaired (Kim et al., 2015; Zhang et al., 2015) compared to controls regarding ambiguity evaluation. From a brain functioning level, risk-taking was related to catecholamine function. In particular, D2/D3 agonists such as pramipexole lead to an increase of risky behaviour in healthy individuals in a context of ambiguity, that is related to a change of activity of ventral striatum (Riba, Krämer, Heldmann, Richter, & Münte, 2008). Also, tryptophan supplementation presumably resulting in elevation of serotonin concentration leads to risk aversion under a condition of gain and risk seeking under a condition of loss (Murphy et al., 2009). Considering that TS is related to putative dopamine hyperactivity (Maia & Conceição, 2017, 2018; Palminteri et al., 2009, 2011), individuals with TS might present a distorted risk evaluation, especially if not medicated.

Overall, these discrepant results call for a more systematic investigation of attitude towards risk and ambiguity in individuals with TS, as well as of the role of comorbidities and medication. This study thus aimed to systematically investigate behaviours of individuals with TS and matched HC following standard procedures in research and investigating decision-related processes under both risk and ambiguity (Ellsberg, 1961; Knight, 1921). In addition, we aimed to manipulate valence values of potential outcomes to assess decision-making aspects specific to the relative processing of gains and losses.

Materials and methods

Subjects

Sixty-four adults with TS and 34 age- and gender-matched HC were recruited through the Tourette Reference Centre at the Pitié-Salpêtrière Hospital in Paris. All participants gave their written consent to participate in the study. For all participants, exclusion criteria were as follows: a lack of capacity or unwillingness to give consent for the study, evidence of either present or prior substance addiction (excluding nicotine and recreational use of cannabis), a past or present history of psychosis, neurological symptoms other than tics for TS, childhood tics and axis I psychiatric disorders for HC. The study was approved by the local ethics committee (CCP16163/C16-07) and preregistered on ClinicalTrial (https://clinicaltrials.gov/ct2/show/NCT02960698).

All participants were assessed for psychiatric disorders [Mini International Neuropsychiatric Interview, MINI (Sheehan et al., 1998)], impulse-control disorders [Minnesota Impulse Disorders Interview, MIDI (Grant, 2008)] and general impulsivity [using the Barratt Impulsivity scale, BIS-11 (Patton, Stanford, & Barratt, 1995)]. Tic severity was assessed using the Yale Global Tic Severity Scale [YGTSS (Leckman et al., 1989)], and any presence of psychiatric comorbidities was evaluated from medical records and psychiatric evaluations prior to inclusion in the study.

Decision-making under risk

The task was programmed using Cogent in Matlab (Fig. 1*a*). A repeated binary decision-making task was designed based on mixed-outcomes probabilistic lotteries. For each trial, participants were presented with two wheels-of-fortune, which defined two options O_k. Each O_k option featured two potential outcomes: a potential gain G_k with a probability of P_k, and a potential loss L_k with a probability of $1 - P_k$.

Option 1 was fixed for all trials, such that:

$$G_1 = 5;$$

$$P_1 = 0.5;$$

$$L_1 = 2;$$

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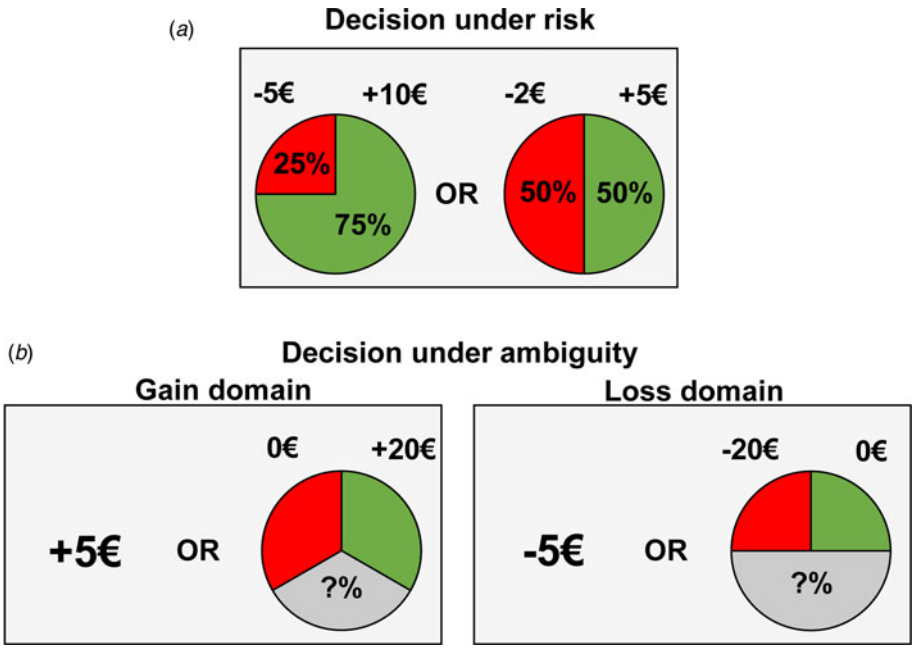

Fig. 1. Experimental task for decision-making under risk (*a*) and ambiguity (*b*).

Option 2 was designed from the following set of features:

$$G_2 \in \{5,\ 10,\ 20,\ 50,\ 75,\ 125\};$$

$$L_2 \in \{5,\ 10,\ 20,\ 50,\ 75,\ 125\};$$

$$P_2 \in \{0.01,\ 0.05,\ 0.10,\ 0.25,\ 0.50,\ 0.75,\ 0.90,\ 0.95,\ 0.99\};$$

The task included 100 trials and followed an adaptive design (Daunizeau, Preuschoff, Friston, & Stephan, 2011) as implemented in the VBA toolbox (Daunizeau, Adam, & Rigoux, 2014). Briefly, we assumed that participants would use a simple version of prospect theory model to render their decisions (Kahneman & Tversky, 1979) (see below). On each trial, our adaptive algorithm selected option 2 to provide the best potential estimation of *PT* parameters, given the current estimation (i.e. selected option 2 that minimised traces of the variance–covariance matrix of the posterior parameters). Thereby, parameters were estimated online on a trial-by-trial basis. Analyses were performed with parameters estimated by this procedure on the last trial of the task (trial 100). In other words, each trial was based on the choice from the previous one in order to progressively estimate the parameters of the model.

Four free parameters were estimated (see online Supplementary method for details): r (utility curvature), λ (loss aversion), γ (probability distortion) and ω (choice inverse temperature).

These parameters could be interpreted as follows: r (utility curvature) is directly related to risk attitude so that risk-seeking profiles imply a high r value while risk-averse profiles are related to a lower r value; λ (loss aversion) describes a tendency to avoid losses than acquiring equivalent gains (high value); γ (probability distortion) relates to the overestimation of low-probability events and the underestimation of high-probability events; ω (choice inverse temperature) characterises a propensity to select high-valued options (high values) or to explore lower-valued options (low values).

Decision-making under ambiguity

The task was adapted from Levy et al. (2010) programmed using Cogent in Matlab (Fig. 1*b*). Similarly to Tymula, Rosenberg Belmaker, Ruderman, Glimcher, and Levy (2013), we designed two symmetrical valence conditions (in gains and loss domains). At each trial, participants were presented with two wheels-of-fortune which defined two options O_k. Each option O_k featured two potential outcomes based on a probability which was partly known (P_k) and partly masked (A_k), so-called ambiguity parameter: a potential gain $G_k \neq 0$ or an absence of gain $G_k = 0$.

Option 1 was fixed for all trials, such that $G_1 = 5$ for the gain condition and $G_1 = -5$ for the loss condition.

Option 2 was designed from the following set of features:

$$G_2 \in \{5,\ 8,\ 20,\ 50,\ 125\};\ \text{under condition of gain}$$

$$G_2 \in \{-5,\ -8,\ -20,\ -50,\ -125\};\ \text{under condition of loss}$$

$$P_2 \in \{0.13,\ 0.25,\ 0.38,\ 0.50,\ 0.75\};$$

$$A_2 \in \{0.00,\ 0.24,\ 0.50,\ 0.74\}$$

The task included 80 trials, 40 under each condition, all presented in random order.

The model features three free parameters: r (utility curvature), β (ambiguity aversion) and ω (choice inverse temperature). We estimated one set of parameters (r, β, ω) per valence condition (gains and losses), leading to a total of six free parameters (hereafter referred to as r_G, β_G, ω_G, r_L, β_L, ω_L).

This additional parameter (β, ambiguity aversion) could be interpreted as summarising the preference for situations where risks are known (high value).

Statistical analyses

All statistical analyses were performed using R (R Core Team, 2013) and Matlab (Matlab, 2018). Demographic and clinical comparisons between individuals with TS and HC participants were

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Table 1. Demographics and clinical characteristics of the participants

	HC	TS	*p*	bf
N	32	54	–	–
Gender (M/F)	24/8	42/12	0.975	0.338
Age	31.16 ± 10.03	31.09 ± 10.96	0.978	0.232
Education (years)	14.44 ± 2.94	14.11 ± 2.54	0.603	0.263
BIS-11	57.84 ± 9.08	65.56 ± 10.52	**<0.001**	**33.964**
MIDI	0.45 ± 0.85	1.56 ± 1.33	**<0.001**	**278.985**
YGTSS (/50)	–	15.35 ± 7.01	–	–
Medication (*n*)	–	22	–	–
ADHD (*n*)	–	15	–	–
OCD (*n*)	–	6	–	–
ADHD and OCD (*n*)	–	8	–	–

ADHD, attention deficit/hyperactivity disorder; bf, Bayesian factor; BIS, Barratt Impulsiveness Scale; F, female; HC, healthy control participants; M, male; MIDI, Minnesota Impulse Disorders Interview; OCD, obsessive–compulsive disorder; TS, Tourette syndrome participants; YGTSS, Yale Global Tic Severity Scale. Bold corresponds to significant effects.

completed using two-sample *t* tests or χ^2 and were confirmed using Bayesian analyses. We considered as significant any effect with *p* values $\leqslant 0.05$ and a Bayesian factor (bf) $\geqslant 3$.

Regarding the main parameters, our approach to systematically investigate decision-making under risk and ambiguity in TS followed three steps: (i) we assessed whether individuals with TS differed from HC on any of the decision-making parameters estimated from our computational model, independently (univariate analysis); (ii) we combined all decision-making parameters, and evaluated whether they can jointly account for differences between individuals with TS and HC (supervised multivariate analysis) and (iii) we used a data-driven approach to explore the potential presence of sub-groups, and the role of comorbidities (unsupervised multivariate analysis).

Univariate analysis: t tests and correlations

First, we compared parameter values between HC and TS patients and TS subgroups (i.e. TS with ADHD *v.* TS without ADHD, TS with OCD *v.* TS without OCD, TS under medication *v.* TS unmedicated). These comparisons were achieved by using two-sample *t* tests and Bayesian *t* tests. In addition, correlations between tic severity (YGTSS/50) were performed for all individuals with TS using correlations and Bayesian correlations. We considered as significant any effect with *p* values $\leqslant 0.05$ and a bf $\geqslant 3$.

Supervised multivariate analysis: random forest

Subsequently, we performed a supervised multivariate classification using a random forest algorithm (Cutler, Cutler, & Stevens, 2012; Tin Kam Ho, 1995) (5000 decision trees) with permutations ($n = 1000$) between HC and TS groups and between TS subgroups (i.e. TS with ADHD *v.* TS without ADHD, TS with OCD *v.* TS without OCD, TS under medication *v.* TS unmedicated). Random forest algorithms first divide the whole dataset into several subsets (called 'bagging'), then produce various decision trees (5000 in our case) and finally combine the vote of each tree. This approach utilises several predictors simultaneously, which is more appropriate than simple decision trees. Here, implementing the permutation approach allows us to produce a null distribution by permuting the response variable and then to calculate a *p* value for the importance of each predictor in the classification. This importance corresponds to the loss of model accuracy (so-called 'mean decreased accuracy' and is expressed as percentage) if a predictor is removed from the analysis. For results, we reported the mean decreased accuracy of each predictor and their *p* values and the general accuracy of the model and its *p* value. We considered significant any *p* values $\leqslant 0.05$. This second approach identifies group differences by taking all parameters into account simultaneously. In other words, while we can find no difference by taking our parameters one by one, the association of several parameters taken together could reinforce the ability to find differences between our groups.

Unsupervised multivariate analysis: hierarchical clustering

Lastly, we performed an unsupervised multivariate classification using agglomerative hierarchical clustering on principal component analysis (Maimon & Rokach, 2010). This clustering technique involved building a principal component analysis which is a method to simplify data complexity by reducing it into fewer dimensions. Next, the agglomerative hierarchical clustering builds several clusters of participants whose number is selected by a method called 'higher relative loss of inertia'. This criterion selects the number of clusters with the smaller within-class variability (i.e. individuals in the same cluster are close to each other) and the larger between-class variability (i.e. individuals in different clusters are far from each other). After this classification, we compare participants of each cluster regarding their groups (HC, TS, with ADHD, with OCD, medicated), their demographic and clinical characteristics, and their computational parameters by using inferential (analysis of variance and χ^2) and Bayesian analyses. We considered as significant any effect with *p* values $\leqslant 0.05$ and a bf $\geqslant 3$. This third approach can identify possible subgroups of patients with abnormal behaviours. In other words, it can reveal if an absence of difference between groups is because abnormal behaviours are only related to a subgroup of patients, which is masked by other subgroup(s) with expected behaviours.

Results

Demographic results

Ten individuals with TS and two HC were excluded from our final analyses due to incomplete data. The final sample involved 54 individuals with TS and 32 HC participants (Table 1).

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No significant differences were found between subgroups of TS patients and HC participants regarding demographic variables ($p > 0.6$; bf < 0.34). TS patients showed higher general impulsivity as measured by the BIS-11 ($p < 0.001$; bf = 33.964); and a higher number of impulsive behaviours as measured by the MIDI ($p < 0.001$; bf = 278.985).

Approach 1: univariate analysis

Regarding the models' parameters (Table 2), we found only one difference between HC and TS on the ω parameters during the task of ambiguity gain ($p = 0.029$). However, this effect was not supported by the Bayesian analysis (bf = 2.917).

TS subgroup analyses revealed only one difference supported by two analyses: the r_G parameter (i.e. the utility curvature estimated during the task of ambiguity in gain domain) between individuals with TS with and without OCD ($p = 0.037$, bf = 25.916). Two other effects were found, which were only supported by classical t tests (r_L between TS with and without ADHD: $p = 0.027$, bf = 1.139; γ between TS with and without OCD: $p = 0.013$, bf = 0.936). No significant difference was found between medicated and unmedicated patients.

There were no significant correlations between any parameter and tic severity (YGTSS/50; $p > 0.097$; bf < 1.076; online Supplementary Table S1).

Approach 2: supervised multivariate analysis

The random forest model between HC and TS did not lead to a satisfying accuracy (58.1%, $p = 0.053$) even if one parameter seems relevant (ω_G: mean decreased accuracy = 37.45%, $p = 0.002$; Table 3). The model which compared individuals with TS with and without OCD was the only one with significant accuracy (75.9%, $p < 0.0001$) in contrast to models focused on ADHD (accuracy = 51.9%, $p = 0.342$) and on medication (accuracy = 38.9%, $p = 0.933$). On the OCD model, the r parameter had significant importance in all three tasks ($p < 0.041$) associated with ω during the risk task ($p = 0.047$).

Approach 3: unsupervised multivariate analysis

The hierarchical clustering algorithm determined that the optimal number of clusters is 3. The clusters obtained differentiate on all parameters of the risk task ($p < 0.0001$, bf > 7.992), on β_G ($p = 0.01$, bf = 4.73), r_L ($p = 0.004$, bf = 10.172) and partially on ω_L ($p = 0.038$, bf = 1.548) and β_L ($p = 0.033$, bf = 1.553; Table 4) parameters. Regarding the demographic and clinical differences between all three clusters, we found an over-representation of TS patients with OCD in cluster 2 ($p = 0.046$, bf = 3.741) and a lower education level in cluster 3 ($p = 0.005$, bf = 7.825). No difference was found regarding the distribution of HC, all TS, TS with ADHD or medicated TS. Additionally, we report no difference in age, BIS-11, MIDI and YGTSS/50.

In detail, the first cluster could be characterised as more aversive to risk and ambiguity in a context of loss (higher ω, ω_L and β_L; lower r and β_G). The second cluster corresponded more to a profile aversive to loss, thus with a risk-taking behaviour aiming to decrease a potential loss (higher λ and r_L; lower ω, ω_L and γ). The third cluster is characterised by a higher propensity to play in a context of risk, but not of ambiguity, especially when it involves a potential loss (higher r and γ; lower ω, λ, r_L and β_L).

Discussion

We found no overall risk-taking behaviour in TS compared to controls, using dedicated risk and ambiguity decision-making tasks. Of note, individuals with TS have noisier decisions (i.e. less consistent), likely reflecting response inconsistencies or tendency for exploration. Distortion of the decision-making process in this context was rather related to comorbidities, such as OCD or ADHD, than to TS *per se*. Our findings are important for clinical practice, as they may indicate management of risk-taking issues in everyday life of individuals with TS should focus on treating comorbidities.

TS have noisier decisions in context of ambiguity for a gain

We found that individuals with TS, in comparison with HC, had a lower inverse temperature parameter (ω) in context of ambiguity for a gain, which reflected a higher selection in TS of non-maximal expected values, corresponding to a higher response inconsistency. As this parameter tends to increase with age and brain maturation (Palminteri, Kilford, Coricelli, & Blakemore, 2016), a decrease of this parameter might reflect brain immaturity at a behavioural level as was previously suggested in adults with TS at a brain network level (Nielsen et al., 2020; Worbe et al., 2015). Alternatively, a lower inverse temperature parameter (ω) could reflect exploratory behaviour in TS. Brain imaging studies reported that this tendency to explore environment could be associated with an increased dopamine tone within the prefrontal cortex (Badre, Doll, Long, & Frank, 2012; Frank, Doll, Oas-Terpstra, & Moreno, 2009), a key alteration in TS pathogenesis (Maia & Conceição, 2017, 2018; Palminteri et al., 2009, 2011; Yoon, Gause, Leckman, & Singer, 2007).

Risk-taking behaviours and experimental risk evaluation in TS

Our main result is that TS was not associated with abnormal decision-making behaviours in contexts of risk or ambiguity (i.e. no difference with HC, no correlation with tics severity and no medication effect).

Indeed, individuals with TS may not have risk or ambiguity valuation impairment. If no previous study was performed on this population, several studies on frequent TS-related comorbidities such as ADHD and OCD could support this hypothesis (Cavedini, Gorini, & Bellodi, 2006; Humphreys et al., 2018; Kim et al., 2015; Norman et al., 2018; Starcke, Tuschen-Caffier, Markowitsch, & Brand, 2009, 2010). However, this is unlikely since individuals with TS have a frequent involvement in real-life risky behaviours, as demonstrated by a higher probability of premature death (Fernández de la Cruz & Mataix-Cols, 2020; Meier et al., 2017).

One explanation could be that our task did not accurately capture risk and ambiguity valuation processes. Experimental tasks as used in this study measure traits and performance at the time of the study rather than their average over an extended time period meaning that risky and ambiguous behaviours are considered stable 'traits' (Palminteri & Chevallier, 2018). Moreover, contextual factors (such as the nature of rewards) and task parameters (e.g. 2D *v.* 3D objects, time pressure, cognitive load) can modify preference for risk (Betsch, Haberstroh, Molter, & Glöckner, 2004; De Petrillo et al., 2020; Kocher & Sutter, 2006; Wang, Feng, & Keller, 2013). For example, it was reported that high risk-takers in recreational domains only express moderately risky behaviours when making financial decisions (Hanoch, Johnson, & Wilke,

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Table 2. Means and standard deviations for each parameter of the tasks and groups in comparison with inferential and Bayesian *t* tests

	HC	TS – all	TS – ADHD	TS – no ADHD	TS – OCD	TS – no OCD	TS – Med.	TS – Unmed.
Risk								
ω								
Mean ± s.d.	1.22 ± 1.34	0.99 ± 1.31	1.31 ± 1.48	0.76 ± 1.13	0.59 ± 1.16	1.14 ± 1.34	1.18 ± 1.42	0.87 ± 1.23
p value/bf	$p = 0.459$/bf = 0.296		$p = 0.143$/bf = 0.565		$p = 0.164$/bf = 0.389		$p = 0.409$/bf = 0.376	
r								
Mean ± s.d.	0.87 ± 0.54	0.98 ± 0.62	0.94 ± 0.56	1.02 ± 0.67	1.27 ± 0.73	0.88 ± 0.55	0.88 ± 0.59	1.05 ± 0.64
p value/bf	$p = 0.383$/bf = 0.316		$p = 0.655$/bf = 0.209		$p = 0.084$/bf = 1.209		$p = 0.316$/bf = 0.419	
λ								
Mean ± s.d.	1.36 ± 0.7	1.45 ± 0.77	1.31 ± 0.55	1.55 ± 0.89	1.59 ± 0.77	1.4 ± 0.77	1.42 ± 0.76	1.47 ± 0.78
p value/bf	$p = 0.582$/bf = 0.263		$p = 0.232$/bf = 0.342		$p = 0.426$/bf = 0.232		$p = 0.816$/bf = 0.284	
γ								
Mean ± s.d.	1.05 ± 0.78	1.09 ± 0.77	0.94 ± 0.76	1.2 ± 0.77	0.75 ± 0.44	1.21 ± 0.83	1.32 ± 0.93	0.93 ± 0.61
p value/bf	$p = 0.833$/bf = 0.236		$p = 0.223$/bf = 0.382		**$p = 0.013$**/bf = 0.936		$p = 0.094$/bf = 1.129	
Ambiguity – gain								
ω_G								
Mean ± s.d.	2.4 ± 2.87	1.09 ± 2.09	0.89 ± 1.61	1.24 ± 2.42	1.09 ± 2.09	1.09 ± 2.13	1.14 ± 2.09	1.06 ± 2.14
p value/bf	**$p = 0.029$**/bf = 2.917		$p = 0.537$/bf = 0.224		$p = 0.998$/bf = 0.17		$p = 0.893$/bf = 0.279	
r_G								
Mean ± s.d.	1.05 ± 0.99	1.29 ± 1.55	1.74 ± 2.13	0.95 ± 0.79	2.42 ± 2.43	0.89 ± 0.82	1.06 ± 1.04	1.44 ± 1.82
p value/bf	$p = 0.403$/bf = 0.297		$p = 0.101$/bf = 0.945		**$p = 0.037$/bf = 25.916**		$p = 0.325$/bf = 0.389	
β_G								
Mean ± s.d.	1.03 ± 2.82	0.29 ± 3.13	−0.37 ± 1.93	0.77 ± 3.74	0.52 ± 3.11	0.2 ± 3.17	0.89 ± 3.02	−0.13 ± 3.18
p value/bf	$p = 0.263$/bf = 0.391		$p = 0.153$/bf = 0.427		$p = 0.748$/bf = 0.179		$p = 0.235$/bf = 0.498	
Ambiguity – loss								
ω_L								
Mean ± s.d.	1.46 ± 1.39	1.55 ± 1.89	1.42 ± 1.56	1.65 ± 2.12	1.76 ± 2.22	1.48 ± 1.78	1.47 ± 2.09	1.61 ± 1.76
p value/bf	$p = 0.787$/bf = 0.238		$p = 0.653$/bf = 0.209		$p = 0.669$/bf = 0.19		$p = 0.792$/bf = 0.287	
r_L								
Mean ± s.d.	0.81 ± 0.61	1.2 ± 1.62	0.7 ± 0.46	1.58 ± 2.04	1.29 ± 0.77	1.17 ± 1.84	1.26 ± 1.91	1.16 ± 1.42
p value/bf	$p = 0.115$/bf = 0.487		**$p = 0.027$**/bf = 1.139		$p = 0.744$/bf = 0.175		$p = 0.838$/bf = 0.283	
β_L								
Mean ± s.d.	−1.05 ± 2.7	−1.15 ± 2.88	−1.51 ± 3.09	−0.88 ± 2.73	−1.07 ± 2.91	−1.17 ± 2.9	−1.39 ± 3.21	−0.97 ± 2.66
p value/bf	$p = 0.872$/bf = 0.234		$p = 0.438$/bf = 0.256		$p = 0.914$/bf = 0.171		$p = 0.615$/bf = 0.311	

ω, choice inverse temperature; *r*, utility curvature; λ, loss aversion; γ, probability distortion; β, ambiguity aversion; ADHD, attention deficit/hyperactivity disorder; bf, Bayesian factor; HC, healthy control participants; OCD, obsessive–compulsive disorder; s.d., standard deviation; TS, Tourette syndrome participants; YGTSS, Yale Global Tic Severity Scale. Bold corresponds to significant effects.

2006). Risk-taking in TS adolescents was associated with maladaptive behaviours in classroom settings but not in other public situations (Brandt, Kerner auch Koerner, & Palmer-Cooper, 2019). Thus, risk-taking and ambiguity evaluation in TS as a group might not be affected in financial decision-making as assessed in this study. However, TS patients might still express a risk-taking attitude in some other domains such as, sensation or novelty seeking.

Involvement of individuals with TS in a risky situation might not depend on impairment of risk and ambiguity valuations *per se* but rather due to other factors that were not measured by our tasks. Indeed, a novel conceptualisation puts forth that risk propensity is rather a situation-specific trait. It is contingent upon the domain in which risks are presented and rely on personality traits (i.e. impulsiveness), thus refuting the idea that decision-making is a consistent pattern (Bran & Vaidis, 2020; Howat-Rodrigues et al., 2018; Peters, Västfjäll, Gärling, & Slovic, 2006). Therefore, involvement in a real-life risky situation might be contingent upon a need for arousal and sensation-seeking characterised by an attraction to novel experiences (Lauriola,

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Table 3. Random forest models' results showing the mean decreasing accuracy, the *p* values (computed following permutations) and the general accuracy

	HC *v.* TS	ADHD *v.* no ADHD	OCD *v.* No OCD	Med. *v.* Unmed.
Risk				
ω	−10.27%/p = 0.927	−5.45%/p = 0.689	**12.65%/p = 0.047**	9.25%/p = 0.129
r	−5.2%/p = 0.676	−3.58%/p = 0.574	**14.36%/p = 0.041**	−4.2%/p = 0.595
λ	−8.96%/p = 0.832	8.52%/p = 0.138	−3.67%/p = 0.598	−6.44%/p = 0.697
γ	−7.92%/p = 0.836	7.19%/p = 0.159	10.36%/p = 0.083	8.17%/p = 0.15
Ambiguity gain				
ω_G	**37.45%/p = 0.002**	−11.29%/p = 0.921	12.71%/p = 0.075	−13.59%/p = 0.97
r_G	8.25%/p = 0.142	−5.05%/p = 0.662	**26.09%/p = 0.009**	−5.55%/p = 0.661
β_G	−2.73%/p = 0.51	−2.11%/p = 0.495	−6.2%/p = 0.722	−4.93%/p = 0.605
Ambiguity loss				
ω_L	−7.93%/p = 0.807	−5.92%/p = 0.683	6.08%/p = 0.168	−10.54%/p = 0.91
r_L	−5.15%/p = 0.691	**18.14%/p = 0.021**	**21.09%/p = 0.011**	−3.02%/p = 0.555
β_L	−10.93%/p = 0.932	−5.19%/p = 0.633	−6.2%/p = 0.741	−14.76%/p = 0.983
General accuracy	58.1%/p = 0.053	51.9%/p = 0.342	**75.9%/p < 0.0001**	38.9%/p = 0.933

ω, choice inverse temperature; r, utility curvature; λ, loss aversion; γ, probability distortion; β, ambiguity aversion; ADHD, attention deficit/hyperactivity disorder; HC, healthy control participants; OCD, obsessive–compulsive disorder; TS, Tourette syndrome participants. Bold corresponds to significant effects.

Table 4. Demographics and clinical characteristics of the three clusters obtained with the hierarchical clustering

		Cluster 1	Cluster 2	Cluster 3	*p* values	bf	Post-hoc
N		32	33	21	–	–	–
Gender (M/F)		24/8	27/6	15/6	0.531	0.199	ns
HC		14	10	8	0.417	0.742	ns
TS		18	23	13	0.249	0.927	ns
TS – ADHD		9	8	6	0.738	0.609	ns
TS – OCD		2	9	3	**0.046**	**3.741**	2 > 1; 2 > 3
TS – Med.		8	7	7	0.956	0.496	ns
Age		28.34 ± 8.39	31.76 ± 10.85	34.33 ± 12.36	0.118	0.573	ns
Education (years)		14.94 ± 2.65	14.57 ± 2.67	12.62 ± 2.15	**0.005**	**7.825**	1 > 3; 2 > 3
BIS-11		62.69 ± 12.63	61.39 ± 8.15	64.71 ± 10.95	0.54	0.169	ns
MIDI		1.22 ± 1.2	1.12 ± 1.41	1.09 ± 1.26	0.924	0.113	ns
YGTSS (/50)		16.44 ± 8.04	15.26 ± 7.04	14 ± 5.54	0.638	0.204	ns
Risk	ω	2.46 ± 1.23	0.23 ± 0.24	0.32 ± 0.32	**<0.0001**	**7.992**	1 > 2; 1 > 3
	r	0.51 ± 0.12	1.03 ± 0.5	1.48 ± 0.67	**<0.0001**	**>1000**	3 > 2 > 1
	λ	1.19 ± 0.36	2.11 ± 0.6	0.67 ± 0.31	**<0.0001**	**>1000**	2 > 1 > 3
	γ	0.62 ± 0.32	0.86 ± 0.38	2.12 ± 0.75	**<0.0001**	**>1000**	3 > 2; 3 > 1
Ambiguity gain	ω_G	2.15 ± 3.08	1.3 ± 2.35	1.14 ± 1.31	0.256	0.313	ns
	r_G	1.07 ± 0.82	1.44 ± 1.74	1.02 ± 1.39	0.44	0.203	ns
	β_G	−0.69 ± 2.26	1.42 ± 3.2	1.13 ± 3.24	**0.01**	**4.73**	2 > 1
Ambiguity loss	ω_L	1.94 ± 1.97	0.93 ± 1.26	1.79 ± 1.72	**0.038**	1.548	1 > 2
	r_L	0.72 ± 0.29	1.65 ± 1.88	0.64 ± 0.99	**0.004**	**10.172**	2 > 1; 2 > 3
	β_L	−0.36 ± 1.94	−1.01 ± 3.14	−2.39 ± 3	**0.033**	1.553	1 > 3

ω, choice inverse temperature; r, utility curvature; λ, loss aversion; γ, probability distortion; β, ambiguity aversion; ADHD, attention deficit/hyperactivity disorder; bf, Bayesian factor; BIS, Barratt Impulsiveness Scale; F, female; HC, healthy control participants; M, male; MIDI, Minnesota Impulse Disorders Interview; OCD, obsessive–compulsive disorder; TS, Tourette syndrome participants; YGTSS, Yale Global Tic Severity Scale. Bold corresponds to significant effects.

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Panno, Levin, & Lejuez, 2014). For example, risky driving behaviours were strongly associated not with an impaired risk-valuation process but rather with sensation-seeking (Dahlen, Martin, Ragan, & Kuhlman, 2005). In addition, it is worth noting that sensation-seeking is related to the mesolimbic and mesocortical dopaminergic pathways, both connecting the ventral tegmental area with respectively the ventral striatum and the prefrontal cortex (Romer, Reyna, & Satterthwaite, 2017). Both of these pathways suggested to be involved with tics expression (Atkinson-Clement et al., 2020; Worbe et al., 2013).

Alternatively, affective dysfunctions in TS might increase one's involvement in real-life risky situations. TS patients' emotional reactivity is significantly increased when processing social stimuli (Rae et al., 2018) with a subsequent reduction in logical decision-making (Eddy & Cavanna, 2013). In fact, emotional processes are said to redirect attentional processes to other characteristics of the situation (Weber, Siebenmorgen, & Weber, 2005), change the subjective valuation of an outcome (Tversky & Kahneman, 1992) and influence choice processes itself (Figner & Weber, 2011). TS patients might therefore express an affective response or arousal in response to a particular outcome but still might be able to ignore this response in favour of a more deliberate valuation of risk (Skagerlund, Forsblad, Slovic, & Västfjäll, 2020).

Unexpectedly, we found no difference between medicated and unmedicated TS. To our knowledge, no studies addressed the effect of aripiprazole – the most frequent medication in our group and one of the most frequently used drugs for TS (Cox & Cavanna, 2021) – on risk-preference behaviours, despite several reports of onset of gambling disorder under treatment with this compound in various neuropsychiatric disorders (Etminan et al., 2017), putatively related to the alteration of risk-taking decision making (Schluter & Hodgins, 2021). However, one study using brexpiprazole, an antipsychotic close by action mechanism to aripiprazole, showed to reduce risk-preference in rodent models (Milienne-Petiot, Geyer, Arnt, & Young, 2017). Thus, further studies are required to elucidate the effects of partial dopaminergic agonists such as aripiprazole on decision-making processes under risk and ambiguity.

Based on this finding and our results, we speculate that tics and medication with aripiprazole had no effect on risk preference and that comorbidities are more likely to influence abnormal decision-making in risk and ambiguity contexts.

ADHD is associated with a lower risk-seeking to avoid losses in a context of ambiguity

Association of ADHD with TS induced a decreased utility curvature in context of ambiguity loss (r_L) in comparison with patients without ADHD. This suggests that individuals with TS and ADHD were more risk-seeking in this context to decrease a potential loss (i.e. they choose the option that could lead to avoid a loss instead of choosing the option with a guaranteed small loss). Many factors such as how rewards were presented, age and even ADHD subtypes influence decision-making process under risk in ADHD free of tics (Groen, Gaastra, Lewis-Evans, & Tucha, 2013). Overall, ADHD was suggested not to be associated with risk-taking as defined by behavioural economy theories (Pollak et al., 2016; Schonberg, Fox, & Poldrack, 2011) but more associated with suboptimal decisions when the outcomes chosen were not beneficial in terms of expected value (Pollak et al., 2016). Indeed, while patients with severe ADHD symptoms tend to adopt riskier attitudes, it was not because of risk-seeking behaviours *per se* but rather because the perception of such behaviours were appealing to them (Pollak et al., 2016; Shoham, Sonuga-Barke, Aloni, Yaniv, & Pollak, 2016). Further studies found that the perception of benefits and not risk perceptions explained associations between ADHD symptoms and risky behaviours (Shoham, Sonuga-Barke, Yaniv, & Pollak, 2020).

OCD is associated with a higher risk-taking to increase gain in a context of ambiguity and a higher risk-aversion under conditions of loss under risk and ambiguity

TS patients with OCD showed more risk-taking behaviour in a context of ambiguity and gain. These patients' groups also showed more aversion to risk and ambiguity in the context of gain and less in the context of ambiguity for a loss. While previous research suggested that OCD was essentially associated with risk-aversion (Sip, Muratore, & Stern, 2016), they also found that patients with OCD have suboptimal decisions, especially in context of gain (George, Sheynin, Gonzalez, Liberzon, & Abelson, 2019) likely due to altered values perception. This is in line with our results since our patients with comorbid OCD showed a propensity to risk-taking in order to increase a reward instead of assuring a lower one. They also showed risk-aversion in context of loss, as it was already described in OCD (Sip, Gonzalez, Taylor, & Stern, 2018).

Limitations

The present study had some limitations. First, we based our hypothesis on several studies which reported an increased propensity for risky behaviour in everyday life related to TS leading to premature deaths (Chen et al., 2019; Fernández de la Cruz & Mataix-Cols, 2020; Mataix-Cols et al., 2021; Meier et al., 2017). However, a population-based design of these studies, that favour a relatively small effect, can explain the discrepancy with the present results. Therefore, even if the sample size used in our study was relatively high and the statistical analyses were accurate, we cannot exclude that we missed an effect of very small amplitude. Second, our task captured the risk and ambiguity valuation processes in financial decision making. However, people with TS might express propensity to risky decisions in other domains such as sensation or novelty seeking. Third, OCD and ADHD comorbidities are phenomenologically at opposite ends of the behavioural spectrum and might be also with regards to the risk taking, which could affect our results. To further unravel the question of contribution of ADHD and OCD on decision under the risk and ambiguity, further studies comparing TS, ADHD and OCD are needed.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0033291722002318

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Conflict of interest. None.

Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

References

Atkinson-Clement, C., Porte, C.-A., de Liege, A., Klein, Y., Delorme, C., Beranger, B., … Worbe, Y. (2020). Impulsive prepotent actions and tics in Tourette disorder underpinned by a common neural network. *Molecular Psychiatry*, *26*, 3548–3557. https://doi.org/10.1038/s41380-020-00890-5.

Badre, D., Doll, B. B., Long, N. M., & Frank, M. J. (2012). Rostrolateral prefrontal cortex and individual differences in uncertainty-driven exploration. *Neuron*, *73*(3), 595–607. https://doi.org/10.1016/j.neuron.2011.12.025.

Betsch, T., Haberstroh, S., Molter, B., & Glöckner, A. (2004). Oops, I did it again – Relapse errors in routinized decision making. *Organizational Behavior and Human Decision Processes*, *93*(1), 62–74. https://doi.org/10.1016/j.obhdp.2003.09.002.

Bran, A., & Vaidis, D. C. (2020). Assessing risk-taking: What to measure and how to measure it. *Journal of Risk Research*, *23*(4), 490–503. https://doi.org/10.1080/13669877.2019.1591489.

Brandt, V., Kerner auch Koerner, J., & Palmer-Cooper, E. (2019). The association of non-obscene socially inappropriate behavior with attention-deficit/hyperactivity disorder symptoms, conduct problems, and risky decision making in a large sample of adolescents. *Frontiers in Psychiatry*, *10*, 660. https://doi.org/10.3389/fpsyt.2019.00660.

Byrnes, J. P., Miller, D. C., & Schafer, W. D. (1999). Gender differences in risk taking: A meta-analysis. *Psychological Bulletin*, *125*(3), 367–383. https://doi.org/10.1037/0033-2909.125.3.367.

Cavedini, P., Gorini, A., & Bellodi, L. (2006). Understanding obsessive–compulsive disorder: Focus on decision making. *Neuropsychology Review*, *16*(1), 3–15. https://doi.org/10.1007/s11065-006-9001-y.

Chen, S.-F., Su, Y.-C., Wang, L.-Y., Hsu, C.-Y., & Shen, Y.-C. (2019). Tourette's syndrome is associated with an increased risk of traumatic brain injury: A nationwide population-based cohort study. *Parkinsonism & Related Disorders*, *63*, 88–93. https://doi.org/10.1016/j.parkreldis.2019.02.033.

Cox, J. H., & Cavanna, A. E. (2021). Aripiprazole for the treatment of Tourette syndrome. *Expert Review of Neurotherapeutics*, *21*(4), 381–391. https://doi.org/10.1080/14737175.2021.1893693.

Crawford, S., Channon, S., & Robertson, M. M. (2005). Tourette's syndrome: Performance on tests of behavioural inhibition, working memory and gambling. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *46*(12), 1327–1336. https://doi.org/10.1111/j.1469-7610.2005.01419.x.

Cutler, A., Cutler, D. R., & Stevens, J. R. (2012). Random forests. In C. Zhang & Y. Ma (Eds.), *Ensemble machine learning* (pp. 157–175). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4419-9326-7_5.

Dahlen, E. R., Martin, R. C., Ragan, K., & Kuhlman, M. M. (2005). Driving anger, sensation seeking, impulsiveness, and boredom proneness in the prediction of unsafe driving. *Accident Analysis & Prevention*, *37*(2), 341–348. https://doi.org/10.1016/j.aap.2004.10.006.

Daunizeau, J., Adam, V., & Rigoux, L. (2014). VBA: A probabilistic treatment of nonlinear models for neurobiological and behavioural data. *PLoS Computational Biology*, *10*(1), e1003441. https://doi.org/10.1371/journal.pcbi.1003441.

Daunizeau, J., Preuschoff, K., Friston, K., & Stephan, K. (2011). Optimizing experimental design for comparing models of brain function. *PLoS Computational Biology*, *7*(11), e1002280. https://doi.org/10.1371/journal.pcbi.1002280.

Dekkers, T. J., Agelink van Rentergem, J. A., Huizenga, H. M., Raber, H., Shoham, R., Popma, A., & Pollak, Y. (2021). Decision-making deficits in ADHD are not related to risk seeking but to suboptimal decision-making: Meta-analytical and novel experimental evidence. *Journal of Attention Disorders*, *25*(4), 486–501. https://doi.org/10.1177/1087054718815572.

Dekkers, T. J., Huizenga, H. M., Popma, A., Bexkens, A., Zadelaar, J. N., & Jansen, B. R. J. (2020). Decision-making deficits in adolescent boys with and without attention-deficit/hyperactivity disorder (ADHD): An experimental assessment of associated mechanisms. *Journal of Abnormal Child Psychology*, *48*(4), 495–510. https://doi.org/10.1007/s10802-019-00613-7.

De Petrillo, F., Paoletti, M., Bellagamba, F., Manzi, G., Paglieri, F., & Addessi, E. (2020). Contextual factors modulate risk preferences in adult humans. *Behavioural Processes*, *176*, 104137. https://doi.org/10.1016/j.beproc.2020.104137.

Eddy, C. M., & Cavanna, A. E. (2013). Altered social cognition in Tourette syndrome: Nature and implications. *Behavioural Neurology*, *27*(1), 15–22. https://doi.org/10.1155/2013/417516.

Ellsberg, D. (1961). Risk, ambiguity, and the savage axioms. *The Quarterly Journal of Economics*, *75*(4), 643. https://doi.org/10.2307/1884324.

Etminan, M., Sodhi, M., Samii, A., Procyshyn, R. M., Guo, M., & Carleton, B. C. (2017). Risk of gambling disorder and impulse control disorder with aripiprazole, pramipexole, and ropinirole: A pharmacoepidemiologic study. *Journal of Clinical Psychopharmacology*, *37*(1), 102–104. https://doi.org/10.1097/JCP.0000000000000634.

Fernández de la Cruz, L., & Mataix-Cols, D. (2020). General health and mortality in Tourette syndrome and chronic tic disorder: A mini-review. *Neuroscience and Biobehavioral Reviews*, *119*, 514–520. https://doi.org/10.1016/j.neubiorev.2020.11.005.

Figner, B., & Weber, E. U. (2011). Who takes risks when and why?: Determinants of risk taking. *Current Directions in Psychological Science*, *20*(4), 211–216. https://doi.org/10.1177/0963721411415790.

Frank, M. C., Piedad, J., Rickards, H., & Cavanna, A. E. (2011). The role of impulse control disorders in Tourette syndrome: An exploratory study. *Journal of the Neurological Sciences*, *310*(1–2), 276–278. https://doi.org/10.1016/j.jns.2011.06.032.

Frank, M. J., Doll, B. B., Oas-Terpstra, J., & Moreno, F. (2009). Prefrontal and striatal dopaminergic genes predict individual differences in exploration and exploitation. *Nature Neuroscience*, *12*(8), 1062–1068. https://doi.org/10.1038/nn.2342.

George, S. A., Sheynin, J., Gonzalez, R., Liberzon, I., & Abelson, J. L. (2019). Diminished value discrimination in obsessive–compulsive disorder: A prospect theory model of decision-making under risk. *Frontiers in Psychiatry*, *10*, 469. https://doi.org/10.3389/fpsyt.2019.00469.

Goudriaan, A. E., Oosterlaan, J., de Beurs, E., & van den Brink, W. (2005). Decision making in pathological gambling: A comparison between pathological gamblers, alcohol dependents, persons with Tourette syndrome, and normal controls. *Cognitive Brain Research*, *23*(1), 137–151. https://doi.org/10.1016/j.cogbrainres.2005.01.017.

Grant, J. E. (2008). *Impulse control disorders: A clinician's guide to understanding and treating behavioral addictions*. New York: W.W. Norton.

Groen, Y., Gaastra, G. F., Lewis-Evans, B., & Tucha, O. (2013). Risky behavior in gambling tasks in individuals with ADHD – A systematic literature review. *PLoS ONE*, *8*(9), e74909. https://doi.org/10.1371/journal.pone.0074909.

Hanoch, Y., Johnson, J. G., & Wilke, A. (2006). Domain specificity in experimental measures and participant recruitment: An application to risk-taking behavior. *Psychological Science*, *17*(4), 300–304. https://doi.org/10.1111/j.1467-9280.2006.01702.x.

Hirschtritt, M. E., Lee, P. C., Pauls, D. L., Dion, Y., Grados, M. A., Illmann, C., … Mathews, C. A. (2015). Lifetime prevalence, age of risk, and genetic relationships of comorbid psychiatric disorders in Tourette syndrome. *JAMA Psychiatry*, *72*(4), 325. https://doi.org/10.1001/jamapsychiatry.2014.2650.

Howat-Rodrigues, A. B. C., Tokumaru, R. S., & Izar, P. (2018). Modeling risk-taking from different measurement instruments. *Paidéia* (*Ribeirão Preto*), *28*(0). https://doi.org/10.1590/1982-4327e2828.

Humphreys, K. L., Tottenham, N., & Lee, S. S. (2018). Risky decision-making in children with and without ADHD: A prospective study. *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *24*(2), 261–276. https://doi.org/10.1080/09297049.2016.1264578.

Huys, Q. J. M., Maia, T. V., & Frank, M. J. (2016). Computational psychiatry as a bridge from neuroscience to clinical applications. *Nature Neuroscience*, *19*(3), 404–413. https://doi.org/10.1038/nn.4238.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263. https://doi.org/10.2307/1914185.

Kim, H. W., Kang, J. I., Namkoong, K., Jhung, K., Ha, R. Y., & Kim, S. J. (2015). Further evidence of a dissociation between decision-making under ambiguity and decision-making under risk in obsessive–compulsive disorder. *Journal of Affective Disorders*, *176*, 118–124. https://doi.org/10.1016/j.jad.2015.01.060.

Knight, F. (1921). *Risk, uncertainty and profit*. Boston, New York: Houghton Mifflin Company.

Kocher, M. G., & Sutter, M. (2006). Time is money – Time pressure, incentives, and the quality of decision-making. *Journal of Economic Behavior & Organization*, *61*(3), 375–392. https://doi.org/10.1016/j.jebo.2004.11.013.

https://doi.org/10.1017/S0033291722002318 Published online by Cambridge University Press

Lauriola, M., Panno, A., Levin, I. P., & Lejuez, C. W. (2014). Individual differences in risky decision making: A meta-analysis of sensation seeking and impulsivity with the balloon analogue risk task: Personality and risky decision making. *Journal of Behavioral Decision Making*, *27*(1), 20–36. https://doi.org/10.1002/bdm.1784.

Leckman, J. F., Riddle, M. A., Hardin, M. T., Ort, S. I., Swartz, K. L., Stevenson, J., & Cohen, D. J. (1989). The Yale global tic severity scale: Initial testing of a clinician-rated scale of tic severity. *Journal of the American Academy of Child & Adolescent Psychiatry*, *28*(4), 566–573. https://doi.org/10.1097/00004583-198907000-00015.

Levy, I., Snell, J., Nelson, A. J., Rustichini, A., & Glimcher, P. W. (2010). Neural representation of subjective value under risk and ambiguity. *Journal of Neurophysiology*, *103*(2), 1036–1047. https://doi.org/10.1152/jn.00853.2009.

Maia, T. V., & Conceição, V. A. (2017). The roles of phasic and tonic dopamine in tic learning and expression. *Biological Psychiatry*, *82*(6), 401–412. https://doi.org/10.1016/j.biopsych.2017.05.025.

Maia, T. V., & Conceição, V. A. (2018). Dopaminergic disturbances in Tourette syndrome: An integrative account. *Biological Psychiatry*, *84*(5), 332–344. https://doi.org/10.1016/j.biopsych.2018.02.1172.

Maimon, O., & Rokach, L. (Eds.). (2010). *Data mining and knowledge discovery handbook*. Boston, MA: Springer US. https://doi.org/10.1007/978-0-387-09823-4.

Martino, D., Ganos, C., & Pringsheim, T. M. (2017). Tourette Syndrome and Chronic Tic Disorders: The Clinical Spectrum Beyond Tic. *International review of neurobiology*, *134*, 1461–1490. https://doi.org/10.1016/bs.irn.2017.05.006.

Mataix-Cols, D., Brander, G., Chang, Z., Larsson, H., D'Onofrio, B. M., Lichtenstein, P., … Fernández de la Cruz, L. (2021). Serious transport accidents in Tourette syndrome or chronic tic disorder. *Movement Disorders*, *36*(1), 188–195. https://doi.org/10.1002/mds.28301.

Matlab (2018). *9.7.0.1190202* (*R2019b*). Natick, Massachusetts: The MathWorks Inc.

Meier, S. M., Dalsgaard, S., Mortensen, P. B., Leckman, J. F., & Plessen, K. J. (2017). Mortality risk in a nationwide cohort of individuals with tic disorders and with Tourette syndrome: Mortality risk in tic disorders/Tourette syndrome. *Movement Disorders*, *32*(4), 605–609. https://doi.org/10.1002/mds.26939.

Milienne-Petiot, M., Geyer, M. A., Arnt, J., & Young, J. W. (2017). Brexpiprazole reduces hyperactivity, impulsivity, and risk-preference behavior in mice with dopamine transporter knockdown – A model of mania. *Psychopharmacology*, *234*(6), 1017–1028. https://doi.org/10.1007/s00213-017-4543-7.

Montague, P. R., Dolan, R. J., Friston, K. J., & Dayan, P. (2012). Computational psychiatry. *Trends in Cognitive Sciences*, *16*(1), 72–80. https://doi.org/10.1016/j.tics.2011.11.018.

Murphy, S. E., Longhitano, C., Ayres, R. E., Cowen, P. J., Harmer, C. J., & Rogers, R. D. (2009). The role of serotonin in nonnormative risky choice: The effects of tryptophan supplements on the 'reflection effect' in healthy adult volunteers. *Journal of Cognitive Neuroscience*, *21*(9), 1709–1719. https://doi.org/10.1162/jocn.2009.21122.

Nielsen, A. N., Gratton, C., Church, J. A., Dosenbach, N. U. F., Black, K. J., Petersen, S. E., … Greene, D. J. (2020). Atypical functional connectivity in Tourette syndrome differs between children and adults. *Biological Psychiatry*, *87*(2), 164–173. https://doi.org/10.1016/j.biopsych.2019.06.021.

Norman, L. J., Carlisi, C. O., Christakou, A., Murphy, C. M., Chantiluke, K., Giampietro, V., … Rubia, K. (2018). Frontostriatal dysfunction during decision making in attention-deficit/hyperactivity disorder and obsessive–compulsive disorder. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *3*(8), 694–703. https://doi.org/10.1016/j.bpsc.2018.03.009.

Palminteri, S., & Chevallier, C. (2018). Can we infer inter-individual differences in risk-taking from behavioral tasks? *Frontiers in Psychology*, *9*, 2307. https://doi.org/10.3389/fpsyg.2018.02307.

Palminteri, S., Kilford, E. J., Coricelli, G., & Blakemore, S.-J. (2016). The computational development of reinforcement learning during adolescence. *PLOS Computational Biology*, *12*(6), e1004953. https://doi.org/10.1371/journal.pcbi.1004953.

Palminteri, S., Lebreton, M., Worbe, Y., Grabli, D., Hartmann, A., & Pessiglione, M. (2009). Pharmacological modulation of subliminal learning in Parkinson's and Tourette's syndromes. *Proceedings of the National Academy of Sciences*, *106*(45), 19179–19184. https://doi.org/10.1073/pnas.0904035106.

Palminteri, S., Lebreton, M., Worbe, Y., Hartmann, A., Lehéricy, S., Vidailhet, M., … Pessiglione, M. (2011). Dopamine-dependent reinforcement of motor skill learning: Evidence from Gilles de la Tourette syndrome. *Brain*, *134*(8), 2287–2301. https://doi.org/10.1093/brain/awr147.

Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the Barratt Impulsiveness Scale. *Journal of Clinical Psychology*, *51*(6), 768–774.

Peters, E., Västfjäll, D., Gärling, T., & Slovic, P. (2006). Affect and decision making: A 'hot' topic. *Journal of Behavioral Decision Making*, *19*(2), 79–85. https://doi.org/10.1002/bdm.528.

Pollak, Y., Oz, A., Neventsal, O., Rabi, O., Kitrossky, L., & Maeir, A. (2016). Do adolescents with attention-deficit/hyperactivity disorder show risk seeking? Disentangling probabilistic decision making by equalizing the favorability of alternatives. *Journal of Abnormal Psychology*, *125*(3), 387–398. https://doi.org/10.1037/abn0000140.

Rae, C. L., Polyanska, L., Gould van Praag, C. D., Parkinson, J., Bouyagoub, S., Nagai, Y., … Critchley, H. D. (2018). Face perception enhances insula and motor network reactivity in Tourette syndrome. *Brain*, *141*(11), 3249–3261. https://doi.org/10.1093/brain/awy254.

R Core Team. (2013). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/.

Riba, J., Krämer, U. M., Heldmann, M., Richter, S., & Münte, T. F. (2008). Dopamine agonist increases risk taking but blunts reward-related brain activity. *PLoS ONE*, *3*(6), e2479. https://doi.org/10.1371/journal.pone.0002479.

Romer, D., Reyna, V. F., & Satterthwaite, T. D. (2017). Beyond stereotypes of adolescent risk taking: Placing the adolescent brain in developmental context. *Developmental Cognitive Neuroscience*, *27*, 19–34. https://doi.org/10.1016/j.dcn.2017.07.007.

Schluter, M. G., & Hodgins, D. C. (2021). Reward-related decision-making in current and past disordered gambling: Implications for impulsive choice and risk preference in the maintenance of gambling disorder. *Frontiers in Behavioral Neuroscience*, *15*, 758329. https://doi.org/10.3389/fnbeh.2021.758329.

Schonberg, T., Fox, C. R., & Poldrack, R. A. (2011). Mind the gap: Bridging economic and naturalistic risk-taking with cognitive neuroscience. *Trends in Cognitive Sciences*, *15*(1), 11–19. https://doi.org/10.1016/j.tics.2010.10.002.

Sheehan, D. V., Lecrubier, Y., Sheehan, K. H., Amorim, P., Janavs, J., Weiller, E., … Dunbar, G. C. (1998). The Mini-International Neuropsychiatric Interview (M.I.N.I.): The development and validation of a structured diagnostic psychiatric interview for DSM-IV and ICD-10. *The Journal of Clinical Psychiatry*, *59*(Suppl 20), 22–33, quiz 34–57.

Shoham, R., Sonuga-Barke, E., Yaniv, I., & Pollak, Y. (2020). What drives risky behavior in ADHD: Insensitivity to its risk or fascination with its potential benefits? *Journal of Attention Disorders*, *25*(14), 1988–2002. https://doi.org/10.1177/1087054720950820.

Shoham, R., Sonuga-Barke, E. J. S., Aloni, H., Yaniv, I., & Pollak, Y. (2016). ADHD-associated risk taking is linked to exaggerated views of the benefits of positive outcomes. *Scientific Reports*, *6*(1), 34833. https://doi.org/10.1038/srep34833.

Sip, K. E., Gonzalez, R., Taylor, S. F., & Stern, E. R. (2018). Increased loss aversion in unmedicated patients with obsessive–compulsive disorder. *Frontiers in Psychiatry*, *8*, 309. https://doi.org/10.3389/fpsyt.2017.00309.

Sip, K. E., Muratore, A. F., & Stern, E. R. (2016). Effects of context on risk taking and decision times in obsessive–compulsive disorder. *Journal of Psychiatric Research*, *75*, 82–90. https://doi.org/10.1016/j.jpsychires.2015.12.002.

Skagerlund, K., Forsblad, M., Slovic, P., & Västfjäll, D. (2020). The affect heuristic and risk perception – Stability across elicitation methods and individual cognitive abilities. *Frontiers in Psychology*, *11*, 970. https://doi.org/10.3389/fpsyg.2020.00970.

Starcke, K., Tuschen-Caffier, B., Markowitsch, H.-J., & Brand, M. (2009). Skin conductance responses during decisions in ambiguous and risky situations in obsessive–compulsive disorder. *Cognitive Neuropsychiatry*, *14*(3), 199–216. https://doi.org/10.1080/13546800902996831.

https://doi.org/10.1017/S0033291722002318 Published online by Cambridge University Press

Starcke, K., Tuschen-Caffier, B., Markowitsch, H. J., & Brand, M. (2010). Dissociation of decisions in ambiguous and risky situations in obsessive–compulsive disorder. *Psychiatry Research*, *175*(1–2), 114–120. https://doi.org/10.1016/j.psychres.2008.10.022.

Tin Kam Ho. (1995). Random decision forests. Proceedings of 3rd International Conference on Document Analysis and Recognition, 1, 278–282. Montreal, Que., Canada: IEEE Comput. Soc. Press. https://doi.org/10.1109/ICDAR.1995.598994.

Tobler, P. N., & Weber, E. U. (2014). Valuation for risky and uncertain choices. In Paul W. Glimcher and Ernst Fehr (eds.), *Neuroeconomics* (pp. 149–172). Elsevier. https://doi.org/10.1016/B978-0-12-416008-8.00009-7.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, *5*(4), 297–323. https://doi.org/10.1007/BF00122574.

Tymula, A., Rosenberg Belmaker, L. A., Ruderman, L., Glimcher, P. W., & Levy, I. (2013). Like cognitive function, decision making across the life span shows profound age-related changes. *Proceedings of the National Academy of Sciences*, *110*(42), 17143–17148. https://doi.org/10.1073/pnas.1309909110.

Virtanen, S., Sidorchuk, A., Fernández de la Cruz, L., Brander, G., Lichtenstein, P., Latvala, A., & Mataix-Cols, D. (2021). Association of Tourette syndrome and chronic tic disorder with subsequent risk of alcohol- or drug-related disorders, criminal convictions, and death: A population-based family study. *Biological Psychiatry*, *89*(4), 407–414. https://doi.org/10.1016/j.biopsych.2020.09.014.

Wang, Y., Feng, T., & Keller, L. R. (2013). A further exploration of the uncertainty effect. *Journal of Risk and Uncertainty*, *47*(3), 291–310. https://doi.org/10.1007/s11166-013-9180-x.

Weber, E. U., Siebenmorgen, N., & Weber, M. (2005). Communicating asset risk: How name recognition and the format of historic volatility information affect risk perception and investment decisions. *Risk Analysis*, *25*(3), 597–609. https://doi.org/10.1111/j.1539-6924.2005.00627.x.

Worbe, Y., Marrakchi-Kacem, L., Lecomte, S., Valabregue, R., Poupon, F., Guevara, P., … Poupon, C. (2015). Altered structural connectivity of cortico-striato-pallido-thalamic networks in Gilles de la Tourette syndrome. *Brain*, *138*(2), 472–482. https://doi.org/10.1093/brain/awu311.

Worbe, Y., Sgambato-Faure, V., Epinat, J., Chaigneau, M., Tandé, D., François, C., … Tremblay, L. (2013). Towards a primate model of Gilles de la Tourette syndrome: Anatomo-behavioural correlation of disorders induced by striatal dysfunction. *Cortex*, *49*(4), 1126–1140. https://doi.org/10.1016/j.cortex.2012.08.020.

Yoon, D. Y., Gause, C. D., Leckman, J. F., & Singer, H. S. (2007). Frontal dopaminergic abnormality in Tourette syndrome: A postmortem analysis. *Journal of the Neurological Sciences*, *255*(1–2), 50–56. https://doi.org/10.1016/j.jns.2007.01.069.

Zhang, L., Dong, Y., Ji, Y., Zhu, C., Yu, F., Ma, H., … Wang, K. (2015). Dissociation of decision making under ambiguity and decision making under risk: A neurocognitive endophenotype candidate for obsessive–compulsive disorder. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *57*, 60–68. https://doi.org/10.1016/j.pnpbp.2014.09.005.

https://doi.org/10.1017/S0033291722002318 Published online by Cambridge University Press