Experimental Brain Research (2019) 237:2505–2521
https://doi.org/10.1007/s00221-019-05608-w

RESEARCH ARTICLE

Mental representation of the body in action in Parkinson's disease

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Received: 15 February 2019 / Accepted: 17 July 2019 / Published online: 20 July 2019

Abstract
Mixed findings characterize studies in Parkinson's disease (PD): some studies indicate a relationship between physical impairments and the ability to mentally represent the body, while others suggest spared abilities for this cognitive function. To clarify the matter, in the present study we explored the mental representations of the body in action in the same PD patients, taking also into account lateralization of symptoms and visual imagery skills. 10 PD patients with left- (lPD), 10 with right (rPD) lateralized symptoms (lPD), and 20 matched healthy controls have been recruited for the study. All patients were screened for neuropsychological impairments. To explore a more implicit component we used the hand laterality task (HLT), while the mental motor chronometry (MMC) was used to explore a more explicit one. Two control tasks, with objects instead of body parts, were administered to control for visual imagery skills. In the HLT, we detected the effects of biomechanical constraints effects in both controls and PD patients. In the latter group, importantly, this was true independently from lateralization of symptoms. In the MMC, we found the expected positive correlation between executed and imagined movements for both hands in controls only, while all PD patients, again independently form lateralization, only showed this effect for the left hand. In terms of visual imagery, only rPD patients differed from controls when asked to implicitly rotate letters, and in terms of accuracy only. However, this difference is explained by executive functions measured through the neuropsychological assessment rather than by a "pure" visual imagery impairment. In summary, our findings suggest that two different aspects of the mental representations of the body in action, one more implicit and the other more explicit, can be differently affected by PD. These impairments are unlikely explained by a basic visual imagery deficit. When present, impairments concern a higher dimension, related to motor functions and awareness, and not driven by sensory impairments, as shown by the independence of effects from physical laterality of symptoms.

Keywords Parkinson's disease · Body representation · Motor imagery · Hand laterality task · Mental chronometry

Introduction

Since its first description (Parkinson 1817), Parkinson's disease (PD) relation to the body and to action has been evident: cardinal symptoms, such as akinesia and bradykinesia, tremor and rigidity, postural instability (Bereczki 2010), reflect the dysfunction of neural structures responsible for movements selection, coordination, and execution (see Moustafa et al. 2016 for a review). Research has been rightfully devoted to understanding the mechanisms underlying this complex symptomology (Jankovic 2008; Dawson and Dawson 2003) as well as to the development of pharmacological treatments (Seppi et al. 2011) and to deep brain stimulation efficacy (Moro et al. 2002; Deusch et al. 2006). On the other hand, the effect of these symptoms on the cognitive representation of the body is less explored, in spite

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of its importance when planning physical rehabilitation in motor-related conditions (Sedda et al. 2018).

Our physical body represents the bridge between our mind and the environment: it plays a pivotal role in the development of our self, including personal identity and self-esteem (Longo 2015). The brain processes visual, tactile, vestibular and many other sensory inputs and integrates them with top-down information to form a cognitive representation of our body. Disruptions of primary sensory inputs (Berlucchi and Aglioti 2010; Schwoebel et al. 2001) as well as their integration (Blanke 2012; Ehrsson 2012) impact on the integrity of this representation. In PD, sensory impairments (Abbruzzese and Berardelli 2003; Conte et al. 2013) as well as sensory-motor integration difficulties (Tamburin et al. 2003; Almeida et al. 2005; Ren et al. 2018) are reported, corroborating the hypothesis that in this condition the ability to access the mental representation of the body in action might be altered. For instance, individuals affected by PD generally experience tremor during rest, on one side of the body or, as the disease progresses, on both sides. This tremor can be described as an unintentional but conscious movement. Interestingly, tremor can be experimentally induced in healthy individuals, through a phenomenon known as the Pinocchio's illusion (Lackner 1988). In the Pinocchio illusion, individuals feel that their nose, for instance, is elongated due to the vibrations applied to the biceps of the arm touching the nose. The peripheral proprioceptive feedback, altered through this external manipulation, generates the illusion that the arm (hence, the hand) is moving away from the nose, suggesting that the nose is longer as the individual is still able to touch it. This peculiar bodily illusion shows how tremor can impact on how we represent our body, and individuals affected by PD experience a similar, but not experimentally induced, tremor on a daily basis.

As known from other conditions, treatments for movement disorders must take into account also cognitive components to be effective, as impairments to the physical body most often lead to a different representation of the entire body (Fuentes et al. 2013; Fiori et al. 2014; Sedda et al. 2018); for example, individuals with spinal cord injuries represent their body parts as elongated, independently from the lesion level (Fuentes et al. 2013). Similarly, a paralysis of the lower limbs impairs perception of object affordances even when upper limbs are not affected by the injury (Sedda et al. 2018). Hence, understanding how individuals affected by PD access the representation of their body in action is of uttermost importance to further develop treatments and to allow patients to have a better chance at managing physical changes associated with the condition.

Motor imagery tasks allow to explore the mental representation of the body in action (Jeannerod 1994; Schwoebel and Coslett 2005; De Lange et al. 2008). In such tasks, individuals are asked to imagine performing a movement or to imagine rotating a body part to match the position of the corresponding physical part. Motor imagery is influenced by sensations, perceptions, memories, and ideas about one's own and others' anatomy (Berlucchi and Aglioti 1997), but also by posture (Sirigu et al. 1996; Parsons and Lawrence 1994), pain (Schwoebel et al. 2001; Coslett et al. 2010), motor limitations (Fiori et al. 2013; Amesz et al. 2016), and congenital absence of body parts (Funk and Brugger 2008). Focusing on the execution and mental simulation of body movements, in their recent review, Caligiore et al. (2017) report that individuals affected by PD are slower compared to healthy participants, specifically when they are required to move or imagine moving the affected hand. Conson et al. (2014) reported an impairment in PD patients in a task explicitly requiring them to simulate their own body rotation. The task used in this study requires participants to perform left–right judgments on a schematic representation of a human body, whose left or right hand are coloured in black and that can be presented facing towards or away from the observers. Participants judge if the marked hand on the schematic figure is the left or the right hand, after imagining themselves to be in the figure's body position and to have its perspective. Crucially, in the front-facing orientation, participants have to imagine their own bodies in the position of the schematic figure, to perform the left/right judgment. In other words, they need to perform a motor imagery process. However, the study finds impairments for PD patients in the condition with the same perspective of the observer only, the back facing one, and not in the front facing; moreover, this impairment seems to be related to the lateralization of motor symptoms in PD. In spite of the interesting findings and the presence of a control task with non-body stimuli, the data do not allow to conclude for a specific impairment.

More recent studies investigate body scaled action (Smith et al. 2011), mental representation of whole body (Conson et al. 2014), tool embodiment (Scarpina et al. 2019), and body ownership (Ding et al. 2017), but they do not solve the enigma. For example, Ding et al. (2017) use the rubber hand illusion (Botvinck and Cohen 1998) to investigate body ownership (Ehrsson et al. 2005). Ding et al. observe that individuals affected by PD consciously perceive the effect of the illusion not only in the experimental (i.e. when the tactile stimulus perceived on the real hidden hand is synchronous with the view of stroking on the fake hand) condition but also in the control condition (when the stimulation is not synchronous). Moreover, in both conditions, the traditional proprioceptive drift (Tsakiris and Haggard 2005) towards the rubber hand emerges, meaning that the own hand, hidden from view, is perceived to be shifted towards the rubber hand even when the stimulation is not synchronous. The results by Ding et al. (2017) could also be explained by a difficulty in localizing the hand position using proprioception (Conte et al. 2013; Konczak et al. 2009; Mongeon et al.

2009), as well as by aberrant multisensory integration processes (Almeida et al. 2005; Barnett-Cowan et al. 2010), and not necessarily by an impaired representation of the body in action.

Part of the controversy might be related to the use of tasks that explore different components of the motor representation of the body, but never in conjunction or in comparison. Different tasks require a different level of awareness, and this dissociations between more implicit and more explicit components in the awareness continuum of body representation have a long tradition in psychology (Longo 2015). Put it differently, tasks differ in terms of the amount of action monitoring that participants should apply (De Lange et al. 2008). One of the most traditional task to investigate the more implicit components of body representation is the hand laterality task (Parsons 1987), in which individuals are asked to judge if a visual stimulus represents the left or the right hand, independently from its spatial rotation (i.e. the stimulus is shown without any rotation or rotated 180°) and view (i.e. the palm or the dorsum of the hand is shown). To solve the task, individuals imagine rotating the position of their real hand to match that of the visual hand; however, they are not aware of this process and use an implicit motor strategy. An increase in required awareness is observed when individuals are asked to perform or to imagine performing movements with their limbs, such as in the mental motor chronometry task or in tasks with specific instructions similar to the one adopted by Conson et al. (2014), Schwoebel and Coslett (2005) and Sirigu et al. (1996). What more and less implicit tasks have in common is the strong link between physical abilities and the motor representation of the body. In the Mental Motor Chronometry Task, the relationship between the time required to perform an action and that required to mentally simulate represents this tight link (Conson et al. 2010). In the hand laterality task, laterality judgments are more accurate and faster when body parts are shown in a position which is easy and comfortable to reach, mirroring the physical body constraints (Parsons 1987; Sirigu et al. 1996; Conson et al. 2010).

The aim of our study is to explore the access to motor imagery in PD by means of a set of tasks tackling more implicit and more explicit components, as well as including control tasks, to clarify if previous inconsistencies are due to methodological reasons associated with the tasks themselves. We administered a sample of individuals affected by PD with both the hand laterality task (Parsons 1987; Fiori et al. 2013) and the mental motor chronometry task (Schwoebel and Coslett 2005; Sirigu et al. 1996). Furthermore, basing on previous work (Fiori et al. 2014; Brady et al. 2011), we introduced two control tasks, in which "objects" (letters and bars) instead of "body parts" are used to weight the role of visual imagery skills. A final improvement of this study is the selection of cognitively unimpaired patients. Tasks such as the HLT have been proven to be difficult for individuals in which cognitive functioning is compromised (Trojano and Grossi 1994; Bartolomeo 2002) as well as in aging (Saimpont et al. 2013). Instructions might be misunderstood and results misleading. As this might be the case also for previous studies on PD, as this condition is also associated with frontal executive impairments, we took extra care in patients' neuropsychological screening.

If PD does not affect accessing a mental representation of the body in action, no difference should emerge in tasks using body parts between patients and matched healthy controls. On the other hand, with this setup, if an impairment is present, we are able to observe a difference between patients and controls in both more explicit and more implicit tasks using body parts, which would indicate a global compromising in bodily cognition. On the other hand, an impairment restricted to one of the tasks only would indicate a specific dysfunction related to action planning awareness. If participants with PD show a different performance in the hand laterality task, but not in the mental motor chronometry task, we might conclude that the impairment is related to the more implicit components, characterized by a lower level of awareness in terms of motor action and planning. Otherwise, if any difference is found in the mental motor chronometry task, more explicit components might be compromised, informing us on the role of awareness. By means of comparing left and right PD patients, we can also rule out to which extent the differences are affected by symptoms lateralization, in other words by sensory processing, as well as controlling for executive difficulties that could affect task compliance using the neuropsychological information collected.

Methods

The study was approved by the Ethic Committee of the I.R.C.C.S Istituto Auxologico Italiano and was performed in accordance with the Declaration of Helsinki's principles (World Medical Association 1991). All participants were volunteers who gave informed written consent prior to participating in the study, were free to withdraw at any time and were naïve to the rationale of the experiment.

Participants

We recruited 20 individuals affected by PD and 20 matched healthy controls. All were right-handed as confirmed by the Edinburgh Handedness Inventory (Oldfield 1971) and native Italian speakers.

The neurological examination confirmed the diagnosis of idiopathic PD in recruited patients, the side of disease onset and the disease duration. Ten individuals (7 females;

age in years: $M=65$, SD = 7; education in years: $M=9$; SD = 3) had a right-side onset of symptoms (rPD), suggesting a greater left-hemisphere dysfunction. Ten individuals (5 females; age in years $M=61$, SD = 8; education in years = 11, SD = 4) had a left-side onset (lPD; greater right hemisphere dysfunction). For each participant, the score at the motor scale of the Unified Parkinson's Disease Rating Scale (UPDRS) (Fahn et al. 1987) as well years from disease onset were collected. Exclusion criteria were evidence of other neurological conditions (e.g., ictus, traumatic brain injury) as well as the presence of psychiatric syndromes, or drug and alcohol abuse. All patients were assessed during subjective on-phase.[1]

The 20 matched healthy controls (9 females; Age in years $M=59$, SD = 8; Education in years $M=11$, SD = 3) did not report any sensory, neurological or psychiatric impairment. They were recruited outside the clinical institute through personal contacts of the researchers and word-of-mouth.

Neuropsychological assessment

To assess global cognitive functioning, all participants were administered with the mini-mental state examination (MMSE) (Folstein et al. 1975; Magni et al. 1996) and the clock drawing test (Agrell and Dehlin 1998; Mondini et al. 2003). Executive functions, usually impaired in PD (Emre et al. 2007), and specifical inhibition of interference, were assessed with the frontal assessment battery (FAB) (Dubois et al. 2000; Appollonio et al. 2005) and the Stroop test (Stroop 1935, Caffarra et al. 2002). For the Stroop test, time interference, based on execution time, and error, based on number of errors (Caffarra et al. 2002; Scarpina and Tagini 2017) were taken into account. Finally, the short screening test for ideo-motor apraxia (STIMA) (Tessari et al. 2015) was used to estimate the capability to imitate gestures. The neuropsychological tests were administered to patients as part of the hospital assessment protocol.

Experimental tasks

The hand laterality task and the mental motor chronometry task were used to explore, respectively, the more implicit and the more explicit components of motor imagery. The mirror letter discrimination task and the mental bars movement task were administered as control tasks to explore visual imagery skills (respectively, for the more implicit and the more explicit components). In these tasks, objects instead of hands are used as the target of the imagery processes. The order of components (more implicit vs more explicit) was randomized between participants. For each component, the experimental tasks (the hand laterality task and the mental motor chronometry task) were administered after the control task (the mirror letter discrimination task and the mental bars movement task) to ensure consistent activation of imagery processes.

Hand laterality task (Fig. 1a)

This task is a modified version of the hand laterality task (Parsons 1987; Parsons and Lawrence 1994), used in previous studies on spinal cord injured patients (Fiori et al. 2013, 2014). Right-back/palm and left-back/palm pictures of hands are presented in four different orientations: 0°; 90°; 180°; 270°. To detect the effect of stimulus orientation, right and left hands at 0° and right and left hands at 180° are considered. To detect the effect of biomechanical constraints, right hands at 270° and left hands at 90° are used to compute the index for comfortable postures, whilst right hands at 90° and left hands at 270° are used for awkward postures.

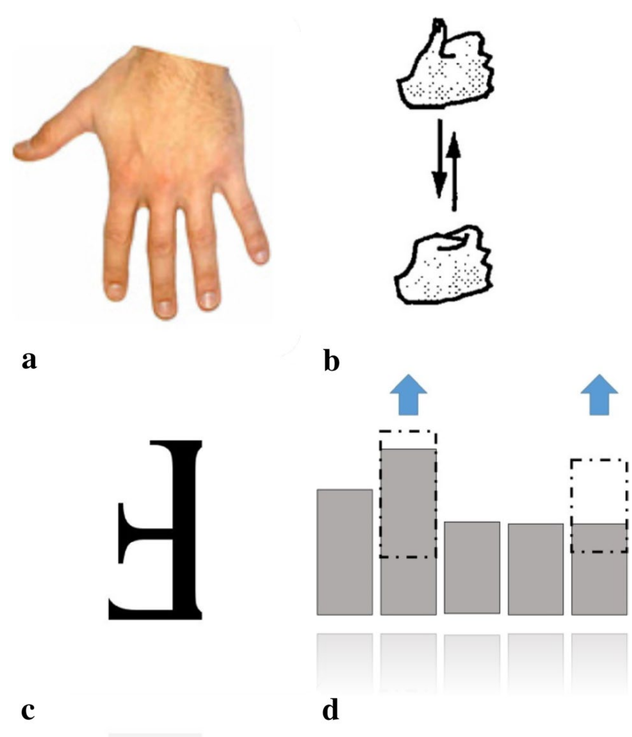

Fig. 1 Example of stimuli for the hand laterality task [left hand rotated 180°] (**a**), the mental motor chronometry [thumb extension from the fist] (**b**), the mirror letter discrimination task [canonical *F* rotated 180°] (**c**) and the mental bar movements [bars movement mimicking the extension of index and the little fingers (**d**)

[1] Individuals affected by PD experience "On-phase" states, when symptoms are managed through medication, and "Off-phase" states, during which symptoms such as tremor, rigidity and slow movements emerge or worsen (Ahlskog and Muenter 2001; Fahn 2004).

Overall, 16 pictures (8 pictures of the right hand and 8 pictures of the left hand) in back or palm perspective are used. The task consists of 96 trials divided into two blocks (48 trials for each block): each stimulus is presented 6 times (3 in the first and 3 in the second block) in a randomized order. In our study, the two experimental blocks were preceded by one practice block, composed of six stimuli selected randomly from the full data set, to familiarize participants with the task. Pictures measured 1100 by 777 pixels to cover a 21 by 23° visual angle when the images were displayed at a distance of 50 cm. All the stimuli were presented on a computer screen (13.3 by 11.6 in.), with a screen resolution of 1920 by 10780, using Psycho-Py 1.83.03 (Psychology software in Python) (Peirce 2007).

Participants sat in front of the computer screen with their left and right index fingers on the "z" and "m" keys of the keyboard. They were asked to judge if the stimulus represented a right or a left hand by pressing, as quickly and as accurately as possible, the "z" key if the picture on the screen was a left hand or the "m" key if the picture was a right hand in one block, and the reverse in the other block. Block order was randomized between subjects: a half part of participants responded with the right hand for right-hand stimuli, and the left hand for the left-hand stimuli in the first experimental block, and vice versa for the second block; a second half of participants performed the experiment with the opposite combination. Each trial was preceded by a fixation cross lasting 1500 ms (ms).

For each trial, reaction time in ms (RT; correct answers only) and the answer provided by participants were recorded. Average RT in ms and average accuracy (the percentage of correct answers) were calculated for each combination of orientation and posture.

Control task for the HLT: mirror letter discrimination task (Fig. 1c)

The same version of Fiori et al. (2013, 2014) was adopted. Participants were required to judge if an alphanumeric character was shown in a canonical or mirror-reversed position. Pictures of the letters "F" and "J" were shown in their canonical or mirrored-reversed positions (type), in four different orientations: 0°; 90°; 180°; 270° (orientation). Number of trials and blocks was the same as in the HLT. The two experimental blocks were preceded by one practice block composed by six stimuli selected randomly from the full data set.

All the stimuli were presented on the same computer as the HLT using Psycho-Py 1.83.03 (Psychology software in Python) (Peirce 2007). Participants seated in front of the pc screen (at a distance of 50 cm) with their left and right index fingers on the "z" and "m" keys, respectively. They were asked to press as quickly and as accurately as possible the "z" key if the picture on the screen represented a canonical letter or by the "m" key if the picture represented a mirror-reversed letter in one block, and in the reverse way in the other block. The block order was randomized between subjects, as done for the hand laterality task. Each trial was preceded by a fixation cross lasting 1500 ms.

As for the HLT, for each trial reaction time in ms (RT) and the answer provided by participant were collected. Average RT in ms and average accuracy (the percentage of correct answers) were calculated for each combination of orientation and type.

Mental motor chronometry task (Fig. 1b)

This task is based on Sirigu et al. (1996); Schwoebel and Coslett (2005) and Zapparoli et al. (2013). Four movements are assessed: (1) index and thumb opposition; (2) thumb extension from the fist; (3) middle finger crossed on the index finger; (4) extension of the index and the little fingers (Schwoebel and Coslett 2005; Sirigu et al. 1996). In the imagery condition, participants are required to imagine performing each movement as quickly and as accurately as possible, five times consecutively; in the execution condition, they are required to perform each movement, five times consecutively, while blindfolded.

The order of movements and of conditions was the same for all participants: the imagery condition was presented first to avoid cognitive strategies, such as counting (Sharma et al. 2009). The starting hand was counterbalanced between subjects; a half started with the right hand, the other half with the left. Both the right and left hand were independently tested.

Overall, the task had 16 trials: 4 gestures for two hands (right and left) for two conditions (imagined vs executed). To ensure participant understood the correct movement, a practice block was run before the experimental task, where the experimenter showed each movement once asking also the participant to perform it once.

Participants sat in front of a computer screen with their left or right index finger (depending on the starting hand) on the spacebar. After the instructions indicating which movement participants were required to perform or imagine, participants were required to close their eyes and to imagine or execute the target movement five times consecutively and, when finished, to press the spacebar to indicate the end of their (imagined or executed) action.

For each movement, the time required to imagine and to execute the five repetitions of each movement was collected, all in seconds.

Control task for the MMC: the mental bars movement task (Fig. 1d)

In this task, participants were required to imagine four movements of bars. The movements paralleled as much as possible those imagined in the mental motor chronometry task: (1) two bars getting close to each other; (2) one bar-raising up from the other bars; (3) two bars crossing each other; (4) two bars extending together from bottom to up. The order of movements was the same for all participants.

At the beginning of each trial, participants read written instructions explaining the target movement and looked at an example. They then closed their eyes and imagined the target movement five times, as quickly as possible. When finished, they immediately pressed the spacebar.

There were two blocks of eight trials: in one block participants responded with the right hand and in the other block they responded with the left hand; thus, both hands were used, mirroring as much as possible the imagery condition for the MMC. The starting hand was counterbalanced between subjects, as done in mental motor chronometry task. To ensure that participants understood the correct movement, a practice block was shown before the beginning of the task, in which the experimenter explained the movement to participants by means of pictures. For each bar movement, the time required to imagine the five repetitions was collected in seconds.

Analyses

Demographical, clinical and neuropsychological description A one-way ANOVA was used to explore any possible difference between the three groups in terms of demographic features (age and years of education) and scores obtained at the neuropsychological tests. Main effects were further explored using Scheffe test. Independent sample *t* tests were used to compare rPD and lPD groups on clinical variables (years of disease and motor UPDRS).

Hand laterality task First, using a threshold of 50% accuracy for the stimuli displayed at 0° (the easiest stimuli, on which one should not expect errors), we checked if participants were randomly guessing their responses. No one fell under this cut-off; hence included data from all participants. RTs and accuracy were analysed separately after data pre-processing for errors and outliers. RTs for trials in which participants gave the wrong response were discarded from the analyses (error pre-processing). Outliers were removed using a cut off of 2 standard deviations above and below the individual participant mean, as indicative of anticipation and lack of attention, respectively (Ratcliff 1993) (outliers pre-processing).

After pre-processing, RTs and Accuracy for each orientation (0°; 90°; 180°; 270°), for the right and left hand separately, were calculated for each participant. RTs were transformed into *z*-scores (RTs-*z* scores) to account for baseline differences between patients and controls, as patients are per se slower than healthy individuals. Two effects were considered of interest for the aims of this study: the effect of stimulus orientation and the effect of biomechanical constraints (Parsons 1987; Fiori et al. 2013, 2014; Conson et al. 2010). The effect of stimulus orientation was investigated through a mixed ANOVA, with orientation (0° vs 180°) and hand (right vs left) as within-subjects factors, and group (rPD, lPd and controls) as between-subjects factor. The effect of biomechanical constraints was explored through a mixed ANOVA with posture (awkward vs comfortable) and hand (right vs left) as within-subjects factors and group (rPD, lPd, and controls) as between-subjects factor. In our analyses, we followed the original theory by Parsons (1987), adopted also in following works (Fiori et al. 2013, 2014), according to which the effect of stimulus orientation pertains more to the first stages of visual processing of stimuli, while the effect of biomechanical constraints is a more powerful index of motor imagery. Reaction times have been demonstrated to be considerably higher for stimuli away from the body midline (+90° for the right hand and −90° for the left hand), than for stimuli across the body midline +270° for the right hand and −270° for the left hand (Parsons 1987; Brady et al. 2011; Fiori et al. 2013). Hence we based our study and analyses on this subset of orientations. In previous works (such as Coslett et al. 2010; Dominey et al. 1995; Helmich et al. 2007), multiple orientations were included in the analyses; however, the extremes, as adopted in the present study, allow to detect the differences as well as to identify more clearly the effect of biomechanical constraints in a clinical setting (Fiori et al. 2013).

Alpha level was set at $p < 0.05$. Post hoc comparisons were conducted using Scheffè test for main effects and estimated marginal means comparisons Bonferroni-corrected for interactions.

Mental letter discrimination task As in the HLT, we checked for responses below 50% and we pre-processed data for errors and outliers. RTs and Accuracy were computed for each orientation (0°; 90°; 180°; 270°) in mirror and canonical positions. RTs were then converted into *z*-scores (RTs-*z* scores) and analysed separately from the accuracy. The effect of stimulus orientation was investigated through a mixed ANOVA with orientation (0° vs 180°) and type (canonical vs mirror) as within-subjects factors and group (rPD, lPD and controls) as between-subjects factor. Post hoc comparisons were carried out using the same procedure as for the HLT.

Mental motor chronometry task For each group, the relationship between the time required to imagine movements and the time required to execute movements, which is an index of motor imagery, was investigated through Spearman's correlation for the right and the left hand. In case of statistically significant correlations, the correlation coefficient values were transformed into z scores to directly compare groups. This transformation is known as Fisher's r to z transformation (Fisher 1915, 1921).

Mental bars movement task For each group, the relationship between the time required to answer with the right hand and the time required to answer with the left hand was investigated through Spearman's correlation, to obtain an index of visual imagery that parallels the one in the MMC. The rational for this index is that there should be a correlation between hands used to respond, as the visual imagery process required to carry out the task should not be affected by which hand is used to press the answer key. Similarly to the MMC, we adopted Fisher's transformation (Fisher 1915, 1921) to compare directly groups' performance.

Results

Demographical, clinical and neuropsychological description

Means and standard deviations of groups are reported in Table 1. The three groups were comparable in terms of age [$F(2, 39) = 2$; $p = 0.15$] and years of education [$F(2, 39) = 1.96$; $p = 0.16$]. Moreover, the two patients groups were comparable in terms of years of disease [$t(18) = 1.42$; $p = 0.17$] and score at the UPDRS motor scale [$t(18) = 0.62$; $p = 0.53$]. The three groups also showed similar scores at the *MMSE* [$F(2, 39) = 0.98$; $p = 0.38$], the clock drawing test [$F(2, 39) = 0.94$; $p = 0.9$], the ideomotor apraxia measure [$F(1, 32) = 3.048$; $p = 0.06$] and at both Stroop's Test indexes, *time* [$F(1, 32) = 1.57$; $p = 0.22$] and *error* [$F(1, 32) = 2.84$; $p = 0.071$]. However, a significant difference emerged at the FAB [$F(1, 32) = 17.65$; $p < 0.001$). Post hoc comparisons using the Scheffè Test showed that rPD ($p < 0.001$) and lPD ($p = 0.014$), while not being different from each other ($p = 0.075$), obtained a significant lower score compared to the controls.

Hand laterality task

Overall, 74.27% of trials in the PD group and 71.87% trials for controls were valid after error pre-processing, while no trials were discarded after outliers processing. In Table 2, RT means and standard deviation for the hand laterality task).

First, we explored the effect of orientation for the RTs-z scores. We found a significant main effect of orientation [$F(1, 37) = 104.62$; $p < 0.001$; $\eta_p^2 = 0.73$] (Fig. 2), confirming

Table 1 Demographical, clinical and neuropsychological features of the 3 groups involved in the study

		Age	Education	Years of disease	Motor UPDRS	MMSE	Clock drawing test	FAB	Ideo-motor apraxia	Stroop's test time index	Stroop's test error index
rPD	*M*	65	9	9	29.3	28.00	9.35	14.50*	71.50	26.30	4.10
$n = 10$	SD	7	3	5	11.1	1.15	0.91	2.17	1.08	10.26	8.42
lPD	*M*	61	11	6	33	28.1	9.5	15.9*	71.56	23.55	0.9
$n = 10$	SD	8	2	4	14.93	1.37	1.5	1.7	1.26	12.8	1.22
Healthy controls	*M*	59	11	–	–	28.53	9.53	17.68*	69.53	19.63	0.29
$n = 20$	SD	*8*	*3*			*1.22*	*1.12*	*0.58*	*3.24*	*9.37*	*0.77*

*Significant difference at $p < 0.05$ (described in the main text)

Table 2 Hand laterality task and the mental letter discrimination task means and standard deviations, for reaction times, in milliseconds

		Hand laterality task								Mental letter discrimination task			
		0°		180°		Awkward		Comfortable		0°		180°	
		Left	Right	Left	Right	Left	Right	Left	Right	Canonical	Mirror	Canonical	Mirror
rPD	*M*	3273	3435	5421	4844	3913	5048	3303	3176	1562	2076	3383	3048
$n = 10$	SD	1364	1237	3025	2639	1905	2714	1233	999	401	846	2291	1513
lPD	*M*	2141	2240	3068	3261	2264	2562	2290	2333	1782	2189	2496	2885
$n = 10$	SD	465	1098	829	1033	679	564	597	602	876	1121	1028	1289
Healthy controls	*M*	3594	3397	6040	5068	3982	4401	4515	3511	1592	2060	3707	3389
$n = 20$	SD	1982	2269	3425	2616	2150	2459	2572	1542	412	621	1695	1945

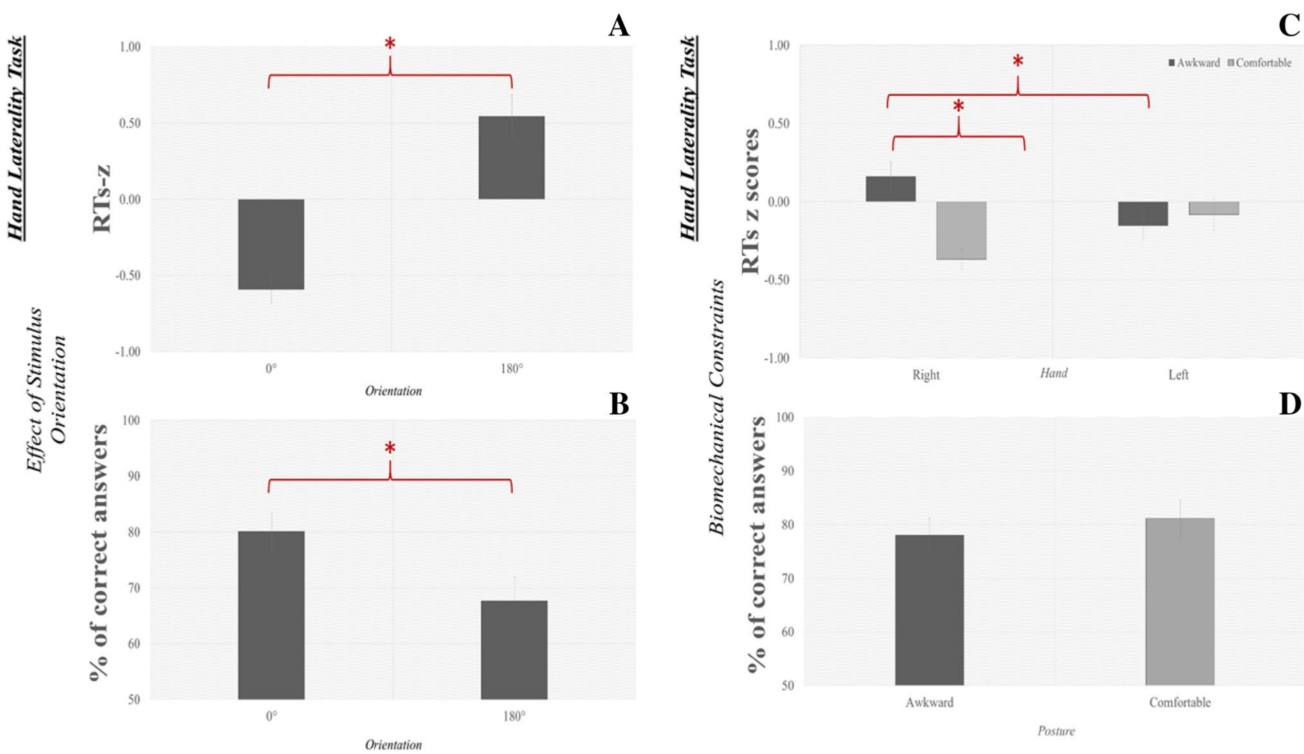

Fig. 2 Hand laterality task. Means (bars) and standard error of the mean (lines) are depicted. The left side of the figure describes the effect of stimulus orientation: upper part represents reaction times transformed into z scores (**a**); lower part accuracy (percentage) (**b**). The right side of the figure shows the effect of biomechanical constraints for reaction times **c** in the upper part and for accuracy in the lower part (**d**). Asterisk denotes a significant difference at $p<0.05$

Table 3 Hand laterality task and the mental letter discrimination task means and standard deviations, for accuracy, as percentage of correct answers

		Hand laterality task								Mental letter discrimination task			
		0°		180°		Awkward		Comfortable		0°		180°	
		Left	Right	Left	Right	Left	Right	Left	Right	Canonical	Mirror	Canonical	Mirror
rPD	*M*	68.75	68.33	66.04	68.54	75.2	76.45	72.77	73.02	67.91	65.41	67.08	64.79
$n=10$	SD	23.01	21.36	19.82	18.53	17.03	17.69	20.47	19.38	22.84	26.52	24.45	25.15
lPD	*M*	74.58	74.16	74.58	76.87	78.54	79.68	76.45	76.77	71.04	71.45	73.54	69.58
$n=10$	SD	25.72	24.95	25.83	23.98	23.4	23.06	23.19	23.07	23.22	22.08	21.46	23.03
Healthy controls	*M*	76.14	76.35	75.41	79.58	82.29	82.29	80.46	79.58	83.33	83.33	82.81	81.97
$n=20$	SD	19.11	18.91	18.84	15.9	15.76	15.84	17.06	16.85	20.32	27.17	19.68	19.9

that individuals were slower when they had to judge stimuli presented at 180° compared to 0°. Neither a main effect of group (rPD $M=0.17$; SD = 0.66; lPD $M=0.14$; SD = 0.78; controls $M=0.08$; SD = 0.76) [$F(2, 37)=0.24$; $p=0.78$; $\eta_p^2=0.013$] nor a main effect of hand (right hand $M=0.001$; SD = 0.81; left hand $M=0.21$; SD = 0.87) [$F(1, 37)=2.86$; $p=0.099$; $\eta_p^2=0.072$) were found. Moreover, the two way interactions orientation*hand [$F(1, 37)=0.96$; $p=2.86$; $\eta_p^2=0.049$], orientation*group [$F(2, 37)=0.62$; $p=0.54$; $\eta_p^2=0.033$] and hand*group [$F(2, 37)=1.95$; $p=0.15$; $\eta_p^2=0.096$) were not significant, as well as the three way interaction between orientation*hand*group [$F(2, 37)=1.067$; $p=0.35$; $\eta_p^2=0.055$].

The same pattern of result emerged when accuracy was taken in account (Table 3): a significant main effect of orientation emerged [$F(1, 37)=19.81$; $p<0.001$; $\eta_p^2=0.34$] (Fig. 2), without any interaction with the factor hand [$F(1, 37)=0.53$; $p=0.46$; $\eta_p^2=0.14$] or group [$F(2,$

37) = 1.55; $p = 0.22$; $\eta_p^2 = 0.077$]. Moreover, no main effect of group (rPD $M = 68.75$; SD = 23.01; lPD $M = 74.58$; SD = 25.72; controls $M = 76.14$; SD = 19.11) [F(2, 37) = 0.63; $p = 0.53$; $\eta_p^2 = 0.033$] or main effect of *Hand* (right hand $M = 75.72$; SD = 19.89; left hand M = 72.08 SD = 23.79) [F(1, 37) = 2.54; $p = 0.11$; $\eta_p^2 = 0.064$] emerged, neither a significant interaction hand*group [F(2, 37) = 0.96; $p = 0.38$; $\eta_p^2 = 0.05$]. Finally, the three-way interaction orientation*hand*group [F(2, 37) = 2.37; $p = 0.1$; $\eta_p^2 = 0.1$] was not significant.

Next, we explored the effect of biomechanical constraints. For RTs-z scores, a significant main effect of posture emerged [F(1, 37) = 8.33; $p = 0.006$; $\eta_p^2 = 0.184$], according to which individuals were slower when they had to judge stimuli in awkward positions ($M = -0.22$; DS = 0.29) compared to those in comfortable positions ($M = 0.005$; DS = 0.41). Secondly, we found a significant interaction between posture and hand [F(1, 37) = 7.6; $p = 0.009$; $\eta_p^2 = 0.17$] (Fig. 2). According to post hoc comparisons, individuals were slower when they had to recognize a right hand compared to a left hand in an awkward position [$p = 0.009$], but not when in a comfortable position [$p = 0.16$]. Furthermore, a right hand showed in an awkward position was recognized slower than in a comfortable position [$p < 0.001$], while this difference did not emerge for the left hand [$p = 0.87$]. No main effect of group emerged (rPD $M = 0.11$; SD = 0.79; lPD $M = 0.14$; SD = 0.9; controls $M = 0.08$; SD = 0.85) [F(2, 37) = 0.24; $p = 0.78$; $\eta_p^2 = 0.013$]. Similarly, no significant interactions between posture and group [F(2, 37) = 2.36; $p = 0.108$; $\eta_p^2 = 0.11$] or hand and group [F(2, 37) = 1.91; $p = 0.16$; $\eta_p^2 = 0.11$) were found, neither posture*hand*group [F(2, 37) = 0.1; $p = 0.89$; $\eta_p^2 = 0.006$].

When accuracy was taken into account, no main effect of group (rPD $M = 75.2$; SD = 17.03; lPD $M = 78.54$; SD = 24.01; controls $M = 82.29$; SD = 15.76) [F(2, 37) = 0.667; $p = 0.51$; $\eta_p^2 = 0.035$], posture (awkward $M = 78.02$; SD = 17.8; comfortable $M = 81.14$; SD = 19.29) [F(1, 37) = 1.6; $p = 0.21$; $\eta_p^2 = 0.042$] or hand (right $M = 80.72$; SD = 18.4; left hand $M = 78.43$; SD = 18.78) [F(1, 37) = 3.91; $p = 0.055$; $\eta_p^2 = 0.096$] emerged, as well as no significant interactions [posture*group F(2, 37) = 0.7; $p = 0.5$; $\eta_p^2 = 0.037$; hand*group F(1, 37) = 3.91; $p = 0.055$; $\eta_p^2 = 0.096$; posture*hand F(1, 37) = 0.43; $p = 0.51$; $\eta_p^2 = 0.012$; posture*hand*group F(2, 37) = 1.57; $p = 0.22$; $\eta_p^2 = 0.078$].

Overall, the main effects of *Orientation* and posture suggest that individuals applied a motor strategy to solve the task. Moreover, the absence of main effects of group indicates that the lateralization of PD symptoms and even PD itself did not affect how patients solved this task.

Mental letter discrimination task

Overall, 71.87% of trials in the PD group and 84.32% trials for controls were valid after error pre-processing, while no trials were discarded after outliers processing (Table 2).

Firstly, the effect of stimulus orientation was investigated. Considering RTs-z scores, a significant main effect of orientation emerged [F(1, 37) = 72.2; $p < 0.001$; $\eta_p^2 = 0.66$] (Fig. 3), as expected. Individuals were faster for stimuli at 0° of rotation compared to those rotated at 180°. Secondly, we found a main effect of type [F(1, 37) = 5.47; $p = 0.025$; $\eta_p^2 = 0.12$] (Fig. 3): individuals were faster when they had to recognize visual stimuli presented in a canonical compared to a mirror position.

However, no main effect of group emerged (rPD $M = -0.038$; SD = 0.78; lPD $M = -0.013$; SD = 0.81; controls $M = -0.022$; SD = 0.89) [F(2, 37) = 0.034; $p = 0.96$; $\eta_p^2 = 0.002$]. Moreover, the interactions orientation*group [F(2, 37) = 2.57; $p = 0.9$; $\eta_p^2 = 0.12$], type*group [F(2, 37) = 0.76; $p = 0.47$; $\eta_p^2 = 0.47$], and type*orientation [F(1, 37) = 4.02; $p = 0.052$; $\eta_p^2 = 0.98$] were not significant. Finally, the three-way interaction orientation*type*group [F(2, 37) = 0.78; $p = 0.46$; $\eta_p^2 = 0.04$] was not significant.

As for accuracy (Table 3), a significant main effect of orientation emerged [F(1, 37) = 12.54; $p = 0.001$; $\eta_p^2 = 0.25$] (Fig. 3), suggesting that individuals were more accurate when they judged visual stimuli presented at 0° than at 180°. Moreover, a main effect of type [F(1, 37) = 5.02; $p = 0.031$; $\eta_p^2 = 0.12$] (Fig. 3) was found: participants were also more accurate for canonical stimuli than mirror ones. No significant interaction orientation*group [F(2, 37) = 0.17; $p = 0.83$; $\eta_p^2 = 0.01$] or type*group [F(2, 37) = 0.99; $p = 0.38$; $\eta_p^2 = 0.05$] or orientation*type [F(2, 37) = 2.6; $p = 0.11$; $\eta_p^2 = 0.06$] emerged, as well as no significant interaction group*type*orientation emerged [F(2, 37) = 3; $p = 0.62$; $\eta_p^2 = 0.14$].

Interestingly, we found a main effect of *Group* [F(2, 37) = 4.44; $p = 0.019$; $\eta_p^2 = 0.19$]: the analyses conducted using Scheffè Test suggest that this effect is driven by a significant difference between rPD and controls [$p = 0.028$], but not with lPD [$p = 0.71$], or between lPD and controls [$p = 0.19$] (Fig. 4).

To further explore this main effect of group, we performed the same analyses introducing FAB scores as a covariate. As previously reported, this score was the only neuropsychological index in which the three groups showed a significant difference, suggesting a different level of executive functioning that could explain our results. An exploration of the relationship between FAB scores and Accuracy showed a positive correlation between this score and accuracy for visual stimuli at 0° of rotation [r(40) = 0.62;

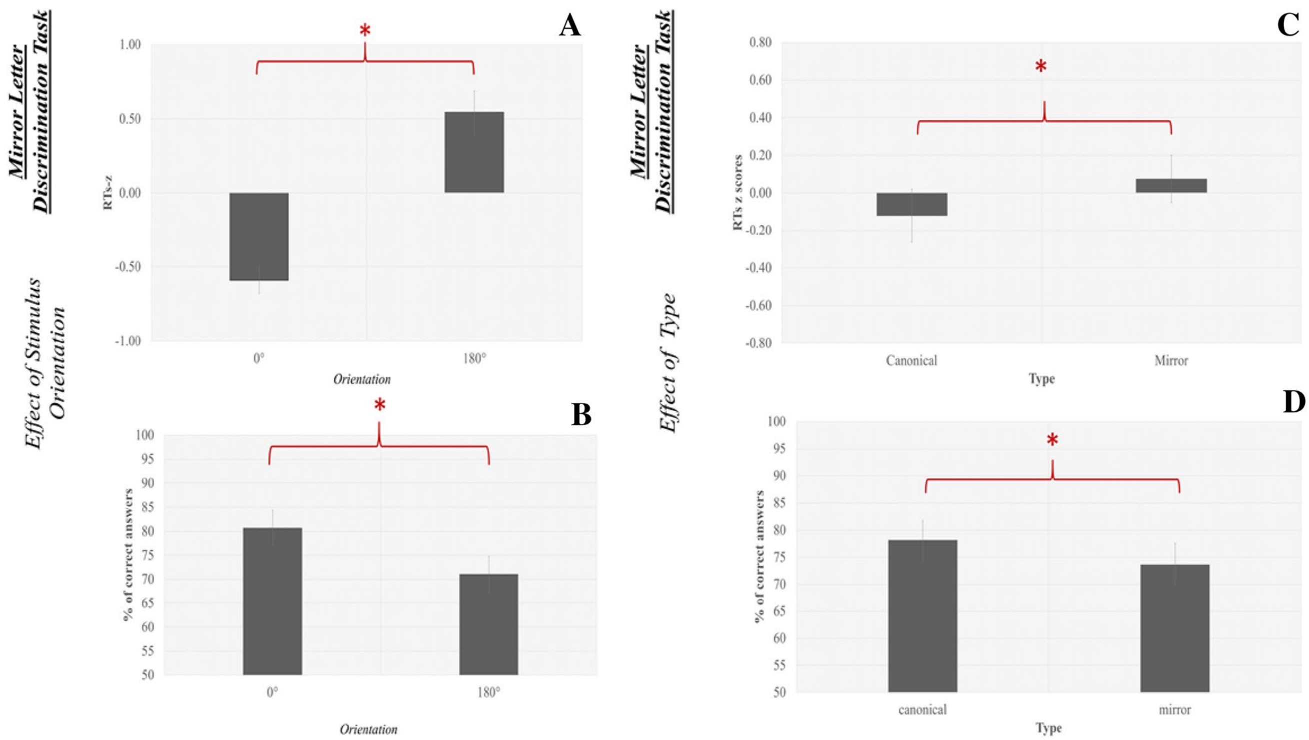

Fig. 3 Mental letter discrimination task. Means (bars) and standard error of the mean (lines) are depicted. **a** (Accuracy) and **b** (reaction times transformed into *z* scores) describe the effect of stimulus orientation in the figure about the effect of orientation (**a**) and type (**b**) relative to reaction times in *z* scores and about the effect of orientation (**c**) and type (**d**) relative to accuracy. Asterisk denotes a significant difference at $p < 0.05$

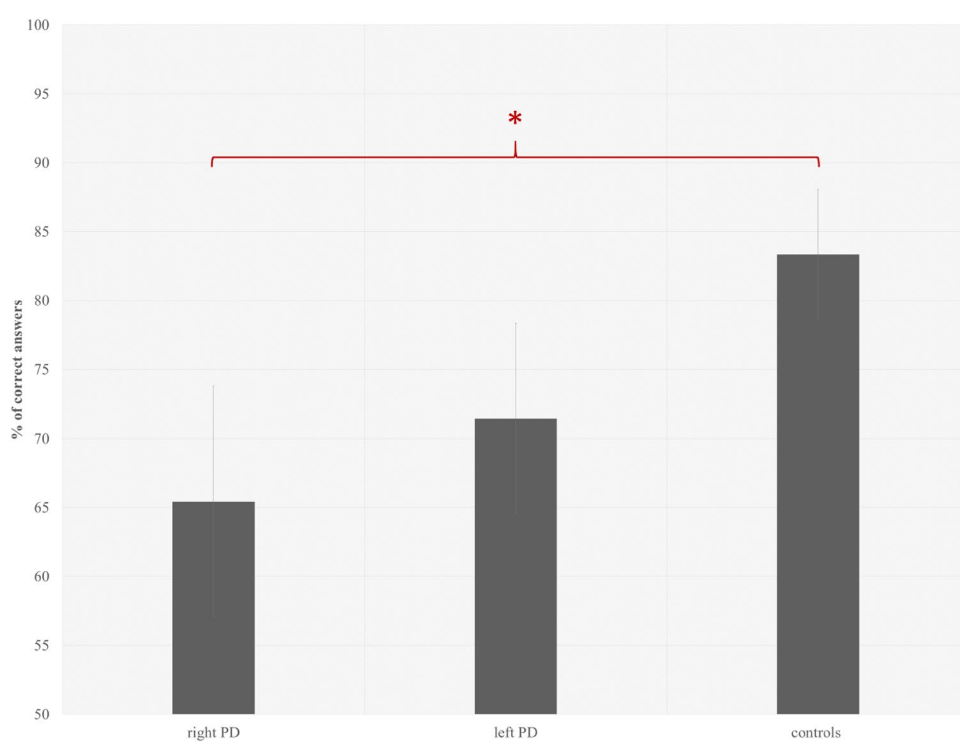

Fig. 4 Mental letter discrimination Task—main effect of Group. Means (bars) and standard error of the mean (lines) are depicting accuracy in the three groups. Asterisk denotes a significant difference at $p < 0.05$ between rPD patients and controls

$p < 0.001$] and stimuli rotated of 180° [$r(40) = 0.47$; $p = 0.002$]. When the mixed ANOVA was run introducing FAB scores as a covariate, the main effect of *Group* was no longer significant [$F(2, 36) = 0.68$; $p = 0.51$; $\eta_p^2 = 0.037$] (estimated means with FAB scores was 16.25; rPD $M = 72.62$; SD = 5.15; lPD $M = 72.9$; SD = 4.66; controls $M = 79$; SD = 3.54), suggesting that cognitive functioning explains the difference between groups on this measure. In this analysis, orientation [$F(1, 36) = 0.049$; $p = 0.82$; $\eta_p^2 = 0.001$] and type [$F(1, 36) = 0.008$; $p = 0.92$; $\eta_p^2 < 0.001$] are not also not significant anymore, further supporting the idea that in this task executive control plays a great role.

Mental motor chronometry task

As expected, controls showed a significant, positive, correlation between the time required to imagine and the time required to performed movements, for the right [$\rho(18) = 0.64$; $p = 0.002$] and the left hand [$\rho(18) = 0.54$; $p = 0.022$]. In rPD individuals', the correlation was significant for the left hand, not affected by PD [$\rho(8) = 0.69$; $p = 0.025$], but not for the right hand, affected by PD [$\rho(8) = 0.56$; $p = 0.09$]. lPD individuals showed a significant correlation for the left hand, in their case affected by PD [$\rho(8) = 0.68$; $p = 0.029$], but not for the unaffected right hand [$\rho(8) = 0.27$; $p = 0.82$] (Fig. 5). Overall (Table 4), this pattern of results suggests that both PD patients' groups show a difference for the more explicit component, for the right hand only, independently from the symptoms' lateralization.

In the mental motor chronometry task, Fisher's analyses were conducted for the left hand. No significant difference emerged between controls and rPd [$z = -0.54$; $p = 0.58$], controls and lPD [$z = -0.5$; $p = 0.61$], as well as between the two PD patients' groups [$z = 0.04$; $p = 0.96$]. Since the absence of significant results, we can conclude that for the left hand the relationship between the time required to execute the movements and the time required to imagine them is similar for the three groups, confirming our previous results.

Mental bars movement task

Controls showed a significant positive correlation between the time required to answer with the right hand and to answer with the left [$\rho(18) = 0.78$; $p < 0.001$] (Fig. 6). The same correlation emerged for both rPD individuals [$\rho(8) = 0.97$; $p < 0.001$] and lPD individuals [$\rho(8) = 0.86$; $p = 0.001$], suggesting the three groups adopted a similar imagery strategy to solve the explicit control task (Table 4).

By means of Fisher's analysis, we highlighted a significant difference between rPD and controls [$z = -2.33$; $p = 0.019$]. This finding suggests that the rPD group's performance differs from controls. No difference emerged between lPD and controls [$z = -0.55$; $p = 0.58$] and between PD patients groups [$z = 1.49$; $p = 0.13$]. Overall, this result mirrors what reported about the mental letter discrimination task.

Discussion

In this study, we explored the ability to access the mental representation of the body in action in PD, by means of motor imagery tasks exploring both more implicit and more explicit components; at the same time, we controlled also for visual imagery processes using control tasks with the same structure but presenting objects, instead of body parts. We enrolled patients with different lateralization of symptoms to account for the role of sensory mechanisms. Finally, we included neuropsychological testing focused on executive functioning to rule out the influence of cognitive impairments that could confound findings.

Our results show an interesting dissociation between more implicit and more explicit components when the two are explored in conjunction within the same sample. Our patients affected by PD differ from controls for the more explicit components only, where they are required to more explicitly adopt a motor imagery strategy based on one's own body to solve the task. PD patients with left-lateralized symptoms as well as with symptoms lateralized to the right side of the body do not show the classic correlation (Parsons 1987; Schwoebel and Coslett 2005; De Lange et al. 2008) between the time required to perform a movement and time required to execute it. Importantly, this motor imagery index is not observed for the right hand, while it is for the left hand, independently from symptoms lateralization, and with the same strength in the three groups. These results cannot be attributed to general difficulties in imagery processes, as suggested by the results in the control task: overall, patients and controls show the same performance when they are tasked to imagine movements of objects instead of body parts. The only difference emerged between rPD and controls when the correlation coefficients were compared. Specifically, for the rPD group the correlation between the time required to solve the task with the right and with the left hand was significantly higher respect to the controls, but not compared to lPD; put it differently, for rPD group, for each patient, the time to provide the answer with the right (affected) hand was more similar to the time of the left (not affected) hand and this bimanual relationship is stronger than in controls. This result seems to be in line with previous evidence reported in literature according to which the lateralized sensory and motor PD symptoms might affect also the other side of the body. The characteristics of the movements of the unaffected hand in PD are adjusted in relation to the movement of the affected one (rather than the

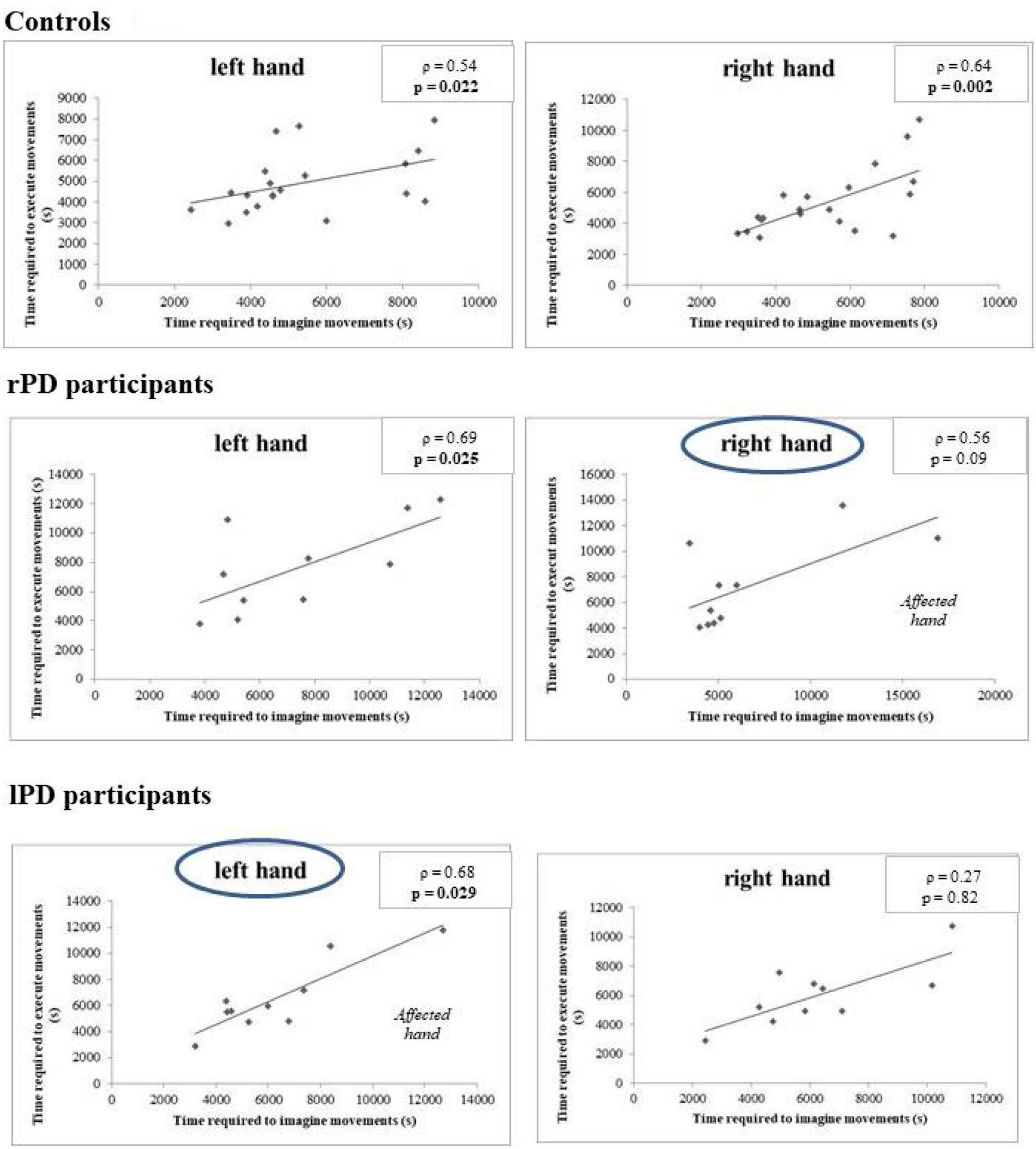

Fig. 5 Mental motor chronometry task. The relationship between the time required to imagine movements (*x*-axis) and the time required to execute movements (*y*-axis) is depicted for both the right and the left hand in each group. *p* value in bold when < 0.05. Affected hand (for patients) circled

opposite) (see for example Almeida et al. 2005; Wu et al. 2010; Byblow et al. 2000, 2002). Since this peculiar pattern of result emerged for rPD patients, and not for lPD, in our sample, possible effects of an interaction between the affected body side and handedness might be hypothesized and are indeed worth exploring further. Secondly, in the more implicit component, PD patients' performance is similar to that of controls. All participants show the effects

Table 4 Mental motor chronometry task and mental bars movement task means and standard deviation, in milliseconds

		Mental motor chronometry task				Mental bars movement task	
		Executed		Imagined		Imagined	
		Left	Right	Left	Right	Left	Right
rPD	*M*	7643	7232	7390	6608	6437	6510
n = 10	SD	3105	3369	3148	4306	3018	3587
lPD	*M*	6533	6044	6305	6300	6786	6366
n = 10	SD	2716	2155	2733	2577	2491	2171
Healthy controls	*M*	4917	5327	5380	5335	4919	5539
n = 20	SD	1474	2081	1950	1667	1736	2051

of spatial orientation and, more importantly, biomechanical constraints (Parsons 1987; Fiori et al. 2013, 2014; Conson et al. 2010). Moreover, the performance was the same when letters were the target of the imagery process, as any difference was explained by executive functioning rather than by visual imagery processes, as shown by taking into account scores at the frontal assessment battery (Dubois et al. 2000; Appollonio et al. 2005).

Our results expand and further corroborates previous studies. Amick et al. (2006), for instance, show that PD individuals are less accurate compared to the control group when hands, and not objects, are the target of the imagery process. The task employed is a matching task—where participants decide if the target stimulus matches the probe, by means of rotating mentally the probe to check if the final position corresponds. Crucially, participants were shown in a practice exercise which strategy to adopt. Hence, the task tackles more explicit motor imagery, making it similar to our mental chronometry. The authors explain their results in terms of visual fields—with differences related to the visual field in which the stimulus is presented. Having a greater left hemisphere dysfunction, right-lateralized patients with PD are supposedly worse with the task when the stimulus occurs in the right visual field. However, the neuropsychological profile of the assessed individuals is unknown, hence the possibility of a confounding role for cognitive functioning. As we demonstrate, these findings on more explicit components of motor imagery cannot be explained by means of cognitive impairment, and, differently from what suggested by Amick et al. (2006), might not be related to hemispheric differences in processing either as the same pattern is shown by left-lateralized patients.

While van Nuenen et al. (2012) show that PD patients are not different from controls in terms of accuracy and reaction times, in line with our work, our results partly differ from some of the previous studies exploring more implicit motor imagery in PD. Helmich et al. (2007), for instance, report that right-lateralized PD patients are slower compared to controls when a right hand is shown in a lateral orientation, despite an adequate level of accuracy. However, this effect is related to the effect of stimulus orientation, and no differences are reported for the effect of biomechanical constrains. The Authors themselves suggest their findings support the idea that all participants, patients and controls, use a motor imagery strategy to solve the task. Considering that patients in the Helmich et al. (2007)'s study have been tested off medications (at least 12 h), their task employed more angles of rotations (hence being more difficult), no control task with objects was used and result on the effect of stimulus orientation was not controlled for frontal executive impairments (the Authors only report that cognitive status was screened using a MMSE cut off of 24, but the other tests are not available nor covaried), the differences for the effect of stimulus orientation could as well be due to cognitive impairments rather than visual imagery deficits. According to our results, the lower level of accuracy in the control task in affected individuals with right lateralized symptoms is related to a lower level of cognitive efficacy in the executive domain. This would suggest that the same reasoning can be applied to the velocity of processing, hence explaining Helmich et al. (2007)'s results. In agreement with this, also Dominey et al. (1995) point out that the difficulties in their patients with object rotations could be due to the task difficulty, as previous studies do not show the same pattern (Dominey et al. 1995, p. 738).

Importantly, in their study, Dominey et al. (1995) explored the issue of motor imagery in PD using a similar experimental setup to that used in the present work, that included both rotation of hands and a mental chronometry task, and their results are strikingly different from ours. The Authors report that PD patients with right lateralized symptoms are slower compared to healthy controls when required to imagine performing or to perform fingers movements with the right (affected) hand when compared to the left (unaffected) hand. This study also shows that PD patients with right lateralized symptoms are slower in identifying the affected right hand compared to the left hand in the traditional hand laterality task (Parsons 1987) when compared to controls. Dominey et al. study seems to suggest that the distortion in the representation for the affected

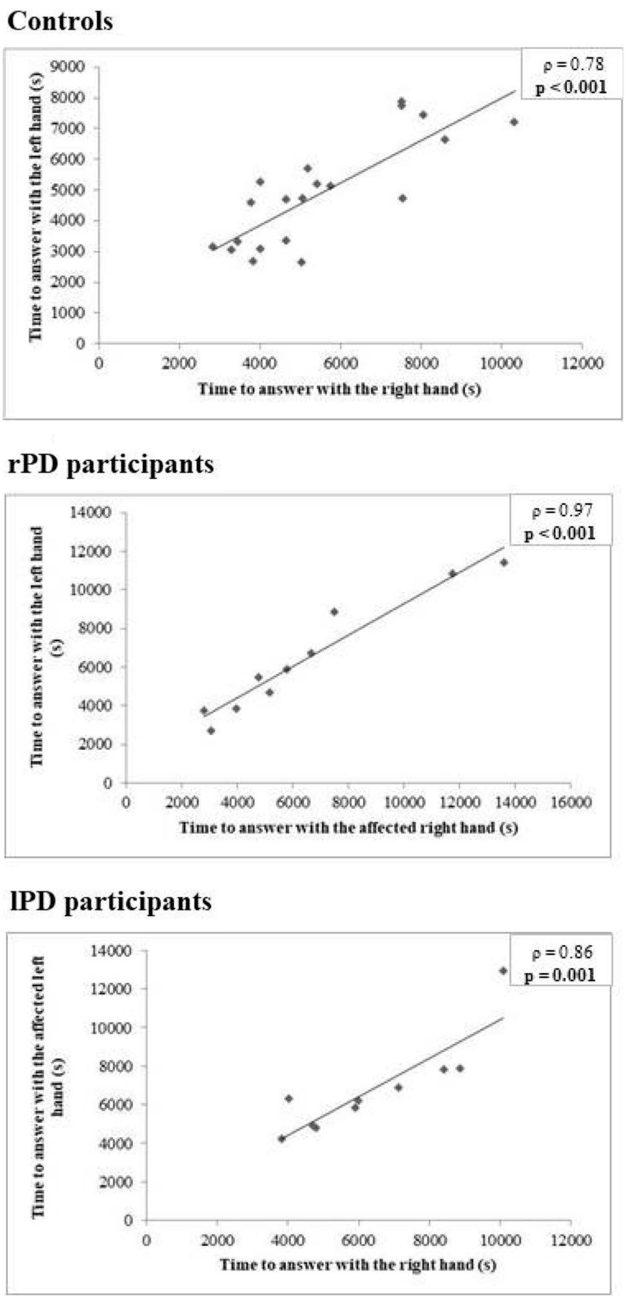

Fig. 6 Mental bars movement task. For each group, the relationship between the time required to answer with the right hand (*x*-axis) and with the left hand (*y*-axis) is shown. *p* value in bold when <0.05

right hand emerges independently from the level of awareness required by the task, contrasting the results reported in the present paper. However, the absence of a left-lateralized group of patients does not allow to conclude for a relationship between motor control and imagery. In fact, we show that independently from the lateralisation of symptoms, it is always the right hand which is affected. Furthermore, the absence of a transformation of scores that accounts for baseline motor difference could have influenced the results. Not by chance, the Authors report that "for the non-affected (left) hand the patients are slower than controls. While all of our patients display an asymmetric motor deficit, they are also impaired, with respect to normal controls, on their non- (or less) affected side" (Dominey et al. 1995; p. 738). This baseline difference, not accounted for when doing group comparisons, could indeed bias the results towards a group difference. Several features differentiate our sample from the one tested in 1995, and one, in particular, could also explain the differences in results and provides a fascinating insight into the importance of clinical features when investigating how we represent our body for action purposes in degenerative conditions. In Dominey et al. (1995), 7 PD patients with symptoms lateralized to the right side of the body were enrolled. Their disease duration varied from 1 to 7 years (mean 3.8 years). In our sample, the 10 patients with right lateralized PD have an average disease duration of 9 years, with a minimum duration of 4 years and a maximum duration of 18 years. Our sample being more chronic, findings could interestingly represent the pattern of changes once that symptoms have progressed and individuals have adjusted to medications.

Summarizing, our data show an effect of PD on motor imagery only when a higher level of awareness is required to carry out the task, in other words when individuals are more explicitly monitoring actions during their execution (Jeannerod and Frak 1999). Our findings suggest that the distortion at a more explicit is relatively independent from sensory and peripheral symptoms, at least after some years of consolidation of symptoms and medications use. In the Mental Motor Chronometry Task, the absence of any significant correlation between the time required to perform physically the action and the time required to imagine performing it was observed for the right hand for both PD groups. Importantly, for PD patients with symptoms lateralized to the right side of the body, the right hand is the most affected one. Differently, for PD patients with symptoms lateralized to the left side of the body, the right hand belongs to the unaffected body side. This pattern of results seems to suggest that the impairment is at higher levels than previously suspected and that handedness plays a pivotal role, given that all our participants were right-handed. Serrien et al. (2006) stress the dominant role of the left hemisphere in the regulation of motor behaviours in different domains, specifically in terms of movement organization and selection, as well as motor imagery. The dominant arm-hemisphere system seems to be specialized for optimizing dynamic features of movement in relation to the dynamic properties of the arm and the task environment (Mutha et al. 2013) and its role emerges specifically in relation to the task complexity (Lutz et al. 2005; Klöppel et al. 2007). If this theory is true, our results could be interpreted as a high-level dysfunction related to action selection and task requirements, such as awareness. Future research enrolling left-handed individuals affected by PD, with a right or a left lateralization of symptoms, could clarify if the dominant arm-hemisphere is the correct model to explain this impairment. This seems particularly interesting in light of previous studies suggesting a role of handedness in motor imagery tasks (Ottoboni et al. 2005; Lameira et al. 2009; Ní Choisdealbha et al. 2011; Jongsma et al. 2013). Moreover, future studies could explore if increasing the number of orientations leads to differences compared to our study where only a limited set was included (Coslett et al. 2010; Dominey et al. 1995; Helmich et al. 2007).

An alternative explanation for our results might also be provided. In the hand laterality task, an external stimulus (i.e. the picture of hand) triggers motor imagery, while in the motor chronometry task individuals need to internally generate the imagery of action. The difference between the two tasks could as well relate to a specific difficulty in spontaneously generating internal motor representations. Stern et al. (1983) suggested that the perceptual-motor deficit generally observed in PD might be not specifically related to motor symptoms, such as tremor and rigidity, but it might read instead as the inability to generate movements based on an internal concept of action. Our findings seem to support Stern et al. (1983)'s hypothesis, and indeed awareness of actions and generation of internal motor representations are two related constructs (Frith et al. 2000; Weiss et al. 2014).

The body itself and the ability to perform actions are strongly affected in PD condition, with a huge impact on individuals' quality of life. As recently discussed by Caligiore et al. (2017), understanding of the relation between symptoms, body and mind in PD might have important consequence on treatment and physical rehabilitation of affected individuals. Independently from which theoretical interpretation accounts for our results, awareness or internal generation, our study shows that in individuals with PD, more and less implicit components can be differently affected. An impairment is clearly apparent only when the feeling of the movement is experienced consciously (Jeannerod 1994). This finding could inform rehabilitation, by guiding the direction of passive versus active exercises, as an example.

Acknowledgements The Authors are thankful for the comments of the anonymous reviewers on this manuscript.

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