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Sensitivity to negative-feedback processing in people with Parkinson's disease and impulsive-compulsive behaviours

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ABSTRACT

Background: Biomarkers of impulsive compulsive behaviors (ICBs) in Parkinson's (PD) are lacking. We combined behavioural and electrophysiological markers of sensitivity to negative feedback to address this lack of knowledge.

Methods: Eighteen PD patients (ICB+, N=8; ICB-, N=10) underwent electroencephalography during the Balloon Analogue Risk Task (BART), a measure of risky behaviour, and the feedback-related negativity (FRN), a measure of negative feedback processing, was recorded. Participants also completed the Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease Rating Scale (QUIP-rs), and underwent cognitive, affective and motivation measures.

Results: Behaviour on the BART and FRN measures did not differ between the ICB+ and ICB- groups. However, a significant positive correlation was observed between the amplitude of the FRN at the Cz electrode and the BART discrepancy score when the two groups were combined into one PD group ($r(18) = 0.52$, $p = 0.03$; 95% CI = 0.07, 0.80). No additional correlations were found between FRN amplitudes and the QUIP-rs score, nor with cognitive, affective, or motivational measures.

Conclusions: Our findings indicate that, regardless of ICB status, PD patients may be able to process negative feedback to mitigate risky behaviour during reward-related decision-making. We observed that a higher feedback-related negativity (FRN) is linked to a decrease in risky behaviour following a balloon burst. However, due to the small sample size, these findings should be interpreted with caution. Future studies should explore both positive and negative feedback processing using a task that maintains the dynamics of the ongoing decision-making process while increasing risk.

Keywords. Parkinson's disease, impulsive-compulsive behaviours, negative-feedback processing, BART, ERP, decision-making.

INTRODUCTION

Detection and evaluation of external feedback are crucial for modulating incentive-driven decision-making process (Sinha et al., 2013). Negative and positive feedback are associated with a phasic decrease and increase in dopaminergic activity in the midbrain, respectively, which updates the cortical-dependent incentive-driven decision-making process, helping to improve task performance (Holroyd & Coles, 2002).

In Parkinson's disease (PD), dopaminergic replacement therapy (DRT) may prevent the physiological dopaminergic neurons from declining after negative feedback, leading to a blunted negative feedback-related cortical activity that principally involves the anterior cingulate cortex (ACC) (Frank et al., 2004). When off medication, PD patients tend to be better at learning to avoid choices that result in negative outcomes than at learning from positive outcomes. However, DRT can reverse this bias, making PD patients more sensitive to positive feedback compared to negative feedback (Frank et al., 2004).

Some patients who are more susceptible to the effects of DRT on dopaminergic neurons during negative feedback may develop impulsive-compulsive behaviours (ICBs) as side effects. This perspective is supported by evidence showing a lack of behavioural adjustment in risky behaviour following negative feedback in a reward-related decision-making task, such as the Balloon Analogue Risk Task (BART) (Martini et al., 2018).

Neurophysiological measures of negative feedback processing may be more sensitive than behavioural measures, which have produced contradictory findings. Some studies indicate that DRT can increase risk-taking behaviour in patients with ICBs (Claassen et al., 2011) and lead to a lack of adjustment in risky behaviour after negative feedback (Martini et al., 2018), while other studies found no changes (Ricciardi et al., 2017). If ICBs exist on a continuum of severity, PD patients who are vulnerable to ICBs may show neurophysiological changes even if their behavioural responses appear normal due to compensatory strategies.

Electroencephalography (EEG) is a method used to study negative feedback processing by measuring the amplitude of the feedback-related negativity (FRN) event-related potential. The FRN is generated in the ACC and can be detected in the frontocentral regions of the brain. It typically arises 200 to 300 milliseconds after negative feedback is presented (Holroyd & Coles, 2002; Talmi et al., 2013). The FRN is thought to mirror rapid feedback evaluation and phasic dopaminergic changes in activity between the basal ganglia and the ACC (Holroyd & Coles, 2002).

The FRN, which can be observed after balloon bursts in the BART, has been investigated in the context of behavioural and pharmacological addictions. These addictions are believed to share some underlying pathophysiological mechanisms with ICBs in PD. Research has shown that adolescents with problematic internet use exhibit a blunted FRN during the BART (Yau et al., 2015). Similarly, individuals with methamphetamine use disorder display a reduced FRN (Zhong et al., 2020). Additionally, a smaller FRN has been linked to a family history of alcohol use disorder (Fein & Chang, 2008).

The status of FRN in PD remains uncertain primarily due to the methodological challenges of conducting these studies on a clinical population whose motor symptoms are not always well controlled. As a result, there are conflicting findings from a relatively small and somewhat dated set of studies.

For instance, one study found that FRN was significantly higher in PD patients compared to healthy controls, regardless of reward magnitude and valence during a reward task (Mensen et al., 2015). In another study, utilizing the Iowa gambling task—which examines decision-making under uncertainty—the FRN amplitude did not show any differences following wins and losses for PD patients (Mapelli et al., 2014).

The amplitude difference between the FRN generated after gains and losses was found to be reduced in PD patients with marked apathy symptoms compared to PD patients without apathy (Martinez-Horta et al., 2014). The error-related negativity (ERN), an ERP component closely related to FRN, has been reported to be diminished in PD patients, regardless of their DRT status (Stemmer et al., 2007; Walsh & Anderson, 2014). This attenuation related to PD was most pronounced when patients were on medication (Seer et al., 2016). In contrast, during a reward learning task, PD patients exhibited smaller ERN amplitudes when off levodopa treatment than when on it, but this was specifically observed in negative learning scenarios (Volpato et al., 2016).

The conflicting results in the literature regarding the FRN or ERN in PD may stem from differences in patient samples and the impact of relevant factors such as whether On or OFF DRT and ICB status.

For example, a study by Marín-Lahoz et al. (2022) found that the amplitude of the FRN between wins and losses in a gambling task could predict the development of ICBs in PD patients. However, it remains unexplored whether an abnormal FRN in the BART could serve as a signature of ICBs, potentially acting as a predictive biomarker to identify PD patients at risk for ICBs. To address this knowledge gap, we recorded the FRN while PD patients with and without ICBs completed the BART. We initially analysed the performance of all PD patients as a single group and then conducted subgroup analyses comparing patients with ICBs (ICB+) to those without (ICB-).

METHODS

Participants

Twenty-one medicated non-demented PD patients were enrolled at the IRCCS San Camillo Hospital Venice (Italy). Inclusion criteria: a) diagnosis of idiopathic PD according to the UK PD Society Brain Bank Clinical Diagnostic Criteria (1992); b) mild-to-moderate PD (i.e., Hoehn and Yahr score 1–3 in the ON condition); c) age between 35 and 85 years. Exclusion criteria: a) co-morbidity for other neurological or psychiatric conditions; b) history of learning difficulty, including dyslexia; c) active malignancy; d) incapacitating dyskinesia on a stable dose of LD; e) medicated with either centrally acting anticholinergic or atypical antipsychotic agents.

Dementia was ruled out based on the criteria established by the Movement Disorder Society and a comprehensive neuropsychological evaluation (Emre et al., 2007). Two experienced neuropsychologists (AM, RS) assessed impulsive-compulsive behaviours (ICBs) using published diagnostic criteria for gambling

disorder and binge-eating disorder (APA, 2013), compulsive shopping (McElroy et al., 1994), hypersexuality (Voon et al., 2006), dopamine dysregulation syndrome (Giovannoni et al., 2000), as well as punning and hobbyism (Voon et al., 2007). The Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease Rating Scale (QUIP-rs) was administered to evaluate the severity of ICBs (Weintraub et al., 2012).

Ten PD patients with active ICBs were assigned to the ICB+ group, and eleven PD patients with no history of ICBs were assigned to the ICB- group. Additionally, participants completed a cognitive test battery and self-report measures for motivation and affection (Table 1). All participants provided written informed consent prior to study procedures. The study received approval from the Ethical Review Panel of Keele University and the Ethical Review Panel of the Venice Province.

The Balloon Analogue Risk Task

In the BART, administered using E-Prime version 2.0 (Psychology Software Tools, Pittsburgh, PA, USA), participants were instructed to press the 'V' key on a QWERTY computer keyboard to inflate the balloon. Each successful pump earned the participant 5 cents. However, if the balloon was overinflated, it would burst, displaying the message "I am sorry, the balloon burst" on the screen for one second, resulting in the loss of all money collected during that trial.

To maximize their earnings, participants needed to stop inflating the balloon before it burst and press the 'N' key. Doing so would trigger the message "Congratulations, you have won XX € for this balloon," which appeared on the screen for one second, and the earned money was then transferred to a virtual bank.

After each trial, whether the balloon burst or money was banked, a fixation cross would appear in the centre of the screen for one second, signalling the start of the next trial. The other keys on the keyboard were obscured to prevent accidental presses.

The balloons were programmed to burst at a random point between 1 and 128 pumps, with the probability of bursting changing after each pump. The chance of a balloon bursting was 1/128 for the first pump. If the balloon did not explode, the probability of bursting then increased to 1/127 for the second pump, and this pattern continued. On average, balloons burst around the 64th pump.

Two dependent variables were recorded in the study. The first was the average number of pumps in trials where balloons were successfully cashed. Higher risk-taking behaviour is associated with a greater number of pumps. The second variable was the average number of pumps for trials immediately preceding and immediately following a balloon burst (Claassen et al., 2011). A lower number of pumps in the trials following a balloon burst, compared to those immediately preceding it, indicates sensitivity to negative feedback, measured as the discrepancy score.

It is important to note that participants were on medication when the Balloon Analogue Risk Task (BART) was administered.

EEG recording

Participants took part in the Balloon Analog Risk Task (BART) while their brain activity was monitored using a 64-channel EEG system with BrainAmp MR plus amplifiers and BrainVision Recorder 2.0 (Brain Products GmbH, Gilching, Germany). Ag/AgCl active electrodes were placed on an elastic cap based on the International 10-20 system. The ground electrode was positioned at Oz, and FCz served as the reference. Data were captured at a sampling rate of 512 Hz. Unfortunately, data from three participants (ICB+, N = 2; ICB-, N = 1) could not be analysed due to an insufficient number of negative-feedback events (ICB+, N = 9-13; ICB-, N = 8). Each participant completed two sessions of 60 trials to increase the number of negative feedback epochs available for averaging, with a 10-minute break between sessions to avoid fatigue. Audio feedback was removed to prevent potential startle responses and muscle artifacts.

EEG preprocessing and feedback-related negativity

The EEG data obtained was imported and pre-processed using the EEGLAB MATLAB toolbox. Subsequently, the EEG continuous data underwent offline filtering with an IIR Butterworth band-pass filter (0.1-30 Hz half-amplitude filter, 12 dB/oct), and a 50 Hz Parks-McClellan Notch filter was applied. Following the filtering process, the data was resampled at 256 Hz. Bad channels were identified visually and interpolated (whole sample: 1.79 ± 1.93). Blinks and eye movements artefacts were corrected via Independent Component Analysis (Makeig et al., 1996). After artifact rejection, the data was re-referenced to linked mastoids (electrodes TP9/TP10), then averaged separately for each participant and electrode. Negative feedback-locked waveforms were based on at least 15 epochs per subject (whole sample: 26.61 ± 9.22), in agreement with a previous study (Yau et al., 2015). ERPs were time-locked to the onset of negative-loss feedback. Continuous data was segmented into epochs of 1000 ms (200 ms before and 800 ms after feedback onset) and then baseline corrected at 200 ms before feedback onset (i.e., -200 to 0 ms).

Finally, the FRN was calculated from the mean amplitude between 200-300 ms at the midline electrodes Fz and Cz. The mean amplitude across a specific interval does not tend to produce consistently larger values in noisier waveforms. Additionally, when compared to other measures of event-related potentials (ERPs), such as peak amplitude, the mean amplitude can be used when the number of trials varies between participants or when comparing groups with different levels of noise (Luck, 2014).

Statistical analysis

Data were analysed with SPSS version 27.0. Between groups Cohen's d effect sizes and 95% CI were analysed using JASP software version 0.10.2. The significance threshold for all the tests was set at $p < 0.05$ (two-tailed), except when Bonferroni correction for multiple comparisons was applied.

For continuous variables, normality of distribution was explored with the Shapiro-Wilks test. Continuous variables were analysed using t-tests or the non-parametric Mann-Whitney. Fisher's exact test or Fisher-Freeman-Halton test were applied to categorical variables.

Group level analysis: relationship between BART performance and feedback-related negativity amplitude

Spearman ρ explored the correlation between FRN for negative-loss feedback (Fz, Cz), and the BART discrepancy score (i.e., the difference in the number of pumps pre and post a balloon burst), cognitive, motivational, and affective measures.

Subgroup analysis: BART behavioural performance

Behavioural BART performances were analysed with a 2x2 mixed-model ANOVA with the between-subjects factor group (ICB+, ICB-) and the within-subject factor feedback (i.e., number of pumps pre, number of pumps post a balloon burst).

Subgroup analysis: feedback-related negativity amplitude

FRN values were analysed via mixed model repeated ANCOVA with mean amplitude of ERP responses to negative feedback as dependent variables, between-subject factors group (ICB+, ICB-), within-subject factor electrode (Fz, Cz), and DA-LEDD as covariate, as DRT may modulate reward/punishment learning.

RESULTS

The groups were matched for demographic and clinical variables, apart from DA-LEDD which was significantly higher in ICB+ (DA-LEDD: $t(16) = 2.27$, $p = 0.04$, $d = 1.10$, 95% confidence interval, CI = 0.06, 2.06). The groups were matched on measures of executive functioning (cognitive control (Stroop), cognitive flexibility (Trails B), and fluid intelligence (Brixton) despite the MMSE being higher in the ICB+ group: ($t(16) = 2.85$, $p = 0.01$, $d = 1.35$, 95% CI = 0.29, 2.37). The data are presented in Table 1.

--insert Table 1 here, please--

Group level analysis: relationship between BART performance and feedback-related negativity amplitude

Spearman ρ documented significant positive correlation between the FRN amplitude in Cz and the BART discrepancy score ($r(18) = 0.52$, $p = 0.03$; 95% CI = 0.07, 0.80). No correlations were found between FRN amplitudes and QUIP-rs score, or measures of executive function and MMSE score.

Subgroup analysis: BART behavioural performance

Risky behaviour did not significantly differ between the PD groups ($t(16) = -0.56$, $p = 0.58$, $d = -0.26$, 95% CI = -1.19, 0.6). ANCOVA showed no significant main effect of group ($F(1, 16) = 0.30$, $p = 0.59$, $d = -0.13$, 95% CI = -13.41, 7.90), or group x feedback interaction ($F(1, 16) = 1.17$, $p = 0.29$), while the main effect of feedback was significant ($F(1, 16) = 11.18$, $p = 0.004$, $d = 0.82$, 95% CI = 2.04, 8.36; Table 2).

Subgroup analysis: feedback-related negativity amplitude

Mixed model repeated ANCOVA showed no main effect of Fz vs. Cz electrode type ($F(1, 15) = 1.32$, $p = 0.27$, $d = 0.03$, 95% CI = -0.92, 1.06), no main effect of group ($F(1, 15) = 0.48$, $p = 0.50$, $d = -0.16$, 95% CI = -7.59, 3.85), and no effect of group x electrode interaction ($F(1, 15) = 0.07$, $p = 0.80$; Fz: ICB+ vs. ICB-, $p = 1.00$, $d = -0.15$, 95% CI = -9.96, 6.50); Cz: ICB+ vs. ICB-, $p = 1.00$, $d = -0.17$, 95% CI = -10.24, 6.21; Figure 1). Excluding either DA-LEDD or MMSE score as covariates did not change the results.

DISCUSSION

The study aimed to investigate sensitivity to negative feedback using both behavioural and electrophysiological measures in PD in general, and ICBs in particular. The findings revealed a significant positive correlation between the FRN amplitude in Cz and the BART discrepancy score in PD. This suggests that the entire cohort of PD patients examined in this study can process negative feedback to reduce risky behaviour during reward-related decision-making.

Specifically, a higher FRN amplitude was associated with a reduction in risky behaviour following a balloon burst, as indicated by a larger discrepancy score on the BART.

However, there was no significant difference in FRN amplitude between PD patients with and without ICBs. The null results between ICB+ and ICB- groups is inconsistent with other research conducted in non-PD samples and showing reduced FRN during the BART in individuals with substance and behavioural addictions (Yau et al., 2015; Zhong et al., 2020). Taken together, these preliminary results may suggest that shared features across the PD cohort could have a greater influence on BART performance than characteristics specific to ICBs.

The study has three main limitations: low sample size, the lack of a healthy control group which would have provided baseline data and the BART paradigm itself, which we discuss in more detail below.

We utilized the original version of the BART, which restricts the analysis of positive feedback processing. This limitation arises from our inability to assess the amplitudes for gain trials, which reflect reward evaluation, feedback valence, and reward magnitude (Yeung & Sanfey, 2004). —In contrast to losses, which are unpredictable and only revealed through feedback, gains are known prior to the positive feedback being given—specifically when participants decide to stop pumping the balloon and secure money in the bank. This early awareness of the win creates a notable shift in the average waveforms during the positive feedback conditions.

Previous ERPs studies implemented a modified BART version to analyse positive and negative feedback. In these variations, participants do not consecutively inflate the balloon; instead, they simply enter the target number of pumps at the beginning of each trial (Euser et al., 2011; Yau et al., 2015). However, these modified versions do not capture the escalating sense of risk that participants experience when they accumulate greater potential rewards and are confronted with increasing possible losses by sequentially pumping the balloon. This escalating risk is documented by changes in the ventromedial prefrontal cortex observed through functional MRI when participants continue to pump (Schonberg et al., 2012).

Future research should also explore whether ICBs in PD are driven by increased sensitivity to rewards rather than diminished sensitivity to negative consequences. Previous evidence indicates that PD patients with impulse control behaviours make riskier choices in gain versus loss conditions (Voon et al., 2011) and exhibit heightened sensitivity to rewards both on and off dopamine replacement therapy (Drew et al., 2020).

FIGURE LEGENDS

Figure 1. Grand average FRN for negative feedback trials. Here are represented the grand average for ICB- (black lines) and ICB+ groups (red lines) and the difference between ICB- and ICB+ (blue lines) at the electrode Fz (Panel A) and Cz (Panel B). Average waveforms were first computed across trials for each subject at electrode site Fz and Cz, and then the waveforms were averaged across subjects of each group. The difference between ICB- and ICB+ groups was computed for each bin. Shaded areas represent the standard error of mean for ICB- (black shade) and for ICB+ (red shade).

Legend. ICB-: patients with Parkinson's disease without impulsive-compulsive behaviours; ICB+: patients with Parkinson's disease and impulsive-compulsive behaviours.

STATEMENTS AND DECLARATIONS

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Competing interests. All authors declare no financial or non-financial competing interests.

Data Availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical Standards. The study was conducted according to the Declaration of Helsinki and approved by the Ethical Review Panel of Keele University and the Ethical Review Panel of the Venice Province.

Author contributions. A.M.: Conceptualization, Methodology, Data collection and Data curation, Writing - Original draft preparation. N.E.: Conceptualization, Methodology, Original draft preparation, Writing - Reviewing and Editing, Supervision. L.W.: Methodology, Data curation, Writing - Reviewing and Editing. S.T.: Methodology, Writing - Reviewing and Editing. R.S.: Data collection, Writing - Reviewing and Editing. J.L.B.: Methodology, Data curation, Writing - Reviewing and Editing. E.M.: Writing - Reviewing and Editing. J.G.: Methodology, Writing - Reviewing and Editing. M.F.L.: Methodology, Writing - Reviewing and Editing. F.P.: Data collection, Writing - Reviewing and Editing. G.L.: Methodology, Writing - Reviewing and Editing. A.A.: Writing - Reviewing and Editing. R.B.: Conceptualization, Data curation, Writing - original draft preparation, Reviewing and Editing, Supervision. All authors critically revised and approved the manuscript.

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