Subthalamic stimulation modulates self-estimation of patients with Parkinson's disease and induces risk-seeking behaviour

Esther Florin,1,2,* Désirée Müller,1,* Johannes Pfeifer,3 Michael T. Barbe,1,4 Gereon R. Fink1,4 and Lars Timmermann1

1 Department of Neurology, University Hospital Cologne, Germany
2 McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University, Canada
3 Department of Economics, University of Mannheim, Germany
4 Institute of Neuroscience and Medicine (INM-3), Cognitive Neuroscience, Research Centre Jülich, Germany

*These authors contributed equally to this work.

Correspondence to: Dr. Esther Florin, Department of Neurology, University Hospital Cologne, Kerpener Str. 62, 50937 Köln, Germany
E-mail: Esther.Florin@uk-koeln.de

Correspondence may also be addressed to: Prof. Dr. Lars Timmermann, E-mail: Lars.Timmermann@uk-koeln.de

Patients with Parkinson’s disease with deep brain stimulation in the subthalamic nucleus postoperatively often display higher impulsivity and therefore may experience difficulties in social interactions. Here, we examined social interactions of patients with Parkinson’s disease with and without deep brain stimulation in the subthalamic nucleus in competitive situations. We hypothesized altered self-estimation and risk-seeking behaviour in this patient group induced by deep brain stimulation in the subthalamic nucleus. To test the hypothesis, an experimental setting was used in which participants performed a calculation task and chose their preferred compensation. Based on their actual calculation performance, more patients with Parkinson’s disease with deep brain stimulation chose a competitive tournament compensation. Assuming rational behaviour, this self-selection pattern reflects increased risk tolerance. Since patients who performed in the lowest quartile chose the tournament option, the data suggest that deep brain stimulation in the subthalamic nucleus results in a loss of the correct reference frame against which patients with Parkinson’s disease evaluate their performance. The stimulation-induced combination of overestimation of their own performance, increased risk-taking, and preference for competitive environments despite poor performance is likely to impact considerably on the patients’ social and work life.

Keywords: basal ganglia; decision making; social interaction

Abbreviations: BDI = Beck Depression Inventory; DBS = deep brain stimulation; STN = subthalamic nucleus; UPDRS = Unified Parkinson’s Disease Rating Scale

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Introduction

Even though overconfidence is a trait found in many humans, inappropriate self-referencing can lead to adverse consequences at the work place or other social environments (Svenson, 1981; Baumann et al., 1991). In patients with Parkinson's disease, deep brain stimulation (DBS) of the subthalamic nucleus (STN) can positively affect motor symptoms and quality of life (Deuschl et al., 2006; Lozano and Lipsman, 2013). This phenomenon is likely to be due to the stimulation-induced modulation of pathological oscillatory activity in the basal-ganglia-thalamo-cortical system (Timmermann and Fink, 2011). Despite these positive effects on motor deficits, patients with Parkinson's disease treated with STN-DBS often struggle at their workplace or in their interactions with social peers (Houeto et al., 2006; Schupbach et al., 2006; Troster, 2008). One explanation for this observation is that STN-DBS influences the impulsivity of patients because of the STN's involvement in decision making (van den Wildenberg et al., 2006; Frank et al., 2007; Cavanagh et al., 2011): DBS patients tend to prefer high-risk options and are—deliberately or not—overconfident. How the higher impulsivity due to STN stimulation relates to self-estimation and risk-seeking behaviour and how it may affect the social life of these patients remains to be elucidated.

The commonly used paradigms in behavioural neuroscience that assess risk-taking typically neglect social context. This makes it impossible to analyse whether subjects correctly self-reference themselves in social situations. To investigate this issue, we analysed pathological changes in risk-taking behaviour of patients with Parkinson's disease with STN-DBS in a social context. We tested the hypothesis that STN-DBS induces a change in self-referencing and competitive behaviour using an experimental set-up from the hypothesis that STN-DBS induces a change in self-referencing Parkinson's disease with STN-DBS in a social context. We tested possible to analyse whether subjects correctly self-reference them-

This experimental design allowed us to analyse whether STN-DBS changes the social behaviour of patients with Parkinson's disease in competitive situations and to further analyse the STN's influence in decision-making. In particular, it allowed for (i) controlling of other factors that may influence competitive behaviour, such as the objective performance of the patients; (ii) deriving the optimal competitive behaviour; and thereby; (iii) drawing conclusions about the economic consequences of this behaviour; and (iv) evaluating the changes in self-assessment of DBS patients. Accordingly, we tested the following hypotheses: based on the reports of higher impulsivity and more risky behaviour due to stimulation of the STN (Frank et al., 2007; Troster, 2008), we expected STN-DBS patients to select themselves into developed by Niederle and Vesterlund (2007) (Fig. 1). The experimental design consisted of four conditions. In the first three conditions, each person in a group of four was asked to add as many sets of five integers from 1 to 99 as possible in 5 min. This simple mathematical addition task was chosen because no differences have been reported in the mathematical abilities of non-demented patients with Parkinson's disease compared with healthy controls (Zamarian et al., 2006). The social interaction context came into play with a different pay-off structure for each condition. In the first condition, subjects received a piece-rate compensation, while in the second condition the compensation followed a tournament competition scheme, where only the best-performing subject was compensated. The first two conditions involved no choice of compensation scheme. In contrast, before calculating in the third condition, participants were asked to decide according to which payment scheme they wanted to be rewarded. Finally, for the fourth condition, subjects only decided retrospectively according to which payment scheme they would like to be rewarded for Condition 1, without having to calculate again. After these four tasks, participants guessed their own rank relative to the other participants in Conditions 1 and 2.

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the competitive situation inefficiently often. The normative benchmark for efficiency that we apply is the expected utility framework of von Neumann and Morgenstern (1944) with risk neutrality, which—loosely speaking—assumes that individuals act rationally to maximize the expected value of the pay-off. In principle, we would have to account for different degrees of risk aversion, i.e. underlying preferences regarding risk. However, for the relatively small stakes involved in our experiment, agents with normal degrees of risk tolerance can be treated as approximately risk-neutral (Rabin, 2000).

As the stimulation of the STN is thought to ‘release the brakes’ (Frank et al., 2007), a greater impulsivity due to STN-DBS may entice patients into not well-deliberated action: they may spontaneously attracted by the potentially higher pay-off without properly considering the odds. This hypothesis was tested using the third condition, where the patients selected the compensation scheme. Furthermore, also based on reports of higher impulsivity (Frank et al., 2007; Troster, 2008; Cavanagh et al., 2011), we expected DBS patients to systematically overestimate their own performance. This hypothesis was tested by self-assessment of the participants.

Overall, this experiment analysed the ability of patients with Parkinson’s disease to correctly self-reference their own achievements and to gauge their competitive behaviour. As both are necessary traits in social and professional life, they may yield an indication as to why STN-DBS patients may have trouble in everyday life social situations (Houeto et al., 2006; Schüpbach et al., 2006; Troster, 2008). To the best of our knowledge, we are the first to present evidence that modulation of basal-ganglia-cortex circuits by STN-DBS leads to overly competitive behaviour that may be economically harmful, mostly for the patients themselves.

Materials and methods

In total, 68 male patients with Parkinson’s disease participated in the experiment. They were all diagnosed with Parkinson’s disease according to the UK Brain Bank criteria (Hughes et al., 1992). Nine patients were excluded after they performed the experiment, because they had a Beck Depression Inventory (BDI) (Beck et al., 1961) >20 or only solved, at most, one of the addition tasks correctly. This left 29 patients with Parkinson’s disease without DBS (referred to as ‘non-DBS’) and 30 DBS patients implanted in the dorsolateral STN (Voges et al., 2002), which was confirmed by matching presurgical MRIs with postoperative, stereotactic x-rays. In addition, 23 male age-matched control subjects performed the experiment. Of the latter group we excluded four subjects after the experiment, because they had a previous neurological disease or a BDI >20 (Supplementary material). Thus, 19 age-matched control subjects were included in the subsequent analysis. In order to maintain a group size of four participants in each trial, we asked five additional subjects to fill in for ‘no-shows’, but who did not match our inclusion criteria. All participants were male to avoid putative gender differences (Niederle and Vesterlund, 2007).

Age did not significantly differ between the groups (age, DBS: 57.9 ± 9.4 years; non-DBS: 57.4 ± 9.2 years; controls: 56.5 ± 7.2 years). As the implantation of DBS electrodes is commonly only made after several years of Parkinson’s disease and we wanted to match the patients according to their current Unified Parkinson’s Disease Rating Scale (UPDRS) Part III score, disease duration for the DBS patients was significantly longer than for the patients with Parkinson’s disease without DBS (DBS: 11.2 ± 6.5 years; non-DBS: 5.3 ± 3.7 years, P < 0.001). All subjects gave written informed consent to participate in the experiment. The study was approved by the local ethics committee (study no. 2459) and conducted in accordance with the Declaration of Helsinki.

Paradigm

For each experimental session a group of four subjects was formed. The patients with Parkinson’s disease were measured separately from the control subjects and a patient group consisted of two DBS patients and two patients with Parkinson’s disease without DBS (non-DBS). The groups were formed in this way to avoid healthy control subjects playing against patients and might thus infer that they faced weaker opponents (or the other way around). The DBS patients were on their current medication and stimulation parameters, while the patients with Parkinson’s disease without DBS were only on their current medication. The participants were not informed about the intended comparison between DBS patients with Parkinson’s disease and patients with Parkinson’s disease without DBS and they were not informed about the health state of the other participants. In particular, they did not know whether the other patients had DBS or not. Participants were kept separate to avoid communication before and during the experiment.

All instructions were presented to the participants on a computer screen to avoid any bias that might occur with oral instructions. Instructions were the same for all participants. For the experiment, the subjects were asked to perform a mathematical addition task that consisted of adding up sets of five randomly drawn numbers in the range from 1 to 99 for 5 min. They had paper and a pen at hand, so that they could either add the numbers on the paper or mentally. On the computer screen of each participant their own number of correct answers was displayed. The participants were not informed about the number of correct answers of the other participants.

The addition task was repeated three times under different experimental conditions (Niederle and Vesterlund, 2007) (Fig. 1). To incentivize the subjects, they were paid according to their performance in one randomly chosen condition. In addition, subjects received a show-up fee (5€), a participation fee (5€), and were reimbursed for their travel expenses.

Condition 1

Piece-rate compensation: participants were asked to calculate as many sums as possible in 5 min. Each correct answer was rewarded with 50 cents.

Condition 2

Tournament compensation: participants were asked to perform the same addition task, but only the best of the four players received 2€ per correct answer.

Condition 3

Before calculating, participants individually decided whether they wanted to be paid according to the piece-rate or tournament compensation. If a participant chose the tournament option, he was paid 2€ per correct answer, if he performed better than the other participants in the previous round (Condition 2). The evaluation in comparison with the previous round was made, because people potentially perform better under the tournament incentive. Thus, a comparison with those who have chosen the piece-rate compensation in the third condition would be invalid. Furthermore, the decision to enter the
treatment was not influenced by strategic considerations whether the other participants would enter the tournament or not.

Condition 4
In this condition the participants retrospectively chose (after being reminded of their own performance in Condition 1) how they wanted to be paid (piece-rate or tournament compensation) for their correctly solved addition tasks in Condition 1.

After the experiment was completed, subjects filled out the BDI, the Barratt Impulsiveness Scale, and answered questions concerning their professional, educational, and social background. The UPDRS III was then determined by a MDS-certified rater (M.T.B.). After completion of the experiment, subjects were paid their earnings and informed of their actual performance.

Statistical analysis
Statistical analysis was performed using gretl and IBM SPSS Statistics Ver. 19. For the comparison of the number of correctly solved addition tasks between the three subject groups t-tests were used, which were type I error-corrected (Benjamini and Hochberg, 1995). For the analysis of the rank guesses, an ordered probit regression was conducted. The inter-group comparisons of percentages were made with a two-sample test between two binomial populations and also type I error-corrected (Benjamini and Hochberg, 1995).

To compute the conditional winning probabilities, we drew $n = 10000$ randomly sampled groups of four people. The patient treatment groups each consisted of two DBS patients and two patients with Parkinson’s disease without DBS (non-DBS), and the control treatment groups each consisted of four control subjects. For each combination of correctly solved addition tasks $x_i$ and patient type $j$ (DBS, non-DBS, controls), we computed the share of times this number would have been sufficient to win the tournament, i.e. $PR(x_i \geq x...j)$, where $x...j$ denotes the correct answers of the other people in the group.

The optimal rank guess was calculated conditional on a combination of correctly solved addition tasks $x_i$ and patient type $j$ using a bootstrap approach as above. For each combination, we computed the optimal rank as the mode of the simulated rank distribution in these random samples. The optimal rank was compared with the guessed rank using a $\chi^2$ test.

Results
In all three conditions the control subjects solved significantly more addition tasks correctly than the STN-DBS patients (Table 1). For patients with Parkinson’s disease neither the medication differed significantly between the two groups (total L-DOPA equivalent dosage, DBS: $529.0 \pm 338.6$; non-DBS: $661.0 \pm 528.6$; L-DOPA equivalent dosage agonists only, DBS: $239.8 \pm 162.1$; non-DBS: $329.5 \pm 446.5$) nor did the UPDRS III [DBS: $20.4 \pm 8.9$; non-DBS: $25.8 \pm 7.8$ ($P = 0.09$)], indicating that both groups were not differently affected by the Parkinson’s disease motor symptoms. Motor symptoms, as assessed by the UPDRS III, had a slightly negative effect on the number of correctly solved addition tasks for STN-DBS patients in Condition 3 and patients with Parkinson’s disease without DBS in Condition 2 (DBS: $P = 0.27$, $\rho = -0.03$; non-DBS: $P = 0.03$, $\rho = -0.06$; Condition 3, DBS: $P = 0.01$, $\rho = -0.07$; non-DBS: $P = 0.26$, $\rho = -0.03$). Furthermore, no significant difference was found between the three groups for the BDI, Barratt Impulsiveness Scale, and the number of school years (BDI, DBS: $7.1 \pm 5.0$; non-DBS: $8.2 \pm 5.6$; controls: $4.7 \pm 4.8$; Barratt Impulsiveness Scale, DBS: $56.3 \pm 7.9$; non-DBS: $59.2 \pm 6.8$; controls: $59.4 \pm 10.2$; Education, DBS: $14.6 \pm 3.7$; non-DBS: $14.2 \pm 3.6$; controls: $14.7 \pm 2.8$).

In order to determine whether STN-DBS patients actually chose the tournament option more often, we computed the participants’ ex-post optimal strategy and compared it with their actual strategies. That is, for any actualized realized performance level, we first determined the probability of winning the tournament in Condition 2 for DBS patients, patients with Parkinson’s disease without DBS, and controls (Fig. 2A). Given that the tournament pays four times as much per correct answer as the piece-rate, i.e. $p_{	ext{tournament}} = 4 \cdot p_{	ext{piece rate}}$, a risk-neutral subject with $x$ correct answers would be indifferent between both payment schemes, if his/her winning probability is $25\%$, i.e. if

$$E(x \cdot p_{\text{piece rate}}) = 0.5 \cdot x = 0.25 \cdot 2 \cdot x = E(x \cdot p_{\text{tournament}})$$

where $E$ denotes the mathematical expectation operator. Risk neutrality means that a subject only cares about the expected pay-off, i.e. he/she is indifferent between a safe pay-off $x$ and a risky gamble that has the same expected value. Therefore, risk-neutral subjects should optimally choose the tournament, if their expected probability of winning is $>25\%$. Under the assumption of risk neutrality and that the performance in Condition 3 is exactly like the one in Condition 2, $33.3\%$ of the DBS patients, $51.7\%$ of the patients with Parkinson’s disease without DBS, and $42.1\%$ of the control subjects should have chosen the tournament condition in Condition 3. However, $60\%$ of the DBS patients actually chose the tournament condition, i.e. $26.7\%$ made a choice only a risk-seeking person would make. In contrast, for the patients with Parkinson’s disease without DBS, $0\%$ made such a risky choice. This results in a significant ‘self-selection gap’ of $26.7\%$ between the two patient groups ($P = 0.004$). The gap was also significant between control subjects and DBS patients ($P = 0.044$), but not between control subjects and patients with Parkinson’s disease without DBS ($P = 0.221$). The tournament entry decision was not significantly influenced by the subjects’ Barratt Impulsiveness Score (Patton et al., 1995), the age, the disease duration, the total L-DOPA equivalent dosage or the dopamine-agonist’s L-DOPA equivalent dosage. For the DBS patients, the decision to enter the tournament was also not influenced by the number of months since the operation. This was determined with a probit regression with the tournament entry decision as a dependent variable. These data are compatible with our first hypothesis that not patients with Parkinson’s disease in general, but specifically patients with Parkinson’s disease with STN-DBS choose the

| Table 1 Mean and standard deviation of correctly solved addition tasks |
|--------------------------|--------------------------|--------------------------|
|                         | Condition 1              | Condition 2              | Condition 3              |
| DBS                     | $5.17 \pm 3.06$          | $5.27 \pm 2.66$          | $5.50 \pm 2.43$          |
| Non-DBS                 | $6.52 \pm 4.39$          | $7.48 \pm 5.09$          | $8.17 \pm 4.66$          |
| Controls                | $9.74 \pm 3.48$          | $10.74 \pm 3.71$         | $10.74 \pm 4.03$         |
treatment option irrationally often. In the following, we analyse which factors might explain this difference in self-selection due to stimulation of the STN.

**Does past or future performance predict tournament entry?**

Figure 2B shows the fraction of subjects choosing the tournament option, conditional on their performance quartile in Condition 2. The monotonically increasing pattern for the control subjects and patients with Parkinson’s disease without DBS indicates that both groups partly base their tournament entry decision on their past performance. In contrast, STN-DBS patients in the lowest quartile had the highest proportion (significantly) of all patients entering the tournament. Overall, eight out of 10 DBS patients and three out of nine patients with Parkinson’s disease without DBS from the lowest quartile entered the tournament (binomial test: \( z = 2.06; \) \( P = 0.020 \)).

As past performance may be a poor indicator for future results and rational agents should be forward-looking, it is conceivable that STN-DBS patients correctly anticipate an increase in their performance in Condition 3. However, only control subjects correctly solved significantly more mathematical addition tasks in Condition 3 (Mann-Whitney-U: \( P = 0.045 \)), if they decided for the tournament option (Table 1), while STN-DBS patients did not improve in Condition 3.

**Is the entry decision determined by beliefs on relative performance?**

While performance should be an important factor for the tournament entry decision, an equally important determinant from a subjective point of view could be the beliefs of one’s own relative ranking. Therefore, after completion of all four conditions and being reminded of their own correctly solved tasks, subjects were asked to guess their rank for Conditions 1 and 2. When comparing this guessed tournament rank (Condition 2) with the optimal rank guess, they differed significantly for the DBS patients (\( \chi^2_{df = 3} = 8.59; \) \( P = 0.033 \); exact Fisher-test: \( P = 0.032 \)), indicating that DBS patients estimated themselves to perform better than they actually did. In contrast, for patients with Parkinson’s disease without DBS and controls, no significant difference was found (Supplementary material).

Ordered probit regressions of the guessed tournament rank on the number of correctly solved problems in Task 2 and the difference between the number of correctly solved problems in Tasks 1 and 2 showed that past Condition 2 performance had a significant influence for DBS, patients with Parkinson’s disease without DBS, and control subjects (DBS, regression coefficient \( \gamma: -0.28, P = 0.003 \); non-DBS: \( \gamma: -0.10, P = 0.032 \); controls: \( \gamma: -0.35, P = 0.007 \)). Thus, the more addition tasks were solved correctly, the more likely it was that subjects assigned themselves a high rank. Additional robustness checks revealed no significant influence of other control variables e.g. the number of school years or the BDI.

**Difference in compensation choice due to performance difference**

A third possible explanation why STN-DBS patients suboptimally often selected the tournament option could be that—*ceteris paribus*—their general performance was unexpectedly worse than that of the patients with Parkinson’s disease without DBS. STN-DBS patients might have considered their performance to be normal and thereby lost track of the correct reference group for their choice. Since STN-DBS is more frequently applied in later stages of the disease, we wanted to control for all external factors not relating directly to the modulation of neuronal activity in the STN. To this aim, we performed a counterfactual experiment where we matched both groups in such a way that the performance between both groups did not differ significantly. Therefore we excluded all patients whose performance was within the lowest quartile of the DBS patients and above the fourth quartile for the patients with Parkinson’s disease without DBS. This left us with 20 patients in the group with Parkinson’s disease without DBS and 23 patients in the DBS group, where the two new groups now exhibited no significant performance differences.
For these groups we calculated the optimal choice in Condition 3 based on the performance in Condition 2. Even after controlling for performance, 13% of the DBS patients made a risk-seeking choice, while 0% of the patients with Parkinson’s disease without DBS did so (P = 0.047). Comparing the percentage difference between the baseline experiment and this performance-matched group, 14% fewer of the DBS patients suboptimally selected the tournament option. Therefore, the loss of the correct reference frame may account for up to half of the observed effect. This indicates that the stimulation of the subthalamic nucleus and not the cognitive performance or the disease stage was largely responsible for the difference in behaviour.

Excluding the role of non-tournament-specific factors

A fourth potential explanation as to why STN-DBS patients may have self-selected into the tournament compensation scheme for Condition 3 more frequently than patients with Parkinson’s disease without DBS could be that they derived utility from engaging in a tournament, i.e. simply preferred to perform in a tournament situation. To control for this potential effect, patients had to retrospectively choose in Condition 4 whether they wanted to be compensated according to the tournament or the piece-rate scheme for their performance in Condition 1. As subjects did not perform again, all effects that were directly influenced by the actual presence of the tournament situation and the mathematical addition task were excluded.

We calculated the winning probabilities for correctly solved addition tasks based on the results from Condition 1. This computation revealed that 30.0% of the DBS patients (number of correct answers x_i ≥ 7), 48.3% of the patients with Parkinson’s disease without DBS (x_i ≥ 8), and 36.8% of the controls subjects (x_i ≥ 10) should enter the tournament. Compared to these ex-post optimal decisions, 58.6% of patients with Parkinson’s disease without DBS actually chose the tournament option in Condition 4, as did 60.0% of the DBS patients, and 42.1% of controls subjects. While the discrepancy was largest for the DBS patients with 30%, their group as a whole did not differ significantly from the patients with Parkinson’s disease without DBS and the control subjects. However, when splitting up the groups according to their performance in Condition 1 (Fig. 3), significantly more DBS than non-DBS patients in the lowest quartile submitted their piece-rate result to the tournament payment scheme (binomial test: z = 2.18; P = 0.015).

Economic consequences

If the winning probability conditional on performance is >25%, subjects forgo a higher expected pay-off by not selecting the tournament (under-entry). Similarly, if the winning probability is <25%, selecting the tournament (over-entry) is associated with an expected loss of money compared with choosing the piece-rate compensation. Overall, the costs of under-entry into the tournament are higher, because the performance distribution has more mass in its right tail. This is also the case in our results for the patients with Parkinson’s disease without DBS in Condition 3 (Table 2). Here, two subjects had decided not to enter the tournament, although they performed well above average, so that the total costs of just these two subjects amounted to 50€. Overall the total costs as well as just the costs of under-entry were highest for the patients with Parkinson’s disease without DBS. In contrast, the STN-DBS patients had the highest costs of over-entry. These results underpin the potentially important economic consequences of STN-DBS patients overestimating their own performance.

Discussion

In this paper we compared the willingness to compete of patients with Parkinson’s disease with and without STN-DBS. Both patient groups were on dopaminergic treatment during the experimental conditions. The groups did not differ significantly in the basic clinical parameters, emphasizing that differences between the two groups are likely due to the modulation of basal-ganglia-cortex-loops by STN-DBS. The experimental set-up included a social context that required the participants to rank their own performance relative to the other participants’ performance. We expected STN-DBS patients to overestimate their own performance, thereby leading to an increased willingness to compete. Indeed, when asked in the third condition of the experiment, if they would rather be paid according to the piece-rate scheme or according to the tournament situation, significantly more DBS than non-DBS or control subjects made a risky choice, i.e. decided for the tournament option where, according to their previous performance, the piece-rate scheme would have been the better choice. Overall 26% of the DBS patients made this risk-seeking choice.

We then tried to differentiate the factors that might have influenced the subjects’ decision for the tournament option. Interestingly, in particular DBS patients whose performance was within the lowest quartile in the second condition chose to enter the tournament in the third condition. This suggests that these DBS patients engage in an extremely risky gambling behaviour. However, this behaviour may be partly driven by an inability to correctly evaluate their probability of winning and thus to rank their own performance correctly. DBS patients significantly overestimated their own ranking for the second condition, which was not the case for the two other groups (non-DBS and controls). Note that overconfidence may be evolutionary beneficial/stable in...
regular populations as long as benefits from contested resources are sufficiently large compared with the cost of competition (Johnson and Fowler, 2011). However, while this result is able to explain some degree of overconfidence in the regular population due to its evolutionary benefits, it cannot explain a pathological increase in overconfidence in subjects suffering from Parkinson’s disease compared with the normal population since this trait is not hereditary. Furthermore, the core finding of our study is that STN-DBS in patients with Parkinson’s disease leads to substantial difficulties with respect to estimating their actual rank and therefore to establish a correct reference frame.

While most of our conclusions are conditional on performance in Condition 2, we can exclude the possibility that we were using the wrong benchmark to compute the objective winning probabilities. It was not the case that participants correctly anticipated an improvement in their performance in Condition 3 compared with Condition 2. Neither the tournament nor the piece-rate subgroup of DBS patients were able to improve their performance.

Finally, letting participants retrospectively decide whether they wanted to be compensated according to the piece-rate or the tournament option for their Condition 1 performance allowed us to disentangle whether the difference of the tournament choice in Condition 3 was due to tournament-specific factors or not. The discrepancy between the number of subjects who opted to enter the tournament and those who actually did was still largest for STN-DBS patients, albeit not significantly. The DBS patients accordingly found. However, in the case of the STN-DBS patients, their performance was worse than that of the other two groups (non-DBS, controls). Thus, their strategy of choosing the tournament condition is irrational. While this could, at least in principle, be due to a higher risk tolerance, their preference for a smaller chance of a higher pay-off compared with a secure profit requires an exaggerated degree of risk-seeking given their low success probability. Looking at the total costs for over-entry, DBS patients accordingly had the highest costs, whereas for the case of under-entry the non-DBS patient group had the highest total costs. The data suggest that the strategy between the two patient groups differed. While the patients with Parkinson’s disease without DBS tended to choose the secure piece-rate and thereby mainly accepted costs due to under-entry, the stimulation of the STN led to a significantly altered behaviour: STN-DBS patients chose the riskier option of tournament entry and therefore had higher costs than the other groups due to over-entry.

### Decision-making

Participants twice decided between a high-risk/high-reward and a low-risk/low-reward scheme. Previous studies investigated the decision behaviour of patients with Parkinson’s disease using the Iowa Gambling Task and the Game of Dice-Task (Brand et al., 2004; Mimura et al., 2006; Pagonabarraga et al., 2007; Kobayakawa et al., 2008; Delazer et al., 2009; Euteneuer et al., 2009; Ibarretxe-Bilbao et al., 2009). For both paradigms deficits were found in patients with Parkinson’s disease, which were related to the involvement of the STN in decision-making. These paradigms, however, do not test for the influence of social interactions as well as self-referencing, which are important components of decision-making in real life. This is a novel and important

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<tr>
<th>Table 2 Economic costs for all participants</th>
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<td><strong>Condition 2 performance</strong></td>
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<td>Performance entry threshold</td>
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<td>Average cost over-entry</td>
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<td>Total expected cost of over- and under-entry</td>
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The first two rows display the minimum number of correctly solved addition tasks required for tournament entry to be optimal and the number of participants who scored above this value. The next rows provide the costs for those participants who should have entered but did not (under-entry) and those who should not enter, but nevertheless did so (over-entry).
aspect, and our study thus extends previous studies on decision-making. Using a simple two-choice gambling task, it has been shown that in drug-naïve patients with Parkinson’s disease the neural response to gamble outcomes is compromised (van der Vegt et al., 2013). This study also did not consider the social context and cannot explain the difference between non-DBS and DBS patients, who should be similarly affected by both Parkinson’s disease and dopaminergic medication.

Neuronal basis of risk-taking

Previous work in healthy subjects demonstrated that inhibiting the right dorsolateral prefrontal cortex leads to higher risk-taking (Knoch et al., 2006). DBS electrodes in Parkinson’s disease usually target the motor part of the STN. Nevertheless, changes in glucose metabolism of the associative and limbic basal-ganglia loops due to STN-DBS were detected with PET (Le Jeune et al., 2010). In particular, hypometabolism in the right dorsolateral prefrontal cortex was detected, which might explain the higher risk-seeking of the DBS patients. Additionally, a hypometabolism in the insula was detected by Le Jeune et al. (2010). Studies analysing risk-taking behaviour in healthy subjects found that insula activation scales with the expected risk, i.e. greater insula activation leads to safer choices in healthy subjects (Kuhnen and Knutson, 2005; Preuschoff et al., 2006, 2008; Mohr et al., 2010). Thus, the higher risk-taking observed in our STN-DBS patients might also be related to remote DBS effects exerted upon the insula, whose activity has been shown to be affected by DBS (Kahan et al., 2012). Moreover, a tractography study has shown pathways connecting the STN with the insula (Lambert et al., 2012). The underlying reason for the influence of STN-DBS on the limbic basal-ganglia loop might be the spread of current from the original motor target area to more ventrally located parts of the STN (Mallet et al., 2007; Volkmann et al., 2010). These more ventrally located parts are associated with the limbic loop influencing impulsive behaviour, mood and decision-making. It may be that DBS makes up, at least to a certain extent, for the loss of dopamine in patients with Parkinson’s disease. Therefore, it may have similar effects to dopaminergic medication in healthy individuals, which is known to influence impulsivity and the evaluation of work load (Pine et al., 2010; Boehler et al., 2011). Dopamine agonists are linked to a higher impulsivity (Weintraub et al., 2006; Bödi et al., 2009). In our study most patients also received dopamine agonists. However, there was no significant difference in the medication with dopamine agonists between the non-DBS and DBS patients and the agonist dosage did not have an influence on the tournament decision. Therefore, the medication cannot explain the difference we found.

Another potential explanation for the increased risk-taking might be the direct involvement of the STN in decision-making. Zaghloul et al. (2012) found a correlation between the firing in the STN and a decision conflict. The high frequency stimulation in the STN of the DBS patients might, however, disenable the STN cells to modulate during the decision process such that a well-deliberated decision might no longer be possible. Therefore, we speculate that the observed effect of higher risk-taking might be a result of stimulating the STN and thereby eliminating its ability to control the decision process.

Monetary incentives

The participants in the study were paid afterwards according to their performance in one of the four conditions. They received 50 cents for a correct answer in the case of the piece-rate compensation and 2€ in the case of the tournament compensation. This compensation scheme was used in order to give the subjects a real incentive to perform in this study. The incentives for the subjects in the present study are the same as in the original study by Niederle and Vesterlund (2007) in which these incentives were high enough to detect significant differences in the tournament decisions of healthy subjects. Moreover the incentives in the present study are comparable to those used in other behavioural economics studies (Houser et al., 2008).

Theoretical results suggest that for reasonable stakes people are approximately risk-neutral and their behaviour should only change for large stakes (Rabin, 2000). Additionally, a study in behavioural economics tested the influence of the actual monetary reward (Holt and Laury, 2005). In this study the amount offered to the subjects led to decreased risk-taking by the subjects once the real—and not hypothetical—stakes were significantly increased. Using such stakes is, however, impractical for several reasons. Firstly, it quickly becomes prohibitively expensive. Secondly, economic theory suggests that it is not the absolute stakes that are relevant, but their value relative to total wealth. As it is difficult to assess the wealth of subjects and as this may depend on the duration of the disease, raising the stakes to levels where the risk-attitude matters, would introduce an additional confound. In contrast, for the stakes used in the present study, we would expect subjects to behave approximately risk-neutral, regardless of the individual wealth level and, importantly, subject group. Therefore, even though it is conceivable that risk-taking was higher in our study than it would have been in the case of higher monetary rewards, this bias would be the same for all tested subject groups. Moreover, the lower stakes should introduce a bias to not finding different risk-taking behaviour as both risk-aversion and risk-seeking people should behave approximately risk-neutral. Thus, our results may be overly conservative but the rewards offered to our subjects produced a realistic scenario.

Mathematical addition task

There are certainly individual differences in the ability to add numbers. However, these differences are independent of whether a person has Parkinson’s disease, DBS or is healthy (Zamarian et al., 2006). Therefore, these differences level out in the present study design. Furthermore, one is usually aware of one’s own ability to solve an addition task, which gives one a reference frame for the subsequent estimation of the own rank and the decision whether to enter the tournament or not.

An unexpected result was that STN-DBS patients solved a significantly lower number of addition tasks correctly than the control subjects. A previous study reported no difference in calculation performance in early stages of Parkinson’s disease (Zamarian et al., 2006). Therefore, our results may be overly conservative but the rewards offered to our subjects produced a realistic scenario.
Self-estimation due to STN-DBS in Parkinson’s disease

et al., 2006). Zamarian et al. (2006) found, however, a difference in working memory and complex mental calculation. All participants in our study were able to use paper and pen, so that differential working memory capacity cannot account for this difference. Rather, patients with Parkinson’s disease without DBS in our study had a disease duration comparable to the study by Zamarian et al. (2006), while DBS patients in our study had a longer disease duration than the patients with Parkinson’s disease in that study. Unfortunately, this is difficult to avoid because the invasive STN-DBS treatment is, to date, only used in later stages of Parkinson’s disease. Thus, even though the motor performance in both patient groups was the same as evidenced by the UPDRS III and although our patients were younger, cognitive decline may have further progressed in our STN-DBS patients either due to DBS (Rinehardt et al., 2010; Smeding et al., 2011) or longer disease duration. Unfortunately, we cannot directly disentangle whether this effect is due to DBS or frontal atrophy, because we did not obtain MRIs from DBS patients due to safety considerations at our centre, which does not perform MRIs in DBS patients without clear clinical indication. However, frontal atrophy is an exclusion criterion for the implantation of DBS electrodes at our centre. Therefore at least at the time of operation, DBS patients did not show frontal atrophy. Consistent with this, preoperative comprehensive neuropsychological testing did not reveal executive dysfunction. Furthermore, when using disease duration measured in years as a control variable for the decision to enter the tournament, we did not find a significant effect. Moreover, there was no significant correlation between the disease duration and the number of correctly solved problems. Therefore, disease duration neither had a significant influence on the performance nor on the decision to enter the tournament. Taken together, our results suggest that frontal atrophy does not constitute a significant confound for our findings. Still, in order to control for the decreased mathematical problem-solving ability of the DBS patients, we matched performance of both groups. Even after this matching, 13% more DBS patients chose the tournament option in Condition 3 than would have been expected based upon optimal behaviour.

Self-selection into deep brain stimulation

We found significant differences in the risk-taking behaviour of DBS and non-DBS patients after controlling for potentially confounding factors like performance or UPDRS III, suggesting that STN-DBS might alter risk-taking behaviour. One could argue then that this difference might reflect a self-selection bias: as DBS surgery is an inherently risky invasive procedure, it could be the case that patients with Parkinson’s disease who tend towards risk-taking behaviour opt for this treatment more often than those who do not. In other words, a patient’s decision to opt for a potentially risky procedure like the implantation of cerebral stimulation electrodes could per se reflect a more ‘risk-taking’ personality than that of a patient who decided against taking the risk of undergoing DBS implantation. At least in principle, it is not possible to control for this putative confound. However, since the completion of the current study, seven of the patients with Parkinson’s disease without DBS choose to opt for DBS treatment and have been implanted with DBS electrodes at our centre. An additional seven patients have also chosen DBS implantation and will either be implanted in the near future or did not meet our criteria for implantation. The fact that 50% of patients with Parkinson’s disease without DBS have already opted for DBS suggests that the discussed putative self-selection bias is small. Moreover the treatment with DBS was covered by the German mandatory universal health insurance, we can at least exclude a selection bias due to only patients with high risk-high reward jobs being able to afford the treatment.

Previous studies used a so-called ON/OFF design to control for this potential bias. In this design, DBS patients perform the task once with the DBS on and once with it turned off. We did not choose an ON/OFF design, because the patients with DBS turned off would have been a lot worse in their motor skills. This could potentially have reduced the number of correct answers in the given time limit purely due to difficulties in entering the results. The second reason was that we did not want the patients to know beforehand that this study was a comparison between DBS and non-DBS so that they might have inferred that they were deliberately set at a disadvantage, leading to an experimenter bias. Thirdly, we wanted to create as realistic a social context as possible. Letting patients with DBS on play against patients with DBS off would have produced a natural bias. Lastly, doing the paradigm twice, once with DBS on and once with DBS off might have changed the strategy of the patients and a potential learning effect might have confounded the results. In summary, we cannot completely rule out a putative self-selection bias reflecting an a priori higher risk-taking personality of the DBS patients. Nevertheless, our results suggest that the loss of the correct reference frame as we observe it in this study, is not best explained by this putative confound.

Conclusion

Overall, our results suggest that STN-DBS patients are impaired in relating their own performance to a correct reference frame and that they tend to overestimate their own performance. Retrospectively, this effect is less pronounced, which may indicate that DBS patients in addition prefer to perform in competitive situations. This finding suggests that STN-DBS influences pathways involved in evaluating risk. The combination of self-overestimation and high risk-taking are two potential factors that are likely to influence the patients’ social and work life. Given the inherent tournament characteristics of many real-life work situations, this might lead to serious adverse (financial) consequences. Therefore, our results extend previous studies on decision-making in DBS patients by a social context. Our data might thus help to explain the social difficulties that some STN-DBS patients suffer.

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Supplementary material
Supplementary material is available at Brain online.

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