The role of the subthalamic nucleus in response inhibition: Evidence from deep brain stimulation for Parkinson’s disease


A R T I C L E  I N F O

Article history:
Received 12 February 2009
Received in revised form 4 June 2009
Accepted 11 June 2009
Available online 21 June 2009

Keywords:
Stop-signal task
Thalamocortical circuits
Inferior frontal gyrus

A B S T R A C T

We measured reaction times during a stop-signal task while patients with Parkinson’s disease were on and off unilateral deep brain stimulation (DBS) of the subthalamic nucleus (STN). While reaction times to a “go” stimulus improved, there was no change in reaction times to the “stop” stimulus (SSRTs). However, changes in SSRTs induced by DBS were highly dependent on baseline SSRTs (measured off stimulation), with the greatest improvements being achieved by those with particularly slow reaction times. We therefore selected only those patients whose baseline SSRTs were within the limits of a control sample (N = 10). In this group, SSRTs became slower when DBS was on. This finding suggests a role for the STN in response inhibition, which can be interrupted by DBS, observable only when more general improvements in Parkinson’s function are minimised. We also compared the effects of unilateral left and right sided stimulation. We found a greater increase in SSRTs after DBS of the left STN.

1. Introduction

The ability to inhibit a pre-planned or ongoing motor response is essential for optimal performance of almost every motor act. It is frequently studied using a stop-signal paradigm (see Logan, Cowan, & Davis, 1984) in which a “stop” response is pitted in a race against a “go” response, described as the race model. Typically, choice reaction times to an imperative go-stimulus are measured, and are followed on a proportion of trials by a stop-stimulus instructing participants to withhold their response. The delay between the go- and stop-signal is adapted to each subject’s ability to inhibit their responses, so that 50% of the stop-signals lead to successful inhibition. The stop-signal reaction time (SSRT) is then estimated by calculating the difference between the median go- and the average stop-signal.

Response inhibition is found to be dependent on activity in the right inferior frontal cortex (IFC) (Aron & Poldrack, 2006; Aron, Robbins, & Poldrack, 2004; Forstmann et al., 2008; Xue, Aron, & Poldrack, 2008). The left IFC is not thought to be involved, as event related potentials (ERPs) (Schmajuk, Liotti, Busse, & Woldorff, 2006) and BOLD responses (Aron & Poldrack, 2006) in this area were not evoked during stopping, and repetitive transcranial magnetic stimulation (rTMS) did not affect stopping performance (Chambers et al., 2007). However, see (Swick, Ashley, & Turken, 2008).

Recently, it has been suggested that the subthalamic nucleus (STN) of the basal ganglia is also involved in response inhibition (Aron, Behrens, Smith, Frank, & Poldrack, 2007; Aron & Poldrack, 2006; Eagle et al., 2008; Ray Li, Yan, Sinha, & Lee, 2008; van den Wildenberg et al., 2006). It has been proposed that, during stopping, the right IFC sends a signal via the “hyperdirect” pathway (Nambu, Tokuno, & Takada, 2002) to the right STN, which enables the inhibition of activity in thalamocortical loops related to the action to be inhibited (Aron & Poldrack, 2006). The STN is also an important node in associative/limbic basal ganglia-thalamocortical loops, which may have implications for the cognitive aspects of stop-signal tasks.

Deep brain stimulation (DBS) of the STN in Parkinson’s disease (PD) patients was found to improve SSRTs (van den Wildenberg et al., 2006). However, SSRTs also improved during stimulation of the ventral intermediate nucleus of the thalamus (VIM), suggesting that decreases in reaction times depended on more general improvements in Parkinson’s function. To address this issue we measured SSRTs in PD patients during stimulation of either the right or left STN alone, and while neither STN was being stimulated. Unilateral stimulation was used in order to limit the treatment effect of DBS, which is greater for each hemibody during bilateral than unilateral stimulation (Bastian, Kelly, Revilla, Perlmutter, & Mink, 2003; Tabbal et al., 2008). Next, to more fully control for DBS induced improvements on the task, we selected only those patients who...
performed the SSRT task within normal limits based on the 95% confidence intervals of a control sample (see Chen et al., 2006).

We were also interested in determining if DBS of the right STN affects SSRTs more than DBS of the left STN, since the right IFC and the right STN are thought to be dominant for response inhibition.

2. Methods

2.1. Participants

Participants were 16 right-handed Parkinson’s patients (Table 1 summarises patient’s details), recruited during routine follow-up clinic appointments after DBS surgery. Patients had been receiving bilateral DBS of the STN for an average of 0.5 years at the time of testing. All had significant benefit to Parkinson’s disease motor symptoms on both sides during stimulation. The stop-signal task was always performed while the patients were on their usual Parkinsonian medication, specified in Table 1.

An aged matched control sample (N=10) with no neurological condition were used to determine normal performance on the stop-signal task, so that patients performing within the normal range could be selected (mean age was 52.3, age range: 46–64; 4 females, 6 males).

2.2. Surgical procedure

DBS electrodes were implanted bilaterally in the STN. Our surgical procedure has been detailed elsewhere (Aziz et al., 2001). DBS electrodes were considered accurately placed in the STN by the surgical and clinical team if there was effective intraoperative and postoperative stimulation, and postoperative MRI confirmation of at least one electrode contact in the STN region. It is important for the interpretation of our findings that there were no systematic errors in electrode placement that resulted in one area of the STN being targeted more frequently in one hemisphere over the other. While it is true that current methods of surgical targeting produce some variation in electrode location, it is unlikely that these variations were different for the left and right IFC. Further, models of the current spread during stimulation suggest that even cells outside the boundaries of the STN are activated during stimulation (McIntyre, Mori, Sherman, Thakor, & Vitek, 2004), which suggests that deviations in electrode placement will still result in the activation of an imprecise area of the STN region. Further, recent data suggests that even the motor effect (motor UPDRS) is uncorrelated with electrode placement (McClelland et al., 2009). For these reasons, we can assume that the effects of stimulation of the left and right STN are equivalent in these patients.

3. Materials and procedure

3.1. Stop-signal task

Patients and controls were seated in front of a computer screen on which the task was displayed. The task started with a fixation cross, followed by a green arrow (the “go” stimulus) pointing either left or right. Participants are instructed to respond by pressing the appropriate left or right button on a button box as fast as possible. On 34% of the trials the green arrow turns red (the “stop” stimulus), indicating that the participant should withhold their response. The “stop” stimulus appears randomly and is extinguished after duration of 1 s, or upon an uninhibited response from the participant. The trials are shuffled at the beginning of the task so that subsequent presentations of the task are different from the last. Participants are instructed that “going” is as important as “stopping”, and that it will be impossible to inhibit their responses on some of the stop-trials. Each task constituted 150 trials.

The delay between the go- and stop-signal was adaptive, increasing by 50 ms after successful inhibition of a previous stop-trial and decreasing by 50 ms after unsuccessful inhibition. The first 20 delays were disregarded in order to give participants time to adapt to around a 50% accuracy rate. SSRTs were then estimated by subtracting the mean delay between the go- and stop-signals from the median go-reaction time (GORT). This procedure controls for differences in go-reaction time. The stop-trials were inspected in each participant and in each condition to ensure that they approximately followed a pattern of respond and inhibit, in order to yield around a 50% accuracy rate. During the occasional recurrence of tremor or bradykinesia symptoms some go-responses were artificially extended. Therefore go-reaction times longer than 4000 ms were removed from the data. This did not amount to more than three trials in any one patient, and most were completely unaffected.

Patients were told that we would be turning DBS on and off during the task, but that they would not know when. After settings were changed, patients rested for 10–15 min in order to allow...
the effects of stimulation during the previous session wear off. The patients completed the task in each of the following conditions: on stimulation only in the left STN, on stimulation only in the right STN and off stimulation. The left STN on condition was always performed with the right hand and the right STN on condition was always performed with the left hand. The off stimulation condition was performed once with each hand, and each of these blocks were compared with the same hand during the on stimulation conditions. 3 patients completed only the left-handed conditions and 3 only the right-handed conditions. This was due to either excessive motor symptoms in the untested hand, or time constraints. A further 3 left sides and 2 right sides were removed due to a failure to achieve ~50% accuracy, leaving data from 10 left and 11 right sides (Table 1 indicates which sides were excluded (no asterisk)). The order in which the conditions were presented was counterbalanced to control for practice and fatigue effects.

Of the controls, 2 completed the task with only their right hand and 2 only with their left hand, and left hand data from one control was excluded due to a failure to achieve ~50% accuracy, leaving 15 sides. Due to the counterbalancing in patients, half of the group performed the off DBS condition first, and half performed it second. Therefore to match possible practice and fatigue effects, control participants also completed the task twice with each hand. Half of the control data was selected from the first block and half from the second.

3.2. Selection of patients performing within the limits of the control sample

A previous study (Chen et al., 2006) found that patients with normal performance on a motor task, defined by a control sample, became impaired on that task during DBS of the STN. We therefore selected a subset of patients from the total sample whose SSRTs were within the limits of a control sample. Controls’ SSRTs were converted to z-scores, and the upper 95th confidence limit was determined as the SSRT corresponding to the 1.96th z-score. Patients with at least as fast SSRTs as this limit were selected for further analysis. This left 13 sides from 10 patients indicated with a double asterisk in Table 1.

3.3. Summary of selection criteria

16 patients were recruited for this study. In some patients we only tested one hemibody, and those not achieving ~50% accuracy were excluded. This left 21 hemibodies in total for the overall analysis. Next we selected only those trials in which off stimulation SSRTs were within normal limits of a control sample, leaving 13 hemibodies from 10 patients. These were 7 left hemibodies and 6 right hemibodies.

3.4. Clinical assessment

A specialist nurse completed the Unified Parkinson’s Disease Rating Scale (UPDRS) for each patient, which separates motor symptoms by hemibody. When possible, the UPDRS was administered on the same day as the stop-signal task was performed. In a few cases UPDRS scores were obtained no longer than 3 months later.

4. Results

All patients completed the stop-signal task while on and off DBS. Table 2 summarises the observed SSRTs and GORTs. Other parameters of interest are accuracy and reaction times of uninhibited stop-trials. SSRTs and GORTs were compared for all hemibodies on and off STN DBS. For the statistical analysis we will treat each hemibody as an independent sample (see discussion below). Paired samples t-tests revealed that DBS induced a significant improvement to GORTs ($t=2.6, P<0.05, df=20$), but not SSRTs ($t=0.44, P=0.67, df=20$) (see Fig. 1).

Fig. 2 shows the relationships between baseline SSRTs and the percentage improvements during DBS. A Pearson’s correlation found that percentage improvements in SSRTs during DBS were significantly correlated with off stimulation SSRTs ($r=0.678, P<0.01, N=21$). The graph shows that those with the fastest SSRTs off stimulation tended to perform slower when DBS was turned on. However, overall, this effect is likely being obscured by the more general improvements induced by DBS. Therefore, in order to control for treatment effects further, we determined normal performance on the stop-task using data from 10 aged matched controls (15 sides). These subjects had significantly faster SSRTs ($t=2.46, P<0.05, df=34$), but not significantly different GORTs ($t=0.78, P=0.41, df=34$) from the patients (see Table 2 for a summary of results). The lack of a difference in GORTs is most likely explained by the very simple nature of the go part of the stop task i.e. press the left button for the left pointing arrow, and the fact that only a small movement (finger press) is required. A 2-sample F-test revealed that the variance between the patient and control GORTs are not significantly different ($F=2.23, P=0.10$), but as can be seen from Table 2 these variances are quite far apart. The t-test reported above comparing patient versus control GORTs does not therefore assume equal variances.

The upper 95th confidence limit for control SSRTs (found by converting SSRTs into z-scores) was used as a cut off to select patients

Table 2

<table>
<thead>
<tr>
<th></th>
<th>GORT on</th>
<th>SSRT on</th>
<th>Accuracy on</th>
<th>Failed on</th>
</tr>
</thead>
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<tr>
<td>All hemibodies (N=21)</td>
<td>753.2</td>
<td>680.9</td>
<td>284.3</td>
<td>277.1</td>
</tr>
<tr>
<td>Mean (ms)</td>
<td>753.2</td>
<td>680.9</td>
<td>284.3</td>
<td>277.1</td>
</tr>
<tr>
<td>SD (ms)</td>
<td>753.2</td>
<td>680.9</td>
<td>284.3</td>
<td>277.1</td>
</tr>
<tr>
<td>Hemibodies with normal baseline SSRTs (N=13)</td>
<td>744.4</td>
<td>685</td>
<td>227.1</td>
<td>263.1</td>
</tr>
<tr>
<td>Mean (ms)</td>
<td>744.4</td>
<td>685</td>
<td>227.1</td>
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<tr>
<td>SD (ms)</td>
<td>744.4</td>
<td>685</td>
<td>227.1</td>
<td>263.1</td>
</tr>
<tr>
<td>Hemibodies with slow baseline SSRTs (N=8)</td>
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<td>674.4</td>
<td>377.2</td>
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<tr>
<td>Mean (ms)</td>
<td>720.2</td>
<td>674.4</td>
<td>377.2</td>
<td>299.8</td>
</tr>
<tr>
<td>SD (ms)</td>
<td>189.9</td>
<td>117.9</td>
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</tr>
<tr>
<td>Controls (N=15)</td>
<td>669.2</td>
<td>219.5</td>
<td>49.37</td>
<td>582.23</td>
</tr>
</tbody>
</table>
with normal baseline performance (see dashed line in Fig. 1). The remaining patients (N=13) are indicated with a double asterisk in Table 1. We ensured that the counterbalancing remained unbiased. A repeated measures t-test revealed that while SSRTs became impaired in these patients during DBS (t = -2.46, P < 0.05, df = 12), GORTs continued to improve (t = 2.35, P < 0.05, df = 12) (see Fig. 1). As expected, in the remaining patients with slow SSRTs, there was a significant improvement during DBS (t = 4.5, P < 0.01, df = 7) (data not shown).

We were also interested in how the impairment in SSRTs due to DBS is effected by the side of stimulation. All patients who performed the task with both the left and the right hand (including those with slower than normal SSRTs), and who attained ~50% accuracy for both hands were selected for the following analysis. In the off stimulation conditions this left 9 patients, and 8 remained in the on stimulation conditions. Repeated measures t-tests found that neither GORTs (t = 0.1, P = 0.9, df = 8) or SSRTs (t = 0.6, P = 0.5, df = 8) were significantly different between the left and right hands when patients were off stimulation. Further, off stimulation, left and right hand GORTs (Pearson’s: r = 0.78, P < 0.05, N = 9) and SSRTs (r = 0.72, P < 0.05, N = 9) were significantly correlated. Similarly, GORTs (t = -1.42, P = 0.2, df = 7) and SSRTs (t = -0.2, P = 0.91, df = 7) during left STN stimulation and right STN stimulation were not significantly different. However, while GORTs during left and right stimulation were correlated (r = 0.77, P < 0.05, N = 8), SSRTs were not (r = -0.02, P = 0.97, N = 8).

As above, we wanted to control for the DBS induced treatment effects that may have obscured any changes in GORTs and SSRTs during left and right STN stimulation that were not related to more general improvements in motor function. After selecting patients with normal baseline SSRTs, data for 7 left hands and 6 right hands, both off stimulation and during contralateral stimulation, remained. Baseline GORTs and SSRTs were not different between these sides (GORT: t = -1.23, P = 0.25, df = 11; SSRT: t = 0.94, P = 0.37, df = 11). The motor subsection of the UPDRS was also not significantly different between sides either on or off medication (on: t = 0.68, P = 0.51, df = 11; off: t = 1.39, P = 0.2, df = 11). GORTs and SSRTs were not significantly different during stimulation of the left and right STN (GORT: t = -0.8, P = 0.44, df = 11; SSRT: t = -0.75, P = 0.47, df = 11). In order to determine whether changes in SSRTs induced by stimulation of the left and right STN were different, we computed a mixed design ANOVA with stimulation condition (on/off) as the within subjects variable and side of stimulation (left/right) as the between subjects variable. This ANOVA revealed a significant interaction between side of stimulation and stimulation condition (F = 9.5, P < 0.01, df = 11), showing that the effects of stimulation are different when applied to the left versus the right STN. The equivalent analysis was not significant for GORTS (F = 0.01, P = 0.92, df = 11). Repeated measures t-tests, with alpha reduced to 0.025 to control for multiple comparisons, revealed that stimulation of the right STN had no effect on either SSRTs (t = -0.46, P = 0.67, df = 6), or GORTs (t = 1.68, P = 0.15, df = 6). However stimulation of the left STN impaired SSRTs (t = -3.3, P < 0.025, df = 5), while GORTs were
Fig. 3. Percentage change in GORTs and SSRTs after left and right STN DBS. Boxes are 25th and 75th percentiles. Thick horizontal lines are medians, whiskers represent the maximum/minimum value within whisker length (1.5 times interquartile range). Stars are outliers.

unaffected ($t = 1.5, P = 0.2$, df = 5) (see Fig. 3). Fig. 3 reveals that the change in SSRTs due to left STN DBS may be positively skewed (kurtosis = 1.5). While repeated measures ANOVAs are not particularly susceptible to skewness, we computed a non-parametric Wilcoxon rank sum test to compare change in SSRT after left versus right STN DBS ($Z = −2.07, P < 0.05$). We also computed a Wilcoxon rank sign test to compare on SSRTs while patients were on and off DBS in the right STN ($X = −0.68, P = 0.5$) and the left STN ($Z = −2.2, P < 0.025$ (alpha corrected for multiple comparisons)). These nonparametric tests confirm the previous ANOVAs.

5. Discussion

Across all patients, unilateral DBS of the STN improved GORTs but not SSRTs with the contralateral hand. However, in patients already performing within normal limits of a control sample, DBS continued to improve GORTs, but significantly impaired SSRTs. We also compared the effects of stimulating the left and right STN separately. We found that DBS of the right STN had no effect on SSRTs, but DBS of the left STN significantly impaired them.

Before we attempt to interpret these findings, some limitations of the study must be discussed. Firstly, we must be cautious about inferring normal behavior from a patient sample with known impairments on response inhibition tasks (Gauggel, Rieger, & Feghoff, 2004). To limit the effects of Parkinson's disease symptoms and pathology on task performance, we have chosen to test patients in the medicated state. We acknowledge that dopamine replacement therapy will likely have its own influence over the cognitive aspects of this task, but considered the limitation of disease related motor and cognitive symptoms more important in this case since medication states are identical in the on and off DBS conditions. A second limitation relates to the procedure used to select the subset of trials in which SSRTs were at least as fast as those obtained by a control sample. This left a sample of 3 patients with both hemibodies included and 7 patients with only one hemibody included. In the DBS and Parkinson's disease literature, hemibodies have been considered as separate samples. Often, this procedure is followed when a measurement (for e.g. of pathological oscillatory activity in the left and/or right STN) is associated with motor symptoms in the contralateral hemibody (see Kühn et al., 2008, 2009), or, as in the present study, when stimulation of either the left or right STN is coupled with measurements of motor performance in the contralateral hemibody (see Foffani et al., 2006). We have therefore used a between subjects design when comparing changes in reaction times during left or right STN stimulation. Finally, without a full neuropsychological assessment, we do not know how DBS affects other cognitive processes in these patients. It is possible that these unseen effects might be responsible for the changes in SSRTs. However, previous research has found specific DBS induced effects on response inhibition (Campbell et al., 2008).

With the above caveats in mind, we can now begin to interpret our findings. The lack of an improvement in SSRTs during STN DBS overall is inconsistent with a previous study using bilateral DBS of the STN, in which Parkinson’s patients were able to respond faster to stop-signals when they were being stimulated in either the STN or VIM (van den Wildenberg et al., 2006). In the present study we applied unilateral stimulation to the STN, which is less effective than bilateral stimulation for improving Parkinson’s symptoms in the contralateral hemibody (Bastian et al., 2003; Tabtal et al., 2008). Thus, the present finding suggests that when the treatment effects of DBS are limited, SSRTs do not decrease during DBS in a sample of patients whose off stimulation SSRTs are not restricted. The improvements in SSRTs reported by van den Wildenberg et al. (2006) therefore, as noted by the authors, may be explained by the more general benefits to motor function induced by DBS of the STN and VIM.

There was a close association between baseline SSRTs (off stimulation), and improvements in SSRTs during DBS. Patients with the slowest SSRTs tended to improve the most during stimulation. A similar finding was reported by Chen et al. (2006), who found that DBS induced improvements in finger tapping speed depended on performance measured off stimulation. In both studies, patients with the best off stimulation performance tended to become slower during DBS. These findings are consistent with the idea that at least some of the therapeutic effect of DBS of the STN is due to an
inhibition of the nucleus (Bekar et al., 2008; Benabid et al., 2005; Benazzouz & Hallett, 2000; Dostrovsky & Lozano, 2002). Thus, stimulating the STN may not only interfere with the aberrant activity thought to contribute to PD pathology (Kühn et al., 2008), but might also interfere with any remaining physiological function of the nucleus (Brown et al., 2006; Chen et al., 2006). Therefore, during periods of relatively preserved function (as occurs due to the fluctuating nature of Parkinson’s symptoms) DBS of the STN may actually impair motor control.

Of course, the ability to inhibit responses involves higher order executive, as well as motor process (see Chambers, Garavan, & Bellgrove, 2008), and DBS has been shown to affect cognitive skills in varying ways (Jahanshahi et al., 2000; Pillon et al., 2000; Rivaud-Pechoux et al., 2000; Schroeder et al., 2002). To further test the effects of DBS on SSRTs, we selected only those patients with baseline performance within the limits of an aged-matched control sample. In these patients DBS was found to significantly extend SSRTs. Our finding can be interpreted as evidence for a role of the STN in response inhibition, which is interrupted by high frequency DBS, observable only when more general improvements in Parkinson’s function are controlled for.

Our observation is consistent with a previous study that found that response inhibition is impaired during STN DBS when the cognitive demands of the task (a go-no-go task in this case) are high (Hershey et al., 2004). In a positron emission tomography (PET) study, using the same task, Campbell et al. (2008) found that decreases in response inhibition ability correlated with increased activity in the anterior cingulate cortex (ACC). This finding, and other PET studies (Hilker et al., 2004; Zhao, Sun, Li, & Wang, 2004), are incongruent with the idea that DBS induces a functional lesion of the STN. Instead, Campbell et al., argued that stimulation increases STN output, but causes a more regular firing rate that is not conducive to cognitive processes. The results of the present study could be explained by either of these hypotheses. Further research into the mechanisms of impairment in response inhibition induced by DBS is required to test these competing ideas.

Recently, the role of the STN in response inhibition has been described in terms of the known function of the STN in basal-ganglia circuitry. The STN is an important node of the indirect pathway, thought to contribute to the inhibition of motor programs (Alexander & Crutcher, 1990). Its output is excitatory to the output nuclei of the basal ganglia, which then act to inhibit thalamocortical outflow. Activation of the STN in an fMRI experiment during stop- compared to go-trials was therefore interpreted as evidence that the STN is acting to inhibit activity in basal ganglia-thalamocortical loops related to the go-response (Aron & Poldrack, 2006).

However, a recent study found that STN activity is greatest during unsuccessful compared with successful inhibition, and in those individuals with the longest SSRTs when only successfully inhibited stop-trials are included in the analysis, suggesting that its role may be other than that of simple inhibition (Ray Li et al., 2008). The latter authors suggest that the STN may process attentional aspects of the stop-signal and/or monitor performance, but it is not acting as a pathway for faster inhibition of the go-response. Indeed, lesions of the STN produce attentional deficits in rats (Baunez & Robbins, 1997), and STN activity is modulated during feedback based learning (Brown et al., 2006). Our finding that reaction times to stop-signals are reduced during stimulation of the STN might at first seem more consistent with the former hypothesis, since it implies that manipulations of the STN can effect the speed at which go-responses can be inhibited. However, SSRTs can only be estimated by finding the specific delay at which accuracy begins to fall below 50%. When measured in this way, SSRTs are not only determined by the speed of inhibitory processes, but also the accuracy with which these processes take place. Unfortunately it is impossible with the current data to determine if DBS affects the accuracy or the speed of response inhibition.

In the model described by Aron et al., the right IFC projects directly to the right STN to mediate response inhibition. STN is then proposed to act by inhibiting activity in thalamocortical loops related to the go-response. Supporting this idea Aron et al. (2007), using diffusion weighted imaging, found a connection between the right IFC and the right STN and in an earlier paper, reported right IFC and right STN activity during stop- compared with go-trials (Aron & Poldrack, 2006). If it is true that DBS impairs SSRTs by interrupting normal STN function, these findings would suggest that DBS of the right STN should impair performance more than DBS of the left STN. However we found the opposite to be true; DBS applied to the left STN significantly impaired performance, while DBS of the right STN had no effect. We can only speculate that stimulation of the right STN, as well as inducing some of the deficits seen during stimulation of the left STN, also resulted in counteractive improvements in SSRTs by altering activity in the right cortex, which is dominant for stop-signal processing.

6. Conclusion

In conclusion, we show that response inhibition is adversely affected by STN DBS when more general DBS induced improvements are controlled for. This suggests that, whether the impairment is induced by a functional lesion of the STN or by abnormal stimulation of thalamocortical loops necessary for cognitive processes, STN DBS can disrupt processes normally dependent on the integrity of STN. We also found that stimulation of the left STN is particularly deleterious to response inhibition, as reaction times became significantly longer during stimulation of the left STN than stimulation of the right STN. These outcomes need to be investigated further using imaging methods during unilateral DBS.

Acknowledgments

This work was funded by The Norman Collison Foundation, The Charles Wolfson Charitable Trust, Oxford Biomedical Research Centre & educational grant from Medtronic.

References


