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RESEARCH ARTICLE

Basal ganglia-dependent processes in recalling learned visual-motor adaptations

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Abstract Humans learn and remember motor skills to permit adaptation to a changing environment. During adaptation, the brain develops new sensory–motor relationships that become stored in an internal model (IM) that may be retained for extended periods. How the brain learns new IMs and transforms them into long-term memory remains incompletely understood since prior work has mostly focused on the learning process. A current model suggests that basal ganglia, cerebellum, and their neocortical targets actively participate in forming new IMs but that a cerebellar cortical network would mediate automatization. However, a recent study (Marinelli et al. 2009) reported that patients with Parkinson's disease (PD), who have basal ganglia dysfunction, had similar adaptation rates as controls but demonstrated no savings at recall tests (24 and 48 h). Here, we assessed whether a longer training session, a feature known to increase long-term retention of IM in healthy individuals, could allow PD patients to demonstrate savings. We recruited PD patients and age-matched healthy adults and used a visual-motor adaptation paradigm similar to the study by Marinelli et al. (2009), doubling the number of training trials and assessed recall after a short and a 24-h delay. We hypothesized that a longer training session would allow PD patients to develop an enhanced representation of the IM as demonstrated by savings at the recall tests. Our results showed that PD patients had similar adaptation rates as controls but did not demonstrate savings at both recall tests. We interpret these results as evidence that fronto-striatal networks have involvement in the early to late phase of motor memory formation, but not during initial learning.

Keywords Visual-motor learning · Basal ganglia · Parkinson's disease · Long-term memory · Recall · Internal models

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Introduction

Learning and remembering new motor skills represent vital functions. Upon changes in the environment or one's body or when using new tools, one forms new sensory-motor relationships that can be stored in an internal model (IM) that represents the kinematics (trajectory) and dynamics (forces) of the limb used to perform the task (Shadmehr and Wise 2005). Humans can rapidly form new IMs and transform these into a long-lasting memory that can be recalled successfully, as shown by savings, after delays ranging from minutes to several months (Bock et al. 2001; Brashers-Krug et al. 1996).

Here, we were interested in extending knowledge on how the brain, particularly circuits related to basal ganglia structures, participates in forming IMs from initial practice to automation. Prior work has provided substantial support for a significant role of basal ganglia in learning new skills and habits (Graybiel 2005), motor sequences (Doyon et al. 2009), and arbitrary stimulus–response associations (Bédard and Sanes 2009; Grol et al. 2006; Schultz 2006). Doyon and colleagues proposed a model holding that the basal ganglia and cerebellum, along with their neocortical targets, participated in the initial formation phase of an IM, but only the cerebellar network would participate as learning progresses through automaticity (Doyon et al.

2003; Doyon and Benali 2005). Support for this model comes from neuroimaging work that reported learning-related brain activation in basal ganglia structures during IM formation (Floyer-Lea and Matthews 2005; Krakauer et al. 2004; Seidler et al. 2006; Shadmehr and Holcomb 1999) and studies with patients that have basal ganglia dysfunctions, as in Parkinson's disease (PD), showing reduced adaptation rates (Contreras-Vidal and Buch 2003; Krebs et al. 2001; Messier et al. 2007). Despite these results, other studies found normal adaptation capabilities for PD patients (Marinelli et al. 2009; Paquet et al. 2008; Stern et al. 1988; Weiner et al. 1983; see also Smith and Shadmehr 2005 for Huntington's disease). Most of the above-mentioned studies did not assess recall, leaving the role of basal ganglia in forming and transforming the IM into a long-term representation unclear. To our knowledge, only Marinelli et al. (2009) assessed how basal ganglia dysfunctions affected capability to learn and then to recall an IM. While Marinelli and colleagues found similar adaptation rates for PD patients and healthy controls, they reported no savings for PD patients for tests occurring 24 and 48 h post learning. The "normal" learning and impaired recall by PD patients suggests that frontal-striatal networks may not have a key role in forming new IMs, but instead may participate in transforming an IM into a long-term memory.

Here, we aimed to further understand how basal ganglia circuits participate in forming a new IMs and transforming them into long-term representations. In the Marinelli et al. (2009) study, participants performed only 80 trials as they developed a new IM, much fewer trials than commonly used in similar studies. Although PD patients achieved similar adaptation levels at the end of learning, this relatively short training session may have prevented PD patients from developing a long-lasting memory of the IM and thus showing savings as controls. This seems important since PD patients appear to require more time on task to achieve performance levels similar to those of healthy controls (Behrman et al. 2000; Smiley-Oyen et al. 2006). While not explicitly investigated in the current study, we note that longer practice sessions, perhaps creating *over-learning*, even without further improvements in performance, can nevertheless lead to enhanced long-term retention (Joiner and Smith 2008) and also protect against interference and increase after-effects (Krakauer et al. 2005; Krueger 1929; Luh 1922; Yin and Kitazawa 2001); these measures provide good evidence for consolidation of a memory. Thus, we asked whether a longer training session would allow PD patients to develop a more persistent memory of the IM and allow them to show savings when required to recall the IM.

To achieve our goal, we recruited PD patients and age-matched healthy adults to perform a visual-motor adaptation center-out reaching task with a design resembling, but having key differences to, that of Marinelli et al. (2009). Our participants practiced for 160 trials with only four targets, compared with 80 trials to eight targets in Marinelli et al. (2009), a method that should improve learning and recall capabilities (Krakauer et al. 2000, 2005). We also assessed recall capabilities after a short washout period, a feature that Marinelli et al. (2009) did not employ, as well as long-term recall after 24 h. These two recall tests allowed us to examine whether frontal-striatal networks have more involvement in either an early or a later phase of memory formation. Following upon Marinelli et al. (2009), we hypothesized that PD patients would not exhibit deficits during the Learning phase. Further, we hypothesized that the longer and easier task that we designed will allow PD patients to demonstrate savings in both recall tests.

Materials and methods

Participants

We recruited 12 individuals having a medical diagnosis of idiopathic PD (4 women and 8 men, with a mean ± SD age of 64.3 ± 9 years); all participants were right-handed except one ambidextrous patient, as assessed by a modified handedness scale (Oldfield 1971). Most PD patients were in the early phases of the disease scoring in Stage I–II of the Hoehn and Yahr scale (mean, 1.88; range, 0–2.5) with a mean of 16.75 (range 4–27) on the motor section of the Unified Parkinson's Disease Rating Scale. These assessments, performed by a clinical neurologist, occurred on a separate occasion while patients remained on their anti-parkinsonian medication, as they did for the actual experiment. Two patients had a deep brain stimulator implanted, respectively, in 1999 and 2002; they performed the experimental procedures with the stimulator turned on and had results comparable to others in the PD group, that is, their results were within two standard deviations of the group mean. We also recruited 12 individuals with no history of neurological or motor/sensory disorder to form a control group (8 women and 4 men, 63.9 ± 5 years); two were left handed and they performed with their left hand with comparable results to right-handed controls. There was no significant age differences between groups, $t(22) = 0.12$, $P = 0.91$. All participants provided written informed consent according to established and approved Institution Review Board guidelines for human participation in experimental procedures at Brown University. We adhered to the principles of the Declaration of Helsinki. Participants received modest monetary compensation.

Tasks, apparatus, and procedures

Participants performed a goal-directed, hand-movement task while holding a joystick (Mag Design and Engineering, Sunnyvale, CA) in their dominant hand and while seated at a table and viewing a video monitor (Dell 1,024 × 768 pixels, 19″) located approximately 60 cm in front of them. The joystick rested on the table, aligned with each participant's mid-line and the center of the monitor. Joystick movements displaced a cursor (round black dot; diameter, 0.5 cm) on the monitor. A starting point (black annulus; diameter, 1 cm) positioned in the center of the monitor remained visible for the whole experiment. Targets (black dots; diameter 0.5 cm) appeared at one of four locations on the video monitor, either up, right, down or left from the starting "home" position, always at 5.5 cm eccentricity (Fig. 1). Targets appeared in sequential order (up, right, down, and left) and at intervals of 2–4 s. All targets and the home position were black over a white screen background. We used the Windows version of PsychToolbox v.2.54 (http://www.psychtoolbox.org; Brainard 1997; Pelli 1997) running under Matlab 6.5 (Mathworks, Natick, MA) to generate visual stimuli and record the cursor positions at 500 Hz.

The experimenter trained participants before the experiment for about 40 trials in the *Null* condition (see below). After a target appeared, participants had to try to "hit" the target by displacing the cursor with joystick movements in a quick and ballistic movement while trying to perform movements under the instruction of "as accurately as possible." We requested that participants attempt to avoid making online movement corrections or to perform curved movements and that they should try to improve performance from trial to trial. Participants returned the cursor to the starting position after each movement. Note that we did not constrain MT since this could have unduly affected the performance of PD patients known to have bradykinesia (Berardelli et al. 2001). The experiment comprised two principal conditions. In the *Null* condition, the cursor had a veridical (though transformed) relationship to the joystick: moving the joystick forward displaced the cursor upward on the screen, pulling the joystick inward displaced the cursor downward and moving the joystick right and left displaced the cursor right and left. In the *Learning* condition, the cursor direction was rotated 30° clockwise from the joystick trajectory about the home position. On day 1 (D1), participants first performed 40 trials in the *Null* condition, then two sets of 80 trials with the cursor rotated by 30° (*Learning*), then 80 trials in the *Null* condition to assess after-effects, and finally 80 trials with the cursor again rotated clockwise by 30° to assess immediate recall (*Recall D1*). On day 2 (D2, the next day), participants performed 40 trials in the *Null* condition and then 80 trials with a 30° cursor rotation (*Recall D2*). A short intermediate break (<1 min) was inserted between each daily phase.

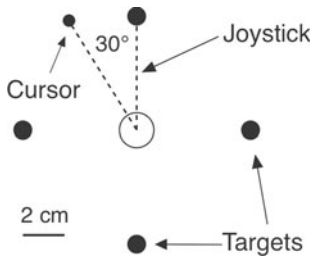

Fig. 1 Schematic of the task requiring participants to displace a joystick from a central position (*open circle*) toward one of four targets (*black circles*). In the perturbation condition, the cursor trajectory was deviated by 30° clockwise from the intended joystick trajectory

Data analysis

We filtered the *x*- and *y*-coordinates of cursor displacements with a low-pass Butterworth filter using a 6 Hz cutoff, and then calculated the cursor trajectory by taking the square root of the sum of squared *x*- and *y*-coordinates at each time point. Inspection of the kinematic data revealed that movements of the PD patients and some controls contained multiple velocity peaks (Rand et al. 2000) rendering the usage of kinematic landmarks (e.g., peak velocity) to measure reaching accuracy more prone to group differences than in studies with neurologically normal participants (Krakauer et al. 2005). We defined movement initiation when the cursor became displaced 0.5 cm from the start position. To assess movement accuracy, we calculated reaching error as the angle between the line that joined the home position to the target with the line that joined the home position to the point reached by the position cursor 100 ms after movement initiation; this measure represents the planning of the initial direction of movements allowing us to evaluate the state of the IM before movement corrections can take place. We averaged reaching accuracy across four successive trials (a "cycle") as in prior work (Caithness et al. 2004; Krakauer et al. 2005; Marinelli et al. 2009). Since we aimed to assess whether a longer training session could allow PD patients to demonstrate savings at the *Recall* tests, we first compared reaching error within groups. In this statistical analysis, we considered Blocks of four trials and phases (*Learning*, *Recall D1*, *Recall D2*) as repeated measures and participants as a random factor. We also compared reaching error between groups with each of the *Learning* and *Recall* phases treating groups as a between factor, Phases as a repeated measure and participants as a random factor. We used the *R* project (R Development Core Team), MATLAB® (R2008b; The MathWorks, Naticks, MA) for data analysis implementation.

Results

Figure 2 illustrates individual movement trajectories of a control (left) and a PD participant (right) obtained during the four different phases of the experiment. During the initial *Null* condition (Fig. 2a; last four trials, trials 37–40, of the initial *Null* phase) participants typically moved in a straight path and had accurate movements. Introduction of the visual perturbation during the *Learning* phase yielded movements that deviated as expected in reaction to the 30° rotation (Fig. 2b; first four trials, black traces). However, with practice movements became straighter (dark gray traces, trials 41–44 of the Learning phase) and at the end of the *Learning* phase, trials 157–160, movements became well aligned with the targets (Fig. 2b; last four trials, light gray traces), suggesting that learning occurred. During *Recall* on D1 and D2 (Fig. 2c, d, respectively), both representative participants initially performed inaccurate movements, but then they quickly improved movement accuracy, seemingly even more quickly than evident during initial learning. However, it seems that this PD patient did not reduce error as fast as the control (note that the dark gray traces are still aligned with the black traces for the PD). This may indicate that PD-impaired recall of the IM developed during the Learning phase.

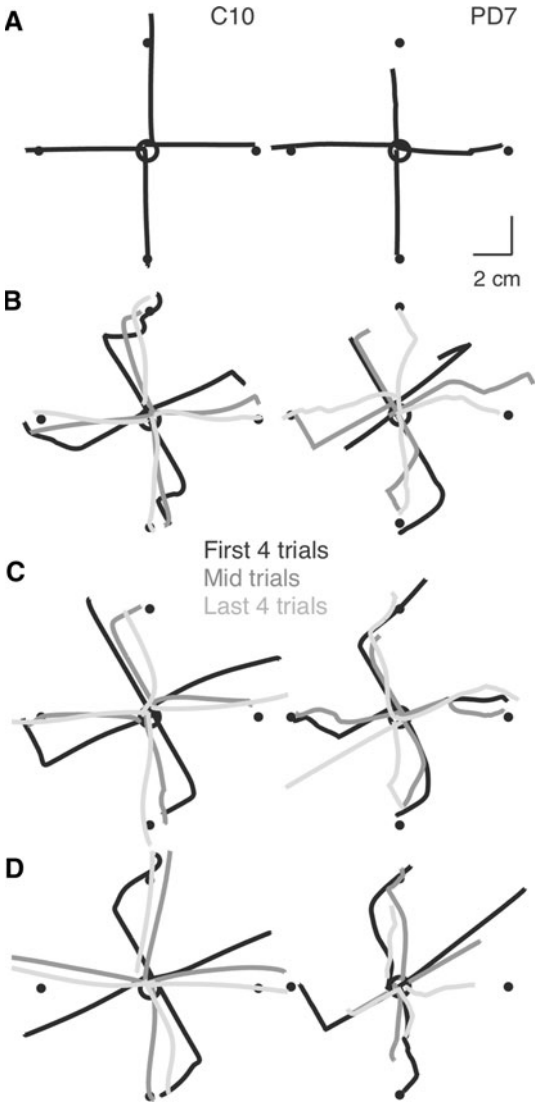

Fig. 2 Trajectories of representative participants for each group in the four conditions of the experiment. **a** *Null* condition (Day 1). **b** *Learning*. Note how the last four trials (*light gray traces*) were more accurate than the first four trials (*black traces*) for both participants. **c** *Recall D1*. Controls and PD volunteers showed more accurate movements in the last four trials (*light gray traces*) than in the first four trials (*black traces*). **d** *Recall D2*. Individuals from both groups exhibited more accurate movements in the last four (*light gray*) than the first four (*black*) trials although PD seemed less accurate for the mid-trials

The sample trajectories illustrated in Fig. 2 indicated that individual control and PD participants could perform all aspects of the experimental conditions: perform visually guided joystick movements, adapt to the changes in the visual environment, re-adapt to normal visual conditions, and possible faster adaptation to visual feedback modifications upon two retests. To assess these qualitative observations, we implemented inferential tests within and between groups during Learning and the two Recall phases.

Our first goal entailed determining whether the two groups exhibited savings (i.e., faster re-learning at either Recall tests than at initial Learning). We accomplished this assessment by implementing, for the control and PD groups separately, a two-way ANOVA with Phases (Learning, *Recall D1*, and *Recall D2*) and Blocks (1–10) as the main effects.

As a group, control participants showed lower reaching error during both *Recall* phases than during *Learning* (Fig. 3a). The Phases by Blocks ANOVA confirmed this observation by revealing a significant main effect of Phases, $F(2, 22) = 6.76$, $P \leq 0.005$, an expected significant main effect of Blocks, $F(9, 99) = 21.72$, $P \leq 0.001$, and a significant interaction, $F(18, 198) = 1.83$, $P \leq 0.05$. Note that using the first five, 15, or 20 trial blocks yielded similar significant main effects and the interaction between Phases and Blocks as using the first 10 blocks ($P \leq 0.05$). Concerning the main effect of Phases, post-hoc tests indicated lower reaching error for *Recall D1* than *Learning* ($t(11) = 3.46$, $P \leq 0.005$) and also lower reaching error for *Recall D2* than *Learning* ($t(11) = 3.13$, $P \leq 0.01$), with no significant difference between both Recall tests ($t(11) = 0.14$, $P = 0.89$). Concerning the interaction effects, post-hoc tests revealed significantly lower error ($P \leq 0.05$) during *Learning* than *Recall D1* at block 1, 2, 5, 6, 7, and 10, lower error during *Learning* than *Recall D2* at block 1, 3, 4, 5, 6, and 7; lower error for *Recall D1* than *Recall D2* at block 2 and the reverse for block 4. Thus,

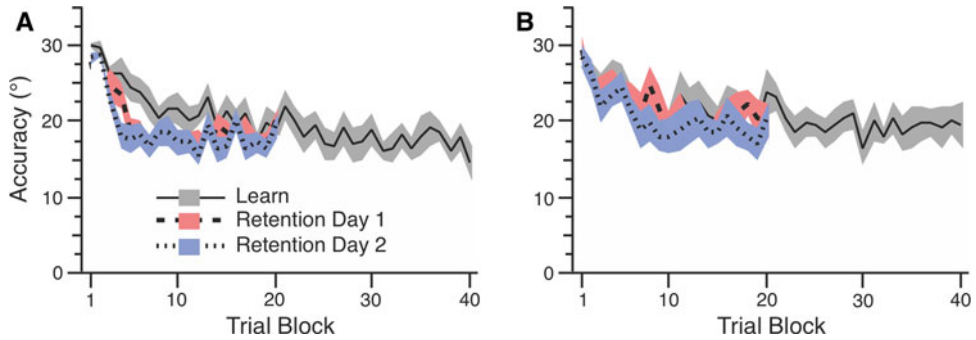

Fig. 3 Reaching error (degrees, mean ± SEM) for both groups during the Learning and both *Recall* phases. **a** Controls had lower error at both *Recall* tests than during *Learning*, thereby demonstrating savings. **b** PD patients showed similar performance at both *Recall* tests than during *Learning*. This lack of savings in PD suggests a role for basal ganglia in forming long-term memory of the visual-motor adaptation

control participants showed faster re-learning at both *Recall* tests than during the early Learning phase, indicating the presence of savings.

Now turning to the performance of the PD patients (Fig. 3b), as a group, the statistical analysis of the accuracy results from these participants revealed no significant main effect of Phase, $F(2, 22) = 0.78$, $P = 0.47$, an expected significant main effect of Blocks, $F(9, 99) = 11.69$, $P \leq 0.001$, and no significant interaction between Phase and Blocks, $F(18, 198) = 0.89$, $P = 0.59$. Note again that using the first five, 15, or 20 trial blocks in this type of analysis did not reveal any significant main effects of Phases or interaction between Phases and Blocks ($P > 0.05$). Thus, while the control group demonstrated savings at each *Recall* phase, PD patients did not show evidence of savings. This apparent lack of savings for the PD group suggests that basal ganglia circuits have involvement in transforming the newly formed IM into a longer-term memory.

Next, we directly contrasted between groups to further assess whether PD-impaired memory formation. Figure 4 illustrates reaching error for the control and PD groups across all the experimental phases (same data as in Fig. 3a–b plotted differently to ease comparison). As can be seen in the figure, both groups exhibited similar reaching accuracy in the *Null* condition for either day. Upon experiencing the visual-motor perturbation during the *Learning* phase (block 11), both groups expressed reaching error close to 30°, though with practice both groups decreased reaching error at similar rates. To assess whether the initial decrease in reaching error differed between groups, we computed the slope of reaching error across the first five trial blocks of the *Learning* phase (blocks 11–15) and tested the null hypothesis of no group difference, which we did not reject ($t(22) = 1.38$, $P = 0.19$; note that using blocks 11 to 16–20 yielded $P = 0.38$, 0.70, 0.27, 0.34, and 0.62, respectively). This analysis indicated that PD participants did not show slower adaptation rates in the early portion of the *Learning* phase. At the end of *Learning*, both groups attained comparable levels of adaptation (means ± SEM of reaching error of the last two blocks were 16.2° ± 1.9 and 17.8° ± 2.2 for controls and PD, respectively, $t(22) = 1.22$, $P > 0.23$; note that using the means of the last three, four, or five blocks yielded $P = 0.30$, 0.41, and 0.47, respectively; further we compared the two groups at each of the last five blocks and none yielded significant difference, all $P > 0.32$). Finally, we compared both groups across the entire *Learning* phase with a two-way ANOVA with groups (controls and PD) and Blocks (11–50, that is, all blocks of the *Learning* phase), which revealed no significant main effect of groups, $F(1, 22) = 0.15$, $P = 0.70$, no interaction, $F(39, 858) = 1.2$, $P = 0.19$, but an expected significant main effect of Blocks, $F(39, 858) = 6.55$, $P < 0.001$. Thus, we found no evidence that PD impaired adaptation rates at any point during the *Learning* phase, thereby suggesting that basal ganglia circuits do not have specific involvement in forming the IM required for adapting to visual rotations.

Reaching errors for the *Recall* tests immediately after (D1) and 24 h later (D2) appear in the middle and right panels of Fig. 4 (blocks 71–90 for D1 and blocks 101–120 for D2). At *Recall D1*, reaching error of control participants seemed to decrease steadily until about block 77 and then remained fairly constant; by contrast, reaching error of PD participants decreased more slowly after the first few blocks. To confirm this observation, we computed the slope of reaching error across the first seven trial blocks and tested the null hypothesis of no group difference between the slopes; we found a marginally significant difference, $t(22) = 1.9$, $P = 0.069$; note that the slope of reaching error across the first eight trial blocks yielded a significant group difference, $t(22) = 2.61$, $P \leq 0.05$. Thus, PD seemed to reduce savings after a short delay during which all participants performed the task under normal visual conditions. At *Recall D2* (block 101–120), 24 h after initial learning and a retention test, the control participants also

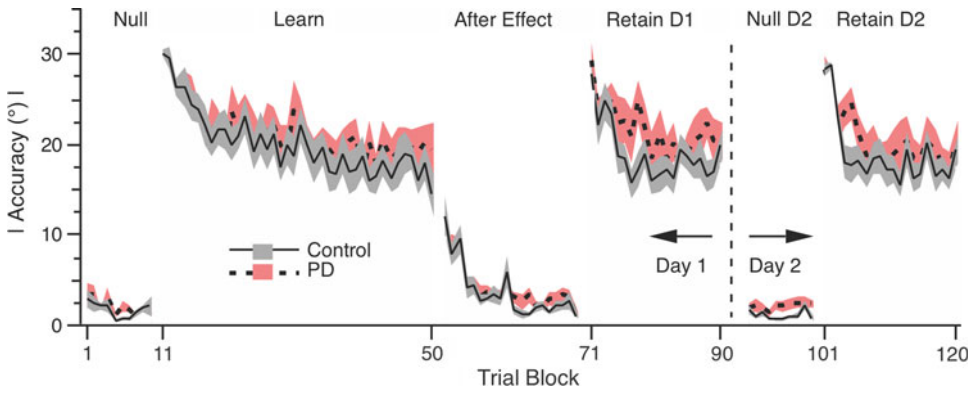

Fig. 4 Reaching error (degrees, mean ± SEM) for both groups across all the experimental phases. PD and control participants exhibited similar reaching error during the *Learning* phase. However, PD patients had higher reaching error than those of controls at both *Recall* tests

decreased reaching error faster than the PD group over the first few trial blocks (Fig. 4, right panel). To verify this observation, we computed the slopes across the first seven trial blocks and tested the null hypothesis of no group difference, which we rejected ($t(22) = 2.22$, $P \leq 0.05$). Thus, although PD patients decreased their reaching error similarly to control participants during the *Learning* phase, they did not exhibit as efficient recall of the IM immediately or 24 h after its formation as age-matched healthy adults. This outcome suggests that basal ganglia circuits do not have involvement in forming an IM but do participate in transforming IMs into a long-term memory.

Discussion

The present experiment aimed to understand more comprehensively a potential involvement of fronto-striatal networks in forming long-term memory of an IM related to sensory-motor adaptation. To achieve this goal, we assessed learning and recall capabilities of PD patients and age-matched controls using a visual-motor perturbation paradigm (e.g., Krakauer et al. 2005). Our findings showed that while basal ganglia dysfunction related to PD did not yield ostensible impairments during the *Learning* phase, PD impaired savings at both *Recall* phases (after a washout session and after 24 h). These findings suggest that basal ganglia do not contribute to dynamics of forming an IM, but do have a role in transforming the initial memory into a long-term representation.

Fronto-striatal networks and learning

During acquisition of the IM, PD patients and controls adapted to distorted visual feedback equivalently, thereby suggesting that fronto-striatal networks do not likely have an overriding role in adjusting motor commands to immediate environmental changes. The current results have consistency and indeed replicate prior findings in PD using similar sensory-motor adaptation paradigms (Marinelli et al. 2009; Paquet et al. 2008), but do not confirm other results (Contreras-Vidal and Buch 2003; Krebs et al. 2001; Messier et al. 2007). The discrepancies between studies may relate to design features. For example, Krebs et al. (2001) and Messier et al. (2007) used a proprioceptive adaptation task that may have exacerbated motor deficits in PD, since PD patients often have proprioceptive deficits (Boecker et al. 1999; Klockgether et al. 1995; Demirci et al. 1997). Similarly, Contreras-Vidal and Buch (2003) employed a 90° rotation that may have caused more adaptation difficulties for PD patients, especially since putamen activation appears to match rotation magnitude (Seidler et al. 2006) and higher rotation magnitudes may require more explicit processing than smaller rotations (Klassen et al. 2005). Prior studies also have found that PD impaired the explicit, but not the implicit, component of motor sequences learning (Muslimovic et al. 2007; Seidler et al. 2007; Wang et al. 2009). One might argue that implicit processes mediate the type of sensory-motor adaptation used in the current work (Mazzoni and Krakauer 2006). Thus, our observation of ostensible normal learning of a 30° rotation in PD may relate to the preservation of implicit learning in PD (Marinelli et al. 2009) but not, or much less capability to adapt, to a 90° rotation (Contreras-Vidal and Buch 2003). While the current results provide support for the conclusions of Marinelli et al. (2009) that PD impairs short-term and longer-term recall of adapted visual-motor behavior, the current work also extends their findings.

In the current study, we tested PD patients while they adhered to their daily medication regimen, though we note that these patients would not be classified as having entirely normal motor function even when on anti-parkinsonian medication. The medicated state of PD patients could explain why they showed comparable adaptation to controls, at least during *Learning*. This finding has consistency with recent results reporting PD-related deficits visual-motor adaptation only when PD patients were off medication (Paquet et al. 2008). Thus, while the outcome of 'normal' learning in PD could relate to medication state, we note that deficits due to PD occurred during both *Recall*

tests even while the same PD patients were medicated. We note that knowledge as to whether and how dopaminergic medication affects sensory-motor adaptation remains inconclusive since prior work found deficits in PD while on medication (Contreras-Vidal and Buch 2003), off medication (Krebs et al. 2001; Messier et al. 2007), or did not find differences between medicated, drug-naive PD patients, and healthy controls (current results; Marinelli et al. 2009; Stern et al. 1988; Weiner et al. 1983). Certainly the role of dopamine and how it influences fronto-striatal networks beyond reducing PD symptoms warrants more examination.

Our results also showed that PD patients had similar reaching accuracy as the controls across the *Learning* phase. Thus, in agreement with Marinelli et al. (2009), we also found that PD patients did not adapt more slowly or require more trials to achieve similar performance as controls during *Learning*, even though the task in the current work stipulated double (160 vs. 80) the number of trials than used previously. However, we also assessed whether a larger number of learning trials could help PD patients to form a more resilient memory of the IM, as occurs in young healthy adults (Krakauer et al. 2005; Joiner and Smith 2008). We found that adding extra trials did not influence the savings deficit evident in PD immediately after forming the IM and one day later. However, despite the evident savings deficits, PD patients also showed evidence of retaining the IM, since by the end of each *Recall* phase, the performance of PD patients did not differ from that of age-matched control participants.

Fronto-striatal networks in recall

Despite the ostensible ability of PD patients to learn a visual-motor transformation successfully (current results), the extent to which they can also form stable, long-term motor memories without entirely intact fronto-striatal networks remains debatable. Prior work, using a similar task as ours (Marinelli et al. 2009), while also not revealing learning impairments in PD, did find recall impairments (measured at 24 and 48 h post-learning). Others have found that PD impaired recall of movement sequences (Agostino et al. 2004; Doyon et al. 1998; Mochizuki-Kawai et al. 2004; but see Smiley-Oyen et al. 2006). These results collectively suggest that basal ganglia structures have involvement in forming long-term motor memories. Since our work most closely mirrored that of Marinelli et al. (2009), we tested whether a larger number of training trials coupled with an easier adaptation task would allow PD patients to form a more robust IM. As noted, compared to Marinelli et al. (2009), we doubled the number of trials during *Learning* (from 80 to 160) and reduced the number of targets (from eight to four), two features that promote adaptation and memory formation (Krakauer et al. 2000, 2005). It is well recognized that once participants achieve a certain performance level, additional training commonly has little effect on initial adaptation but can yield enhanced long-term retention (Krueger 1929; Luh 1922; Yin and Kitazawa 2001; Krakauer et al. 2005; Joiner and Smith 2008). As such, PD patients can exhibit similar recall capabilities as controls, if they have sufficient training (Behrman et al. 2000; Smiley-Oyen et al. 2006).

Despite these design changes to promote learning and retention, we still found recall impairments in PD immediately after initial practice and also 24 h later. The reduced savings in PD at the *Recall D1* and *D2* phases (Fig. 3b) and their higher reaching error at each recall test compared to controls (Fig. 4) suggest that fronto-striatal networks indeed have involvement in transforming memories of a motor IM into a long-term representation. Further, the savings impairment of PD patients at *Recall D1* further suggests that basal ganglia circuits likely participate relatively early in the process of forming a long-term memory; a feature that Marinelli et al. (2009) did not assess. Therefore, the current results extend prior findings of how the brain forms long-term representations of an IM and suggest involvement of the basal ganglia soon after the initial practice is completed in the process of forming long-term memories. We note here that these concepts contrast with those of Doyon and colleagues (e.g., Doyon and Benali 2005; Doyon et al. 2009) who have suggested that while basal ganglia circuits likely participate in motor sequence learning and adaptation, they do not then continue to contribute to longer-term elaboration of motor adaptation.

Doubling the number of trials and using a task that should promote better learning still failed to yield normal recall in PD, thereby replicating the findings of Marinelli et al. (2009). We do note, however, that even exposure to additional visually rotated trials during *Recall D1* might have, but clearly did not, provided PD patients with an additional opportunity to further develop their IM; at the onset of the *Recall D2* test, participants had practiced 240 trials. Despite this extended practice, PD patients still exhibited deficits in recalling what they had learned and practiced the previous day. Thus, contrary to motor sequence learning for which PD patients appear to benefit from more practice to enhance longer-term memories (Behrman et al. 2000; Smiley-Oyen et al. 2006), forming an IM related to visual-motor adaptation seems to operate differently.

The specific recall deficits in PD could relate to a shift in the memory's brain representation that accompanies long-term memory formation (Doyon and Benali 2005; Doyon et al. 2009). For example, Penhune and Doyon (2002) showed that learning motor sequences yielded brain

activation in the cerebellum and temporal cortex, while recalling these yielded activation in parietal cortex, pre- and primary-motor areas (Doyon et al. 2002; Floyer-Lea and Matthews 2004). A similar shift in the memory's brain representations also seems to take place for sensory-motor adaptation, though involving different brain areas (Doyon and Benali 2005; Doyon et al. 2009; Nezafat et al. 2001; Shadmehr and Holcomb 1997). The absence of a learning deficit in PD but one at recall suggests that as the memory of an IM precedes from initial formation toward automatization, its brain representations change and are increasingly mediated by fronto-striatal circuitry. The current recall test only assessed how the memory's brain representations changed within a relatively small time window, 24 h, while Marinelli et al. (2009) extended this time frame modestly, to 48 h, but only for one of their two tasks. Thus, we cannot exclude the possibility that recall by PD patients of an IM related to visual-motor adaptation might emerge beyond 48 h with possible delayed consolidation.

In conclusion, basal ganglia dysfunction did not impair initial acquisition of a visual-motor IM but it did influence immediate and delayed recall of the IM. These findings replicate the work of Marinelli et al. (2009), while also expanding upon them by showing that extended practice does not provide added benefits in PD to form long-term memory of an IM. Thus, these results support notions that basal ganglia structures participate in learning and remembering habits and skills (Graybiel 2005), such as adaptation, while not supporting the model proposed by Doyon and colleagues (e.g., Doyon et al. 2009) that the basal ganglia have little role in recall of motor adaptation. It remains possible that PD yielded compensatory mechanisms that effectively recruited other brain areas such as the cerebellum and parietal cortex, regions known to participate in adaptation. We have shown this effect in arbitrary associative learning (Bédard and Sanes 2009). The fact that PD patients could not do the same for recalling an IM related to visual-motor adaptation remains more puzzling.

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