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RESEARCH ARTICLE

Essential tremor impairs the ability to suppress involuntary action impulses

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Abstract

Essential tremor (ET) is a movement disorder characterized primarily by action tremor which affects the regulation of movements. Disruptions in cerebello-thalamocortical networks could interfere with cognitive control over actions in ET, for example, the ability to suppress a strong automatic impulse over a more appropriate action (conflict control). The current study investigated whether ET impacts conflict control proficiency. Forty-one ET patients and 29 age-matched healthy controls (HCs) performed a conflict control task (Simon task). Participants were instructed to give a left or right response to a spatially lateralized arrow (direction of the arrow). When the action signaled by the spatial location and direction of the arrow were non-corresponding (induced conflict), the inappropriate action impulse required suppression. Overall, ET patients responded slower and less accurately compared to HCs. ET patients were especially less accurate on non-corresponding conflict (Nc) versus corresponding (Cs) trials. A focused analysis on fast impulsive response rates (based on the accuracy rate at the fastest reaction times on Nc trials) showed that ET patients made more fast errors compared to HCs. Results suggest impaired conflict control in ET compared to HCs. The increased impulsive errors seen in the ET population may be a symptom of deficiencies in the cerebello-thalamocortical networks, or, be caused by indirect effects on the cortico-striatal pathways. Future studies into the functional networks impacted by ET (cortico-striatal and cerebello-thalamocortical pathways) could advance our understanding of inhibitory control in general and the cognitive deficits in ET.

Keywords Essential tremor · Cognitive control · Movement disorder · Cerebellum · Conflict control

Introduction

Essential tremor (ET) is a common neurological movement disorder characterized by an action tremor that interferes with the smooth execution of movements (Bagepally et al. 2012; Benito-Leon and Louis 2006; Benito-Leon et al. 2015; Cerasa et al. 2010). This disruptive tremor has been linked to alterations in cerebello-thalamocortical network activity as evidenced by neuroimaging studies and neurosurgical interventions targeting thalamic structures that ameliorate action tremor (e.g., thalamotomy, deep brain stimulation, focused ultrasound) (Benito-Leon et al. 2019; Buijink et al. 2015; Cerasa and Quattrone 2016; Cernera et al. 2019). Compromised cerebello-thalamocortical circuitries are increasingly associated with changes in executive cognition, neuropsychological studies disclose mild to moderate deficits among ET patients across a range of broad measures of executive functions, including verbal and visual working memory, Stroop interference, and set-shifting (Bhalsing et al. 2014;

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Troster et al. 2002; Passamonti et al. 2011; Janicki et al. 2013).

Given the unique motor control deficits in ET, recent studies have focused on how disruption to cerebello-thalamocortical circuitries in ET alter the proficiency of executive cognitive systems involved specifically in the control of actions (action control) (Brunamonti et al. 2014; Hughes et al. 2019). Using the stop-signal task (SST), a well-established paradigm that allows quantification of the latency to initiate and inhibit reactions, ET patients showed both slower reactions to stimulus events as well as slower stopping when presented with a sudden change in stimulus events. Thus, ET patients not only suffer from slower ability to initiate their actions, but also from diminished ability to control and cancel their actions when attempting to do so intentionally.

While ET is typically attributed to atrophy and abnormal function in cerebello-thalamocortical circuitry (Bhalsing et al. 2014), stopping proficiency has been shown to rely on prefrontal-basal ganglia-thalamic circuits (e.g., inferior frontal cortex (IFC), pre-supplementary motor area (Pre-SMA), subthalamic nucleus, caudate nucleus, anterior insula, (Aron et al. 2016; Cai et al. 2014; Swick et al. 2011). Thus, ET may have directly altered frontal-striatal stopping control circuitries, or indirectly interfered with both cerebello-thalamocortical and frontal-striatal circuitries at the common node (e.g., the thalamus). In both cerebello-thalamocortical and frontal-striatal pathways, the thalamus provides a critical node that connects cortical and subcortical structures (subthalamic nucleus, globus pallidus, cerebellum) (O'Muircheartaigh et al. 2015; Sun et al. 2018). Aberrant activity in the thalamus may underlie the expression of oscillatory tremor associated with cerebello-thalamocortical networks as well as deficits in action control attributed to frontal-basal ganglia circuitries.

In the current investigation, we examined the effect of ET on executive action control; specifically, the suppression of undesired, impulsive, or conflicting response tendencies termed conflict control. We used the Simon conflict task (Simon 1969, 1990) to create conflict between a fast-activating response impulse and a goal-driven alternative response. The Simon conflict task has been used extensively to study the dynamics of motor impulse activation and suppression in clinical populations, including movement disorders (e.g., Parkinson's Disease Laurent et al. 2018; van Wouwe et al. 2016, 2014), and in studies of the underlying neural systems involved in impulse control (Forstmann et al. 2011; Forstmann van den Wildenberg et al. 2008a, b; Georgiou-Karistianis et al. 2007). Distributional analytic methods have been developed to extract and quantify impulse activation and suppression dynamics, providing tools to determine the effects of neurological disease on (1) the strength of the initial activation of an action impulse (impulse capture), (2) the reactive inhibitory control engaged to suppress these impulses (impulse suppression) (Kornblum et al. 1990; van den Wildenberg et al. 2010; Wylie Ridderinkhof Bashore et al. 2010a, b).

Given that ET is clinically expressed by unintentional activations in the motor system, we predicted stronger activation of unintentional impulses that would be reflected by increased rates of fast impulsive action errors compared to healthy controls. In line with ET-related deficit in the ability to intentionally inhibit ongoing actions, we also tested the prediction that ET patients would show reduced proficiency in their ability to suppress interference from unwanted action impulses.

Methods

Participants

The study included 41 patients diagnosed clinically with ET by a board-certified neurologist using published diagnostic criteria (Bhatia et al. 2018) and 29 age-matched healthy controls (HC's). ET patients were recruited from the Movement Disorders Clinic in the Department of Neurology at Vanderbilt University Medical Center, and HC participants were recruited through community advertisement (see Table 1 for demographic information). Prior to participation in any procedures, all participants completed informed consent in full compliance with the ethical guidelines for investigation in human subjects according to the Internal Review Board (IRB) regulations at Vanderbilt University.

All participants had normal or corrected to normal vision and were excluded from the study if they had any pre-existing health conditions associated with significant cognitive impact that might confound study performance, including (1) a diagnosed neurological disease or condition other than ET (2) a health history inclusive of diagnoses and/or treatments capable of impacting cognitive function (e.g., a sleep disorder, untreated or severe psychiatric disorder, diabetes, cancer, etc.).

Participants with ET provided demographic data and completed the Mini Mental-State Examination (MMSE) (Folstein et al. 1975) and the Beck Depression Inventory (BDI) (Beck 1996). The MMSE was used to screen for and exclude anyone with severe gross cognitive deficits or potential indication of early dementia (< 25). In this sample, scores fell in the healthy range (see Table 1). The purpose of the BDI was to screen for and exclude anyone with severe untreated depression (see Table 1). ET participants also received a motor severity evaluation using the Washington Heights-Inwood Genetic Study of ET (Louis et al. 1997) or the Fahn-Tolosa-Marin (FTM) rating scale (Fahn et al. 1993), motor scores are available for a subset of the patients ($n = 24$). ET patients remained on current medications

Table 1 Demographics, neuropsychological variables, and motor scores (means and standard deviation) for the ET patients and aged matched controls

	Group		Between group statistics
	ET ($n=41$)	OHC ($n=29$)	
Age (years)	69.19 (6.68)	67.91 (10.21)	$F(1.68)=0.397$
Sex (M:F)	24 M/17F	13 M/16F	$X^2=0.142$
Education (years) (ET 35: HC 29)	14.03 (2.86)	15.79 (3.62)	$F(1.62)=4.741$*
MMSE	28.85 (1.37)	29.62 (0.78)	$F(1.68)=7.39$*
BDI (ET 37)	8.43 (8.15)		
Disease duration (years) (ET 38)	23.35 (14.78)		
FTM left (ET 21)	13.76 (6.63)		
FTM right (ET 21)	14.14 (5.92)		
WHIGET right (ET 3)	12.67 (5.51)		
WHIGET left (ET 3)	14 (7.21)		

Variables with data available for a subset of subjects have this added between brackets (ET: HC)

*$p<0.05$

MMSE mini mental state examination, *BDI* beck depression inventory, *FTM* Fahn-Tolosa-Marin, *WHIGET* Washington heights-inwood genetic study of ET

during the study (e.g., anti-epileptic drugs, beta-blockers, antidepressants).

Experimental tasks and procedures

The Simon task was administered on a 15.5- inch windows-based laptop computer placed approximately one meter from the participant just below eye level at a comfortable viewing angle. Participants were instructed to focus their attention on a fixation point (small black square against a light gray background) at the center of the screen and to respond as quickly and accurately as possible to the direction of a series of arrows that appeared one at a time either to the immediate left or right of the fixation point along the horizontal plane. An arrow appearing in either visual half-field (length = 2.1 cm; visual angle = 1.4 degrees; edge-to-edge separation between arrow and fixation point = 0.6 cm) could point to the left or to the right.

Using handheld response grips in each hand, participants were instructed to simply make a left or right thumb response corresponding to the arrow direction (i.e., press left to a left-pointing arrow; press right to a right-pointing arrow) as fast and as accurately as possible. When an arrow appeared to the left or right of fixation, it remained on the screen until the participant either made a response or a reaction time (RT) limit of 1000 ms (ms) was reached, upon which the arrow was extinguished and a variable intertrial interval of 750–1250 ms elapsed before another arrow appeared. The fixation point remained on the screen at all times. Thus, each trial was defined by a fixation point that after a variable intertrial interval was, followed by the presentation of the imperative arrow until a response was issued or the time limit elapsed.

The critical independent variable was the relationship between the direction of the arrow and the side of fixation to which the arrow appeared (*Stimulus Correspondence*). A corresponding (Cs) trial occurred when the arrow pointed to the same side as it appeared (e.g., a left-pointing arrow appeared to the left of fixation). A non-corresponding trial (Nc) occurred when the direction the arrow pointed conflicted with the side of fixation to where it appeared (e.g., a left-pointing arrow appeared to the right of fixation). There is extensive literature supporting reactions to Nc trials are both slower and more error prone as compared to reactions to Cs trials, the magnitude of this cost is the Simon effect.

Participants completed 16 practice trials followed by 3 blocks of 104 experimental trials (312 in total). The trials in each block were equally counterbalanced by side of response (equal numbers of required left and right responses) and by stimulus correspondence (Cs and Nc trials occurred with equal probabilities), but the order of trials was random.

Statistical techniques

Statistical analyses focused on the effects of group (ET, HC) and stimulus correspondence (Cs, Nc) on two critical aspects of performance: (1) mean reaction times (ms) and accuracy rates (%), and (2) distributional performance patterns captured in delta plots and conditional accuracy functions. Before analyzing, trials associated with RTs faster than 150 ms (anticipatory guesses) or slower than 3 standard deviations above the mean within each condition were excluded from analysis as outliers, which accounted for fewer than 1% of trials. Accuracy rates were square root-transformed to approximate a normal distribution but were reported in text, tables, and graphs as non-transformed rates for ease of interpretation. Mean RTs and

accuracy rates were computed for each participant to submit to a repeated measures analysis of variance to determine the effects of group and stimulus correspondence.

Distributional patterns of effects, as prescribed by the dual process activation-suppression (DPAS) model, provides quantitative insights into two temporally distinct cognitive processes that unfold during conflict processing (van Wouwe et al. 2016; van Wouwe et al. 2017; Wylie Ridderinkhof Elias et al. 2010a, b; Wylie et al. 2009a, b):(1) the strength of initial activation of the incorrect (fast) action impulse (*impulse capture*) (2) the proficiency of the inhibitory control engaged to suppress the interfering action impulse (*impulse suppression*). To quantify the strength of *impulse capture*, accuracy rates were plotted across 6 successive bins of the reaction distribution (from slowest to fastest reactions) (i.e., a *conditional accuracy function, CAF*) for each level of Correspondence (Kornblum et al. 1990; van den Wildenberg et al. 2010; Wylie Ridderinkhof Bashore et al. 2010a, b). A fast-action impulse is produced in the hand that is on the side of the location of the arrow, the stronger the initial activation, the higher the percentage of fast impulsive errors on Nc trials. Thus, strength of incorrect action impulses is quantified by the accuracy rate on Nc trials associated with the fast bin of the RT distribution (van den Wildenberg et al. 2010).

According to the DPAS model, the initial activation of an incorrect response impulse is counteracted by the engagement of a suppression mechanism to reduce the interference produced by this activation (Ridderinkhof 2002). This suppression process can be visualized and quantified by plotting the size of the Simon effect on RTs (i.e., the cost to RT on Nc compared to Cs trials) across the entire RT distribution, i.e. a *delta plot* (Luce 1986; Proctor et al. 2011). On early segments of the RT distribution when reactions are fast, there is strong interference produced by the incorrect impulse activation because there has not been enough time to build up suppression. However, as suppression builds over time, the delta plot reveals a significant reduction in the magnitude of interference and most often a reversal and reduction in interference at longer latency reactions (i.e., evident at the slow end of the RT distribution) (Ridderinkhof 2002). The slope of the interference reduction between the latest bins of the delta plot describes the proficiency of suppression; leveling, or negative-going, slopes are associated with better inhibition of the action impulse (van den Wildenberg et al. 2010).

Our next set of analyses focused on determining the effects of group on the strength of impulse capture (i.e., accuracy rates from the fasted response time bin of the conditional accuracy function), and on the proficiency of impulse suppression (i.e., the slope between the final two bins of the delta plot. We used a repeated measures analysis of variance to test the effects of group and stimulus correspondence on impulse capture and a one-way ANOVA to determine the effect of group on the final delta slope.

Finally, for a subset of patients with available data, we correlated clinical measures (age, disease duration and motor score) with the delta slopes and impulse capture.

Results

Mean simon effects

Figure 1a, b and Table 2 show respectively the mean RTs and accuracy rates by *Group* and *Correspondence*. Table 3 includes an overview of the statistics. Overall, ET patients and HCs demonstrated robust Simon effects on RT and accuracy rates. Reactions on Nc conflict trials were slower (683 ms) and less accurate (93%) compared to Cs trials (584 ms, 98%) (*Correspondence*, RT: F (1,68) = 297.06, $p < 0.001$, $\eta^2 = 0.81$; Acc: F (1,68) = 79.36, $p < 0.001$, $\eta^2 = 0.54$). Responses were generally slower and less accurate among ET patients (666 ms, 94%) compared to HCs

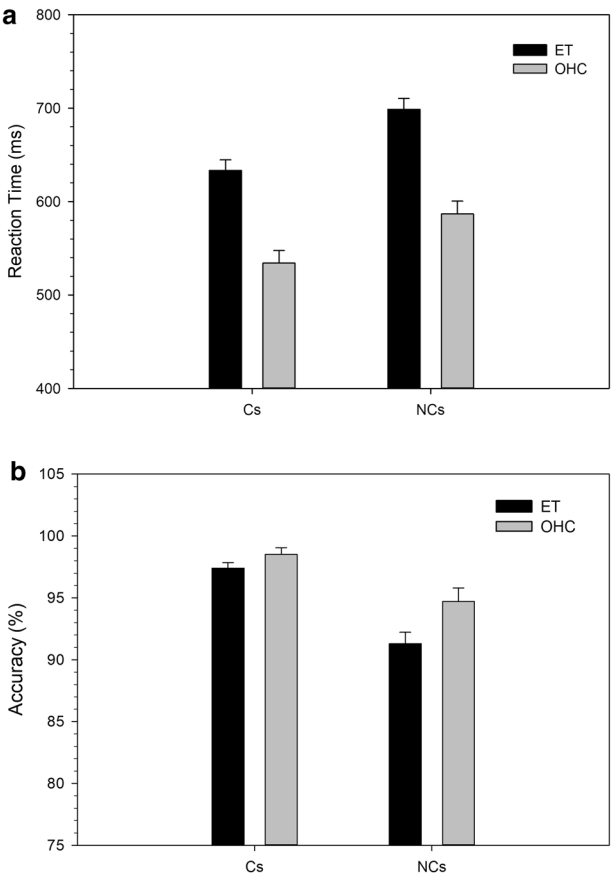

Fig. 1 Mean RTs (**A**) and accuracy rates (**B**) on corresponding (Cs) and noncorresponding (Nc) trial types for ET patients and HC. Error bars reflect standard error of the mean

Table 2 Means and standard errors for the conflict control variables in ET patients and aged matched controls

	Group	
	ET ($n=41$)	OHC ($n=29$)
Cs RT (ms)	633 (11)	534 (13)
NC RT (ms)	699 (12)	586 (14)
Cs Accuracy (% correct)	97.4 (0.01)	98.5 (0.01)
NC Accuracy (% correct)	91.3 (0.01)	94.7(0.01)
Final delta slope	0.06 (0.04)	0.02 (0.05)
First bin accuracy Cs (% correct)	97 (0.01)	99.3 (0.01)
First bin accuracy NC (% correct)	74.4 (0.03)	85.7 (0.03)

Table 3 F-values for main and interaction effects on Simon accuracy and reaction times

	Accuracy	RT
Group	5.29*	36.5**
Correspondence	79.36**	297.06**
Group × correspondence	4.58*	3.45

*$p<0.05$ **$p<0.001$

(560 ms, 97%), (*Group,* RT: F (1,68) = 36.5, $p<0.001$, $\eta^2=0.35$, Acc: F (1,68) = 5.29 $p<0.05$, $\eta^2=0.07$). However, the Simon effect on accuracy, but not RT, was more pronounced among ET patients compared to HCs, (Correspondence × Group, Acc: F (1,68) = 4.58, $p<0.05$, $\eta^2=0.06$; RT: F (1,68) = 3.45, $p=0.07$, $\eta^2=0.05$). That is, the reduction in accuracy produced by the conflict on Nc trials was larger for ET patients (Fig. 1).

Distributional analyses

Impulse capture

Figure 2 shows the conditional accuracy function plotting accuracy rates across the RT distribution separately by group and for Cs and Nc trials. It is visibly evident that the errors on the Simon task are focused on the fastest reaction on Nc trials. Comparing the rates of errors at the fastest bin shows a significantly higher error rate on fast Nc (80% accuracy) trials compared to fast Cs (98% accuracy) trials (*Correspondence*, RT: F (1,68) = 61.94, $p<0.001$, $\eta^2=0.48$). More fast errors are committed by ET patients (86% accuracy) than by HCs (93% accuracy), irrespective of correspondence, (*Group*, F (1,68) = 7.0, $p<0.05$, $\eta^2=0.09$). However, the increase in fast errors on Nc conflict trials compared to Cs trials is significantly more pronounced for ET patients compared to HCs (ET: Nc = 74%, Cs = 97%; HC: Nc = 86%, Cs = 99% correct) (Correspondence × Group, F (1,68) = 4.85, $p<0.05$, $\eta^2=0.07$). This pattern is consistent

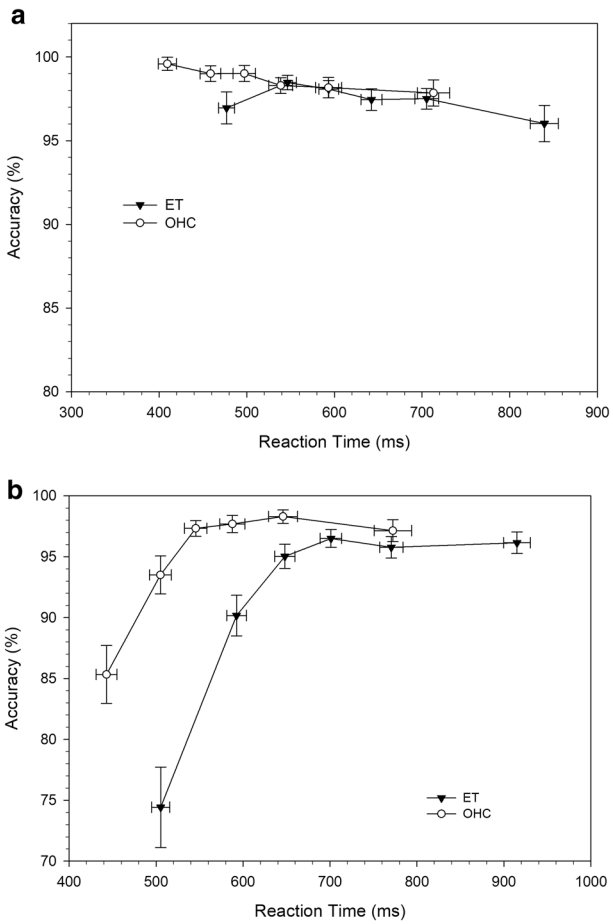

Fig. 2 Conditional accuracy functions for corresponding (**A**, Cs) and non-corresponding (**B**, Nc) trial types for ET patients and HC

with stronger activation and capture by unintentional reaction impulses in ET.

Impulse suppression

Figure 3 shows delta plots depicting the Simon effect across the RT distribution for each group. The plots for both groups show an early steep increase in interference effects that level off toward the middle and tail end of the delta plot. This leveling off is consistent with suppression. Notably, comparing the slope between the final segments of the delta plot does not indicate differences in the proficiency of suppression between ET and controls (*Group*, F (1,68) = 0.35, $p=0.56$, $\eta^2=0.005$).

Correlations

For the subset of patients with an FTM rating ($n=21$), we correlated the total FTM score with impulsive error rates, the delta slopes and RTs on conflict trials. There were no significant correlations, rs < 0.15, ps > 0.63. We also correlated

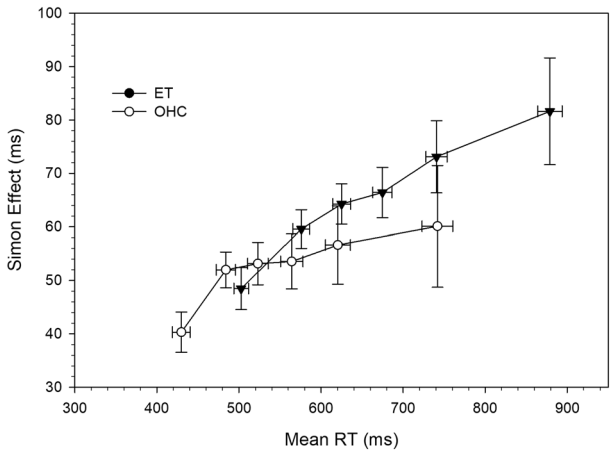

Fig. 3 RT delta plots for ET patients and HC. Each bin contains the same number of trials, averaged across the subjects in each subgroup

disease duration, depression (bdi score) and age (separately for ET and HC) with the action control measures. Disease duration and depression were not associated with impulsive errors, slopes or conflict RTs in ET, $rs < 0.21$, $ps > 0.20$. Age was significantly linked to slower RTs in conflict trials in both HCs ($r = 0.41$, $p = 0.03$) and ET ($r = 0.37$, $p = 0.02$).

Discussion

The current investigation tested predictions about the effects of ET and, by association, the effects of cerebello-cortico-thalamic circuitry dysfunction on the activation and suppression of unintended action impulses. Using the combined framework of the Simon conflict task and the DPAS model, ET patients and HCs produced expected Simon effects on RTs and accuracy rates. In both groups, responses were both slower and less accurate on conflict (Nc) trials compared to trials where there was no conflict (Cs). Conditional accuracy functions provided more detail and exposed a pronounced increase in impulsive errors on conflict trials associated with the fastest segments of the RT distribution compared to HCs. Based on DPAS reasoning, ET patients experienced greater difficulty restraining strong, unintended reactive impulses from being expressed in overt movement. Notably, this enhanced susceptibility to acting on strong impulses was not due to strategic tradeoffs between speed and accuracy, as RTs among ET patients were generally slower than HCs.

Contrary to one of our hypotheses, the proficiency of impulse suppression, as reflected in the reduction in the rise of the interference effect at the slowest RTs (i.e., delta plot), was similar among ET and HC groups, even though the magnitude of interference and the slope increase across the distribution appear higher in ET. Despite the visual appearance of a difference between groups, the variability of the late delta plot slope may have been too high to confidently detect a difference. One limitation of the study was an incomplete availability of a single tremor rating scale. Linking clinical tremor ratings to action control measures could be helpful in understanding the variability in suppression among ET patients in future studies.

These results add to a growing body of evidence that ET has an effect on action control beyond tremor. Previous investigations on inhibitory stopping control in ET patients have found slowed action initiation and a reduced ability to stop actions intentionally (Brunamonti et al. 2014; Hughes et al. 2019). Experimental studies of other cognitive control measures like the Attentional Network Task have also observed differences in performance in ET populations. Pauletti et al. (Pauletti et al. 2015, 2013) reported that ET patients showed increased slowing to task conditions that required cognitive control relative to healthy controls. Our current work extends these findings by showing that ET disrupts the ability to restrain unintended action impulses. Underlying this susceptibility may be a lowered threshold for triggering motor actions or stronger activation of incidental motor urges. Future studies could advance our understanding of this effect by manipulating speed or accuracy requirements in a conflict task or by using event-related brain potentials to characterize the magnitude and timing of the lateralized motor potential associated with incorrect response activations in conflict tasks.

Potential neural mechanism

Impulse (or conflict) control has been linked to the frontal-basal ganglia neural circuitry including the dorsomedial prefrontal cortex (dmPFC), anterior cingulate cortex (ACC), pre-supplementary motor area (preSMA), right inferior frontal cortex (rIFC), striatum, and subthalamic nucleus (Botvinick et al. 2004; Cavanagh et al. 2012; Cavanagh et al. 2011; Forstmann, Jahfari, et al. 2008a, b; Forstmann, van den Wildenberg, et al. 2008a, b; Ridderinkhof et al. 2004). DmPFC and ACC are thought to detect (motor) conflict and activate the STN via the hyperdirect pathway (Wiecki and Frank 2013; Zavala et al. 2015). The STN subsequently increases GPi's activity thereby inhibiting the thalamus and motor output, thus pausing or stopping the motor system to allow for more time to select the correct action (Frank 2006).

Although ET pathology has been associated with abnormal signaling in cerebello-thalamic-cortical circuitries and degradation of cerebellar gray and white matter (Cerasa and Quattrone 2016; Hett et al. 2021), gray matter volume loss in cortical areas like the ACC and rIFC (Bhalsing et al. 2014) could potentially explain a reduced ability to detect conflict in ET and result in motor impulsivity. Alternatively, cerebello-thalamocortical networks could play a larger role in impulse control than what is currently been

shown, because conflict control has traditionally been more closely investigated in frontal-striatal networks deficiencies like Parkinson's disease (Alderson et al. 2007; Jahanshahi et al. 2015; Manza et al. 2017; van Wouwe et al. 2016; Wylie et al. 2009a). Parkinson's disease and dopaminergic medication mostly impacted impulse suppression (van Wouwe et al. 2016; Wylie et al. 2012), whereas impulse capture is not always consistently modulated by PD (dependent on disease severity), dopaminergic medication (van Wouwe et al. 2016; Wylie et al. 2012, 2009a) or STN modulation (van Wouwe et al. 2017).

Alternatively, evidence from studies in patients with cerebellar damage has suggested that cerebellar dysfunction might also lead to motor impulsivity by reducing error-based performance monitoring (Peterburs et al. 2015; Schweizer et al. 2007). Likewise, imaging studies on error detection and the ability to adjust performance (Hirose et al. 2014; Ide and Li 2011) have suggested that cortico-cerebellar networks play a role in cognitive control (cerebellum, thalamus, ventrolateral PFC, rIFC). Thus, cerebellar dysfunction and impaired cortico-cerebellar circuits could account for the increase in impulsive errors in ET.

Future neuroimaging studies should aim to investigate how cerebello-thalamocortical network dysfunction in ET relates to action impulsivity. Specifically, imaging studies exploring structural and functional changes related to impulsivity could help disassociate involvement of cerebellar versus cortical-striatal dysfunction related to conflict control in ET. A thalamic stimulation study may also reveal the degree to which these networks can be influenced through stimulation and whether that translates to increased conflict control.

Clinical relevance

Neuropsychological studies have previously pointed at executive control deficits in ET (Bhalsing et al. 2014; Janicki et al. 2013; Passamonti et al. 2011; Troster et al. 2002). The current work, combined with other studies on cognitive control (Pauletti et al. 2015, 2013; Brunamonti et al. 2014; Hughes et al. 2019), confirms that ET entails more than clinical motor symptoms, the present study goes beyond these broad executive deficits by showing specific difficulties with the *control* over actions in ET. Clinically, these findings could translate to recommendations for cognitively demanding situations in which pressure, conflicting information, or even conflicting emotions might benefit from deliberate slowing to avoid making impulsive errors.

Limitations

There are a few relevant limitations in the current study. First, ET patients remained on their regular medications during the study and medication details were not available for the complete dataset. These medications aim to help suppress action tremor, so patients in the treated state may not be fully expressing action control deficits, however, it is unknown how some of these medications may impact action control processes. Future experimental designs should consider testing patients off medication or standardize intake across patients of specific types of medications that may impact performance and control for it in the analysis. Second, we did not have a measure of anxiety included in our study which could have biased attention and thereby task performance. Given the generally higher rates of anxiety in ET patients (Janicki 2013), including an anxiety scale would be recommended for future studies.

Also, it is important to point out that we studied an older group of ET patients, which may be limited in generalizing to younger patients with ET. The reduction of Simon interference as expressed in the delta plot was not as dramatic as depicted in other clinical studies with Parkinson's Disease patients and older healthy controls (Laurent et al. 2018). This could be a reflection of the relatively older participants in this study as inhibitory control skills are known to diminish with age (Kawai et al. 2012; West 1996). A clinically relevant limitation was the inconsistent use of a single tremor rating scale, which limited the analyses between conflict control and clinical motor impairments to a subset of patients.

Conclusion

The current study demonstrates that ET patients are more susceptible to acting on strong response impulses evoked unintentionally in the motor system. These findings point to alterations in cortico-striatal activity induced directly by ET pathological processes or indirectly by alterations at the thalamic node that interfaces both cortico-striatal and cerebello-cortical circuitries.

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Data availability Anonymized data will be available on reasonable request by a qualified investigator.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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