FEATURED ARTICLE

Pathological Gambling in Parkinson's Disease: Subthalamic Oscillations During Economics Decisions

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ABSTRACT: Pathological gambling develops in up to 8% of patients with Parkinson's disease. Although the pathophysiology of gambling remains unclear, several findings argue for a dysfunction in the basal ganglia circuits. To clarify the role of the subthalamic nucleus in pathological gambling, we studied its activity during economics decisions. We analyzed local field potentials recorded from deep brain stimulation electrodes in the subthalamic nucleus while parkinsonian patients with (n = 8) and without (n = 9) pathological gambling engaged in an economics decision-making task comprising conflictual trials (involving possible risk-taking) and non conflictual trials. In all parkinsonian patients, subthalamic low frequencies (2–12 Hz) increased during economics decisions. Whereas, in patients without gambling, low-frequency oscillations exhibited a similar pattern during conflictual and non conflictual stimuli, in those with gambling, low-frequency activity increased significantly more during conflictual than during non conflictual stimuli. The specific low-frequency oscillatory pattern recorded in patients with Parkinson's disease who gamble could reflect a subthalamic dysfunction that makes their decisional threshold highly sensitive to risky options. When parkinsonian patients process stimuli related to an economics task, low-frequency subthalamic activity increases. This task-related change suggests that the cognitive-affective system that drives economics decisional processes includes the subthalamic nucleus. The specific subthalamic neuronal activity during conflictual decisions in patients with pathological gambling supports the idea that the subthalamic nucleus is involved in behavioral strategies and in the pathophysiology of gambling. © 2013 International Parkinson and Movement Disorder Society

Key Words: decision-making; local field potentials; Parkinson's disease; pathological gambling; subthalamic nucleus

Additional Supporting Information may be found in the online version of this article.

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Funding agencies: The study was supported by an ERANET-Neuron Grant, Physiological Mechanisms of Deep Brain Stimulation (PhysiolDBS) (Neuron-48-013) from Fondazione Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS) Ca' Granda Ospedale Maggiore Policlinico (Milan, Italy), Universitá degli Studi di Milano (Italy), Ministero della Sanitá (Italy), Ministero dell'Universitá, e della Ricerca Scientifica e Tecnologica (Italy).

Relevant conflicts of interest/financial disclosures: Nothing to report.
Full financial disclosures and author roles may be found in the online version of this article.

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Received: 13 April 2012; **Revised:** 22 January 2013; **Accepted:** 1 February 2013
Published online 2 April 2013 in Wiley Online Library (wileyonlinelibrary.com).
DOI: 10.1002/mds.25427

Decision-making involves a complex neural network connecting cortical and subcortical brain areas. The subthalamic nucleus (STN) has a well known role in motor control.[1–3] Numerous observations suggest that the STN is also involved in emotional and cognitive processing.[4–8] In patients with Parkinson's disease (PD), stimulus-induced changes in STN activity can affect decision-making[9–15] and the detection of conflict between responses.[9,10,16–18]

From 3.4% to 8% of patients with PD manifest pathological gambling (PG), an impulse-control disorder characterized by an uncontrollable and excessive risk propensity (according to the *Diagnostic and Statistical Manual of Mental Disorders, Revised Fourth Edition* [DSM IV TR][19]) and often associated with dopaminergic therapy.[20] Neuropsychological studies indicate that PG is characterized by deficits in cognitive inhibition, complex executive functions, attention, and decision-making.[21] Although the pathophysiology of PG remains unclear, several data argue for a dysfunction in the basal ganglia circuits involving the STN. Accordingly, STN deep brain stimulation (DBS) variably can reduce,[22–24] induce,[24] or worsen[11,14,24] PG.

In the past 15 years, local field potentials (LFPs) electrophysiologically recorded through DBS electrodes from the STN in patients with PD have provided a wealth of physiological information on the human basal ganglia and on the pathophysiology of PD.[3,25–28] To our knowledge, no studies have assessed STN neuronal activity in relation to economics decision processing in PD patients or have investigated whether economics decisions induce a distinct electrophysiological pattern in patients with PG.

In this study, we aimed to clarify the role of the STN in economics decision-making in PD. We also studied the possible changes in STN LFPs related to PG and to the patients' economics strategies. To do so, we investigated whether and how STN LFPs change in parkinsonian patients with and without PG engaged in an economics decision-making task.

Patients and Methods

Patients

Seventeen patients with PD who had electrodes for DBS implanted bilaterally into the STN were selected and divided into 2 groups. The first group comprised 9 patients without PG (3 men; age, 61 ± 6.07 years; disease duration, 10 ± 2.77 years; education, 8 ± 4.28 years). The second group comprised 8 patients with PG related to dopaminergic therapy (6 men; age, 57 ± 11.90 years; disease duration, 11 ± 4.86 years; education 9 ± 2.75 years) who met criteria for PG according to the DSM IV TR.[19] PG was ascertained during a clinical interview with the patient and caregiver and was evaluated with the South Oaks Gambling Screen (SOGS).[29] Patients in the second group manifested PG at the time of the study.

To exclude cognitive, mood, and anxiety disorders, all patients underwent a cognitive and psychological evaluation, including the Mini-Mental State Examination (MMSE),[30] the Hospital Anxiety and Depression Scale (HADS),[31] subjective mood evaluations with visual analog scales (VAS),[32] the State-Trait Anxiety Inventory (STAI),[33,34] and subjective anxiety evaluation with VAS.[32] Patients' presurgery clinical status was evaluated using the motor part of the Unified Parkinson's Disease Rating Scale (UPDRS III) before (OFF) and after (ON) they received antiparkinsonian therapy. Patients' clinical details are summarized in Table 1.

Because tremor, rigidity, and akinesia or bradykinesia could have interfered with task execution and to magnify gambling-related LFP oscillations,[35,36] all of the patients we studied were receiving chronic medication and were studied in the "ON medication" experimental condition, referred to the effective individual daily dose at the time when study data were collected (Table 1). Some patients with PG had dopamine agonist treatment withdrawn, also for ethical reasons, because of severe gambling; others took a small dopamine agonist dose, because levodopa (L-dopa) alone provided poor motor function control. All patients gave their written informed consent. The study was approved by the Institutional Review Board and conformed with the Declaration of Helsinki (for surgical details, see Supporting Materials and Methods).

Economics Task

Participants were studied 4 days after surgery. A computerized economics decision-making task was used. Six different stimulus pairs were presented (AB, AC, AD, BC, BD, and CD), and participants had to choose 1 of the 2 stimuli (Fig. 1A). A monetary feedback followed the choice to indicate whether it was advantageous or not (Fig. 1B). Stimulus pairs were distinguished in 2 task conditions: (1) non conflictual trials between 2 letters with the same probability of winning and (2) conflictual trials between 2 letters with a different probability of winning (involving possible risk-taking) (Fig. 1C). The task was designed to reward non risky choices, so that the larger the number of non risky choices, the higher was the amount of money earned (see Supporting Materials and Methods).

Clinical and Behavioral Analyses

To exclude clinical differences between patients with and without PG, a 1-way repeated-measures analysis of variance (ANOVA) with between-factor *PG* was run for the variables age, disease duration, UPDRS III

TABLE 1. Patients' clinical details

Patients	Age, y	Sex[a]	Disease duration, y	Behavioral disorders	UPDRS-III scores ON/OFF drugs before surgery	L-Dopa equivalent dose before surgery, mg/d[b]	NMDA antagonist dose before surgery, mg/d[c]	Dopamine agonist before surgery	Enzymatic inhibitor before surgery[d]
1	49	Man	8	PG	12/46	1400	—	—	Carbidopa, entacapone, rasagilin
2	41	Man	15	PG	9/34	550	—	—	Carbidopa, entacapone
3	67	Woman	14	—	21/34	2275	—	Pramipexole	Carbidopa
4	63	Man	15	PG	16/50	2030	—	Ropinirole	Carbidopa, entacapone
5	66	Man	18	PG	16/46	800	200	—	Carbidopa
6	63	Woman	9	—	10/27	257.5	200	Pramipexole	Carbidopa, entacapone
7	61	Man	25	—	28/63	1232.5	200	Ropinirole	Carbidopa, entacapone
8	60	Woman	14	—	11/37	1550	—	Pramipexole	Carbidopa
9	70	Woman	6	—	15/33	1300	200	Pramipexole	Carbidopa, entacapone
10	52	Man	4	PG	17/34	200	—	—	Entacapone
11	60	Woman	6	PG	12/31	940	—	Ropinirole	Carbidopa, entacapone
12	64	Woman	11	—	10/26	910	—	Pramipexole	Carbidopa, entacapone
13	78	Woman	10	PG	21/48	1200	200	—	Carbidopa
14	47	Man	10	—	13/31	820	—	—	Carbidopa
15	61	Woman	11	—	11/28	1100	300	Pramipexole	Carbidopa, entacapone
16	64	Man	9	—	6/15	1280	—	Pramipexole	Carbidopa, entacapone
17	48	Man	10	PG	15/52	900	—	—	Carbidopa

[a]A summary of patients details is provided for 9 men and 8 women.
[b]The preoperative L-dopa equivalent dose expressed in mg/day represents the sum of L-dopa and dopamine agonist. Dopamine agonist equivalent doses were calculated with the following equivalences: 100 mg L-dopa = 2 mg apomorphine =1 mg pergolide = 1.5–2.0 mg cabergoline =1 mg pramipexole = 10 mg bromocriptine =5 mg ropinirole.
[c]The NMDA antagonist dose is the amantadine dose (mg/day).
[d]The enzyme inhibitor involved in degrading L-dopa (enzymatic inhibitor): catechol-O-methyl transferase inhibitor (COMTI), monoamine oxidase inhibitor (MAOI), dopa decarboxylase inhibitor (DDCI).
UPDRS-III, the motor part of the Unified Parkinson's Disease Rating Scale; ON/OFF, after/before receipt of antiparkinsonian therapy; L-dopa, levodopa; NMDA, N-methyl-D-aspartate; PG, pathological gambling.

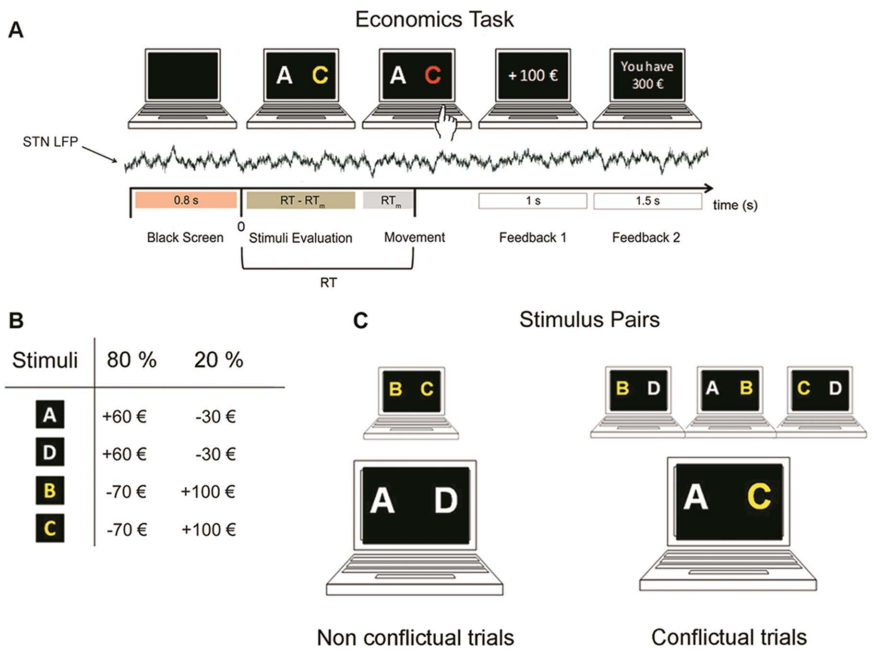

FIG. 1. The experimental protocol and economics task are illustrated. (**A**) Subthalamic nucleus (STN) local field potentials (LFPs) were recorded while patients engaged in the economics task. For the analyses, 3 phases were identified in each trial: the "black screen" phase (0.8 seconds before stimulus pairs were presented); the "movement" phase, corresponding to the mean reaction time for the motor task (RT_m) (see Supporting Materials and Methods) before key pressing; and the "stimuli evaluation" phase, corresponding to the reaction time (RT) for the economics task, leaving the movement phase out of the analysis ($RT - RT_m$). Note that in the example the patient chooses the C letter. (**B**) The monetary feedback and the probability of winning or losing money for each stimulus are illustrated. The letters A and D indicate the non risky choices; the letters B and C the risky choices. (**C**) The economics task, comprised of non conflictual and conflictual trials, is illustrated. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

ON and OFF, and L-dopa equivalent dose. The correlation between presence or absence of PG and sex was assessed with a Pearson's χ^2 test. A 1-way ANOVA with between-factor *PG* was run to test the scores obtained on the SOGS and on cognitive and psychological scales.

Reaction times (RTs) obtained during the economics task were calculated as the mean of conflictual and non conflictual trials for each patient. Differences between RTs in conflictual and non conflictual trials were tested in a 2-way ANOVA with *task condition* as a within factor (conflictual, non conflictual) and with *PG* as a between factor (presence, absence).

An index of risk was calculated as the sum of trials with a risky choice expressed as a percentage of the total number of trials. Pearson's linear correlation coefficient was calculated between the index of risk and the amount of money earned. From the index of risk, we distinguished patients who used a non risky strategy (efficient to maximize gains), patients who used a risky strategy (inefficient to maximize gains), and patients who randomly selected stimuli. Patients who obtained an index higher than 50% + 3% (mean + standard deviation) were considered patients with a risky strategy, and those who obtained an index lower than 50%–3% were considered patients with a non risky strategy. An index within the interval 50% ± 3% corresponded to a random strategy. The correlation between the presence or absence of PG and strategy (risky and non risky) was assessed with a Pearson's χ^2 test.

LFP Recording and Analysis

During the economics task, STN LFPs were bilaterally captured from contact pairs 0 and 2 on the DBS macroelectrodes. LFPs were preamplified, filtered (band pass, 2–512 Hz), differentially amplified (100,000 times), and digitized with a 1024 Hz sampling rate and 12 bit quantization with 5 V range through the Galileo BE Light EEG amplification system (EBNeuro Spa, Florence, Italy). All data were analyzed off-line with MatLab software (version 7.10; The MathWorks, Natick, MA, USA). LFPs were first analyzed in the time-frequency domain to identify the main activated frequency band during economics decisions in patients with and without PG for use in further analyses.[5] The Hilbert transform was applied to obtain the mean frequency band power in different task conditions (conflictual and non conflictual) during the black screen and stimuli evaluation phases that identified each trial (Fig. 1A) (for details, see Supporting Materials and Methods).

To exclude the possible influence of task condition and PG, a preliminary 2-way repeated-measures ANOVA was run to compare STN LFP power during the black screen phase with the within-factor *task condition* (conflictual, non conflictual) and the between-factor *PG* (presence, absence). A global 3-way repeated-measures ANOVA with first within-factor *phase* (black screen, stimuli evaluation) and second within-factor *task condition* and between-factor *PG* was run to assess the global significance of the interactions between these factors. To evaluate the possible influence of patient strategy on STN LFP power, according to behavioral data, for further analysis, we considered only patients who used a clear strategy (risky or non risky) and excluded patients who randomly selected stimuli. A global 3-way ANOVA was repeated with between-factor *strategy* (risky, non risky).

Results

Clinical and Behavioral Results

There were no significant differences between patients with and without PG for age, disease duration, UPDRS III ON and OFF, or L-dopa equivalent dose (ANOVA). Pearson's χ^2 test detected no correlation between sex and PG ($\chi^2 = 3.45$; $P > 0.05$). No difference was observed between the 2 groups in cognitive or psychological assessment scores except for SOGS scores, which differed between patients with and without PG (mean ± standard deviation: 6.80 ± 1.18 vs 0.18 ± 0.37, respectively; $P < 0.0005$).

A 2-way ANOVA used to test RTs revealed no differences either in the factors *task condition* ($F[1,15] = 0.64$; $P > 0.05$) and *PG* ($F[1,15] = 2.58$; $P > 0.05$) or in the interaction between the 2 factors ($F[1,15] = 0.17$; $P > 0.05$). The index of risk ranged widely in the 17 PD patients assessed in this study (from 24.5% to 76.4%). A significant inverse correlation was observed between the index of risk and the amount of money earned ($R^2 = 0.601$; $P < 0.005$). Values for the index of risk indicated that 6 patients used a risky strategy and 6 patients used a non risky strategy. The index for 5 patients came within the interval 50% ± 3%, thus implying a randomized response strategy (ie, patients did not collaborate in the experiment). Pearson's χ^2 test indicated that all patients who used a risky strategy had PG, whereas those who used a non risky strategy did not ($\chi^2 = 12$; $P < 0.05$) (Fig. 2).

STN LFP Power Modulation during Economics Decision-Making

Power in the time-frequency plot showed that, in patients without PG, the principal power modulations during economics decisions involved the low-frequency band (from 2.50 ± 1.97 Hz to 12.50 ± 1.97 Hz) (Fig. 3A). Also in patients with PG, the main power modulations during the economics task involved the low-frequency band (from 2.00 ± 0.63 Hz to 12.00 ± 0.63 Hz) (Fig. 3B).

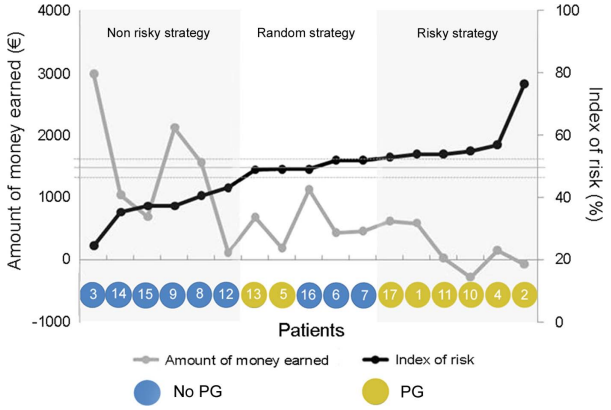

FIG. 2. Behavioral results are illustrated as the index of risk and the sum of money earned for parkinsonian patients with and without pathological gambling (PG) (n = 17). The horizontal lines represent the range (50% ± 3%) of the index of risk: patients who obtained an index of risk in this interval used a random strategy, whereas patients who adopted a non risky strategy are highlighted in the gray area on the left, and patients who adopted a risky strategy are highlighted in the gray area on the right. Each patient is indicated by a number according to Table 1. Note that the gray area on the left includes 6 patients without PG, and the gray area on the right includes 6 patients with PG. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

When we applied the Hilbert transform, a preliminary 2-way ANOVA indicated that *task condition*, *PG*, and the interaction between the 2 factors had no influence on low-frequency power during the black screen phase ($F[1,32] = 0.06$; $P > 0.05$; $F[1,32] = 0.72$; $P > 0.05$; and $F[1,32] = 0.35$; $P > 0.05$, respectively). Therefore, in further analyses, we considered the black screen phase as baseline. A global 3-way ANOVA revealed that the factor *phase* was significant: STN LFP low-frequency power during the stimuli evaluation phase was significantly higher than during the black screen phase for patients with and without PG and under all task conditions ($F[1,32] = 50.80$; $P < 0.05$) (Fig. 3C).

STN LFP Power Modulation in Relation to Patient Strategy

We evaluated data from 12 patients: 6 who used a risky strategy and 6 who used a non risky strategy. The 5 patients who used a randomized strategy were excluded from further analysis. A global 3-way ANOVA revealed higher low-frequency power while patients evaluated economics stimuli than while they observed the black screen ($F[1,22] = 49.70$; $P < 0.05$) and also revealed a significant interaction between the factors *strategy* and *task condition* ($F[1,22] = 5.12$; $P < 0.05$) and between the factors *strategy*, *phase*, and *task condition* ($F[1,22] = 5.11$; $P < 0.05$).

Post hoc 2-way ANOVA for patients who used a non risky strategy demonstrated that low-frequency power increased significantly more while patients evaluated economics stimuli than while they observed the black screen ($F[1,11] = 21.08$; $P < 0.05$), but no differences were demonstrated either in the factor *task condition* ($F[1,11] = 1.82$; $P > 0.05$) or in the interaction between the 2 factors ($F[1,11] = 1.82$; $P > 0.05$). Similarly, post hoc 2-way ANOVA for patients who used a risky strategy demonstrated that the factor *phase* was significant ($F[1,11] = 43.93$; $P < 0.05$) and, conversely, demonstrated a difference both in the factor *task condition* ($F[1,11] = 4.86$; $P < 0.05$) and in the interaction between *phase* and *task condition* ($F[1,11] = 4.84$; $P < 0.05$). The percentage changes in low-frequency power were significantly higher when patients evaluated conflictual stimulus pairs than when they evaluated non conflictual pairs (post hoc: 40.25% ± 15.63% vs 22.79% ± 25.98%, respectively; $F[1,11] = 4.84$; $P < 0.05$) (Fig. 4).

Discussion

In all of the patients with PD we studied, gamblers and non gamblers, LFP low frequencies recorded from the STN were synchronized during economics decisions. In patients who used a risky strategy, STN LFP low frequencies synchronized differently during conflictual and non conflictual decisions. All of these patients had PG. Our findings support the idea that, in patients with PD, decision-making in matters related to economics reflects specific STN activity related to individual behavioral strategies.

STN Low-Frequency Involvement in Economics Decision-Making

The STN low-frequency synchronization we recorded during economics decisions in patients with PD reflects a non motor, cognitive STN activation. This new finding, which was obtained by assessing oscillatory LFP activity recorded from the STN during an economics decision-making task, agrees with previous LFP studies showing that the STN is involved in processing various cognitive and emotional stimuli.[37] In a study investigating STN responses to emotionally arousing pictures, Kuhn et al. (2005) and Brucke et al. (2007) observed that emotional processing modulated 8 Hz to 12 Hz LFP activity, demonstrating affective activation in the STN.[4,7] In our previous research, we also observed that low frequencies (5–13 Hz) underwent specific modulation during moral sentence evaluation.[5] In another study, STN LFPs recorded during a choice conflict task showed low-frequency power enhancement.[9] Our electrophysiological results suggests that, like cognitive processing, the organizational strategy for elaborating economics stimuli also requires STN activity in the low-frequency band.

Because dopaminergic stimulation enhances STN low-frequency oscillations,[28,38] the low-frequency power increase we observed during economics

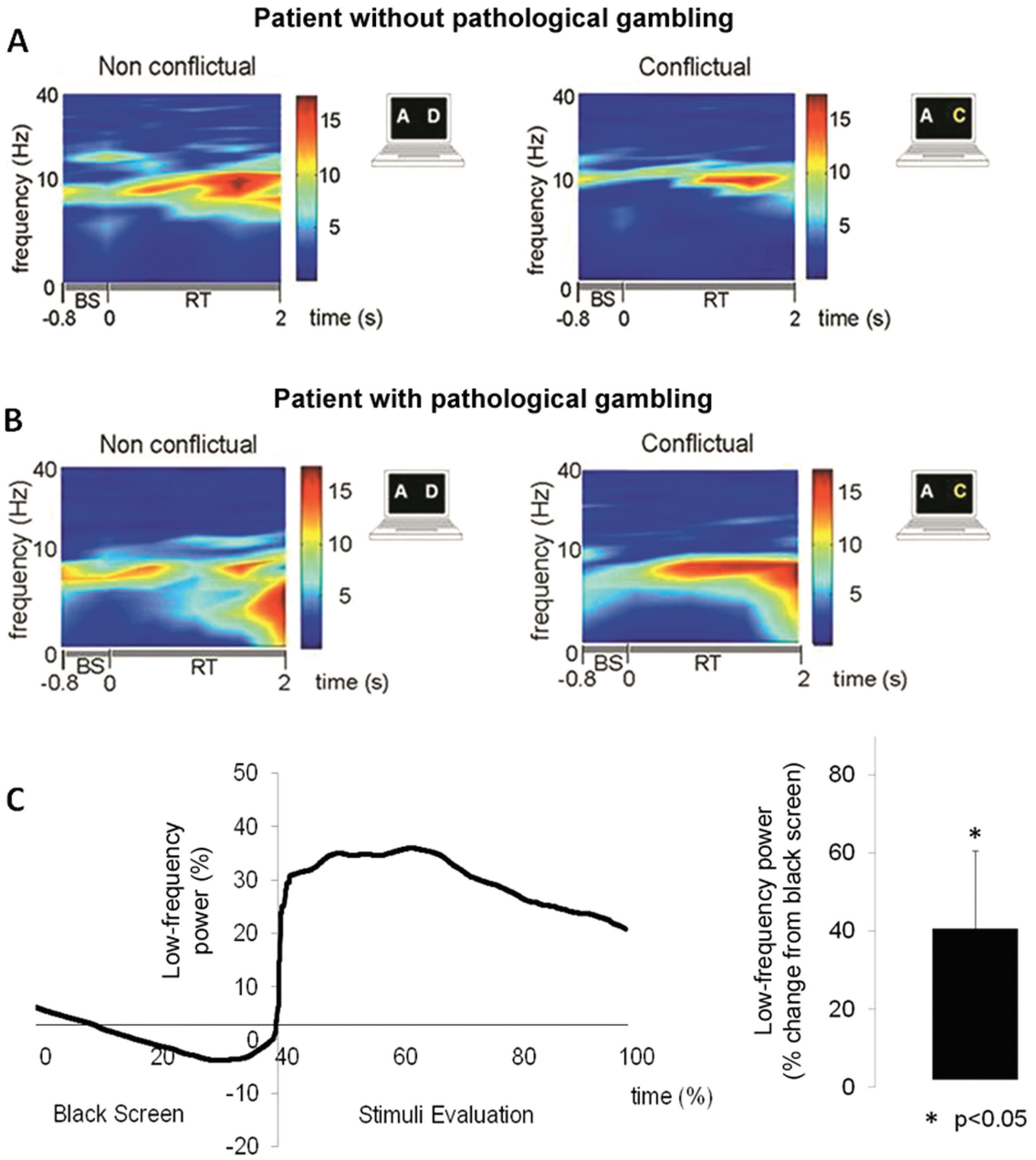

FIG. 3. Low-frequency power modulation during the economics task is illustrated. (**A**) Time-frequency plots of average subthalamic nucleus (STN) local field potential (LFP) power are illustrated in non conflictual (n = 30) and conflictual (n = 60) task conditions in a representative nucleus from a patient without pathological gambling (PG). The graph indicates LFP changes from 0.8 seconds before stimulus pairs appeared (the black screen [BS] phase) to the mean reaction time (RT) values for non conflictual and conflictual task conditions. (**B**) Time-frequency plots of average STN LFP power are illustrated in non conflictual (n = 30) and conflictual (n = 60) task conditions in a representative nucleus from a patient with PG. Plots are organized as indicated in A. (**C**) On the left, the grand average (n = 34) of low-frequency power modulations is illustrated during the black screen phase and the stimuli evaluation phase in all task conditions and in all parkinsonian patients with and without PG. Low-frequency power modulations were expressed as the percentage change from the black screen phase and were estimated from 0.8 seconds before the pair of stimuli was displayed (the black screen phase) to the last reaction time (RT) minus the mean RT for the motor task ($RT - RT_m$) sample (the stimuli evaluation phase). For the purpose of illustration, time is expressed as the percentage time (Fumagalli et al., 2011[5]). The histogram on the right represents the mean low-frequency power modulation during the stimuli evaluation phase. Error bars represent the 95% confidence interval of the estimated mean. Note that, in all parkinsonian patients, there was STN LFP synchronization in the low-frequency band during economic decisions.

decision-making could reflect increased dopaminergic activity in the STN. This electrophysiological finding implies that decisions related to economics could activate the dopaminergic mesocorticolimbic circuit,[39,40] thus suggesting a possible dopamine-dependent STN involvement in economics decision-making.

Behavioral Evidence in Parkinsonian Patients With and Without PG

The behavioral data from our study indicated that PD patients who gambled and those who did not used different strategies. Whereas the PD patients without

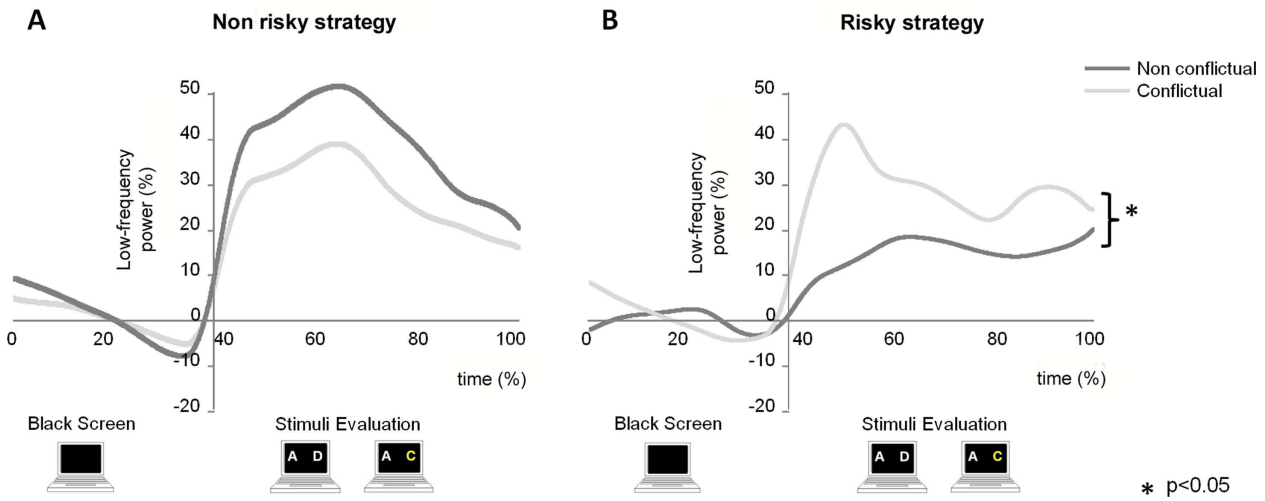

FIG. 4. Low-frequency power modulation is illustrated in relation to patient strategy. (**A**) The grand average (n = 12) of low-frequency power modulations during the black screen phase and the stimuli evaluation phase is illustrated in conflictual and non conflictual trials for patients who adopted a non risky strategy. Low-frequency power modulations were expressed as the percentage change from the black screen phase and were estimated from 0.8 seconds before the pair of stimuli was displayed (the black screen phase) to the last reaction time (RT) minus the mean RT for the motor task ($RT - RT_m$) sample (the stimuli evaluation phase). For the purpose of illustration, time is expressed as the percentage time (Fumagalli et al., 2011[5]). (**B**) The grand average (n = 12) of low-frequency power modulations during the black screen phase and the stimuli evaluation phase is illustrated during conflictual and non conflictual stimuli among patients who used a risky strategy. The plot is organized as indicated in A. Note that, in patients who used a risky strategy, low-frequency synchronization during economics decision-making was significantly greater during conflictual stimuli than during non conflictual stimuli. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

PG used a non risky strategy, preferentially choosing the non risky stimulus during conflictual trials and immediately learning the more advantageous option so that they no longer perceived the choice between the 2 stimuli as conflictual, the patients who gambled used a risky strategy, more frequently choosing the risky stimulus, thus proving susceptible to the conflict between the 2 options. The economics task we used was expressly designed to reward non risky choices, so that behavioral performances confirmed the different strategies used. A strong point in our research is that subdividing patients according to whether they gambled agreed with their behavioral performance and established a direct link between their economics strategy and PG.

How Conflictuality Influences the Relationship between STN Low-Frequency Activity, PG, and Behavioral Strategy

LFP recordings revealed that STN low frequencies varied according to the strategy used. In patients with PG, low-frequency synchronization was significantly greater during conflictual than during non conflictual decisions; whereas, in non gamblers, no significant differences were observed between task conditions. Hence, STN low-frequency oscillations in patients who gamble indicate conflict-dependent dynamics. These results underline the close link between patients' economics strategy, PG, and STN LFP oscillations. This link depends on the mutual factor decisional conflictuality evaluated in the economics task by conflictual trials that assess decisions between stimuli with a different probability of winning or losing.

In agreement with studies showing that the STN dynamically controls the threshold for executing a response, depending on the extent to which multiple responses compete (ie, are conflictual),[9,10,16] our results suggest that the STN sets a different threshold for conflictuality in the 2 groups. Patients with PG who used a risky strategy had a low threshold, STN activity being specifically modulated by the conflictual trials, whereas PD patients who used a non risky strategy had a higher threshold, leaving STN activity unchanged between conflictual and non conflictual trials. Therefore, the STN also is involved in evaluating economics conflictual stimuli and not only, as previously demonstrated, in decisional and moral conflictual stimuli.[5,9] If we compare our results in this study with those from a moral sentence task,[5] we find a major difference in the conflictuality concept. In the moral task, all patients with PD considered conflictual items as posing a conflict; whereas, in the economics tasks, only patients with PG who used a risk strategy considered them conflictual. This difference suggests that conflictuality is a complex construct that individuals perceive in different ways. An STN dysfunction, reflecting an alteration in the basal ganglia circuits to which it belongs, could change the decisional threshold, making it more sensitive to risky options and to a conflict-dependent low-frequency response during economics decision-making in patients with PG.

Finally, our findings indicate a specific link between PG, STN activity, and the behavioral strategy exhibited only during conflictual decisions (involving possible risk-taking) and not during non conflictual decisions. This conclusion supports the hypothesis that the STN low-frequency oscillations we observed are specific for economics decisions that imply a risky choice.

Potential Clinical Implications

Our findings also may have clinical implications for therapeutic DBS. The specific STN pattern related to the economics risky strategy could help in developing a specific DBS protocol or even an adaptive DBS system[27,41–44] to reduce eventual problems related to PG. Another interesting implication comes from emerging evidence that the clinical, phenomenological, and biological similarities between drug dependence and impulse control disorders, such as PG, hypersexuality, compulsive shopping, and compulsive overeating, converge to a unique group of disorders with behavioral and substance addictions.[45,46] Animal studies previously demonstrated the STN's role in reward[47–49] and addiction,[50–53] and some have proposed STN DBS as a treatment for cocaine addiction.[54] Because the STN is involved in orienting to normal or pathological behavior,[6,55] STN DBS could be used to treat addiction disorders. Because our data highlight the STN involvement in economics decisions, future electrophysiological and behavioral studies should evaluate whether STN DBS might subclinically influence economics behavior, even in parkinsonian patients without PG.

Conclusions

The STN is not only movement-related but also participates in the cognitive-affective system that drives our decisions and regulates behavior. In this system, the STN is specifically involved in evaluating conflictual decisions, independent of whether they belong in a moral, economics, or perceptual context. When individuals engage in an economics task, a specific STN activity pattern is related to the presence of PG. Hence, the STN may have a crucial pathophysiological role in PG and other behavioral abnormalities.

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