Determining the Optimal Challenge Point for Motor Skill Learning in Adults With Moderately Severe Parkinson’s Disease

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Objective. To test the predictions of the Challenge Point Framework (CPF) for motor learning in individuals with Parkinson’s disease (PD) by manipulating nominal task difficulty and conditions of practice. Methods. Twenty adults with PD and 20 nondisabled controls practiced 3 variations of a laboratory-based goal-directed arm movement over 2 days. A between-group (PD, nondisabled) 2-factor design compared 2 levels of nominal task difficulty (low, high) and 2 levels of practice condition (low, high demand). Learning was assessed with a no-feedback recall test 1 day after practice. Performance was quantified using a root mean square error difference between the goal and participant-generated movement. Results. All participants improved with practice. Under the low-demand practice condition, adults with PD demonstrated comparable learning to that of controls when nominal task difficulty was low but not high. In contrast, under the high-demand practice condition, adults with PD demonstrated preserved motor learning for both levels of task difficulty, but only if recall was tested under the same context as that used during practice. Conclusions. In general, the predictions of CPF were supported. Together, the level of nominal task difficulty and the inherent demand of the practice condition played a critical role in determining the optimal challenge point for motor learning in individuals with PD. More important, and in contrast to the predictions of CPF, a high-demand practice condition appeared to have a facilitative effect on motor learning. However, this benefit revealed the context specificity of motor learning in adults with PD.

Key Words: Motor learning—Practice order—Feedback frequency—Task demand—Parkinson’s disease—Challenge Point Framework.

Although practice is considered to be the most important factor responsible for the permanent improvement in the ability to perform a motor skill (ie, motor learning), other factors such as the conditions of practice, the difficulty of the task, and the learner’s skill level can significantly influence the proficiency of motor skill learning. The Challenge Point Framework (CPF) has recently been proposed as a means to determine the optimal challenge point for motor learning. Using CPF, interactions between nominal task difficulty of the to-be-learned task and the learner’s skill level together with the specific conditions of practice create a level of functional task difficulty that determines how much information will be available for motor learning. This idea emerges largely from studies done with control populations. The fundamental assumption of CPF is that learning is a problem-solving process and that the information available during and after each attempt to solve the problem is remembered and forms the basis for learning. Too much or too little information will retard learning.

According to CPF, the characteristic of the learner affects how they respond to certain practice conditions. Thus, a practice condition proven to benefit motor learning for nondisabled adults may not benefit or may even degrade motor learning in adults with neurologic deficits such as Parkinson’s disease (PD). Evidence from functional neuroanatomic studies and clinical studies reveals that the integrity of the basal ganglia is essential for both cognitive and motor operations of procedural learning. Although numerous studies have shown that motor learning is impaired in adults with PD, the learning deficits are neither global nor consistently found. The inconsistencies among previous findings are due to variations across studies in task demand and the conditions
of practice (ie, functional task difficulty in CPF) as well as disease severity (ie, learner’s skill level in CPF). In addition, there were variations in the methods used to assess motor learning. For example, several studies did not account for the well-known learning-performance distinction in the experimental design.20

Manipulations of practice order and feedback frequency have been shown to influence motor learning capability. A random practice order (eg, A-C-B-, C-B-A-, B-A-C-, each letter represents a different task) generally benefits motor learning more than a blocked practice order (eg, A-A-A-, B-B-B-, C-C-C-). The benefit of random practice over blocked practice is due to the higher level of contextual interference (CI) induced by random practice order.21,22 One interpretation of the CI effect is that random practice requires more cognitive processing during practice compared to that for blocked practice.21-24 CPF predicts that for less skilled learners, a low CI practice condition would benefit motor learning more than a high CI practice condition. In fact, the findings from a recent study in adults with PD support this prediction.25

Feedback is often provided in the form of knowledge of results (KR). Previous work using relatively simple tasks suggests that feedback using a low frequency of KR is as effective or more beneficial for motor learning than that using a high frequency of KR.26-29 One interpretation of the KR frequency effect is that less frequent KR enhances learning by forcing the individual to engage in cognitive processing essential for skill acquisition. In contrast, a high frequency of KR provides the solution for the learner and, thus, diminishes the cognitive demand for solving the task problem.26,27,30,31 Similar to the CPF predictions for the CI effect, learners with less skill would benefit more from a high frequency of KR compared to that for a low frequency of KR. In agreement with CPF prediction, previous studies have shown that for a relatively difficult task and/or less skilled learners, high KR frequency benefits motor learning more than low KR frequency.28-32

Within CPF, nominal task difficulty reflects a constant amount of task difficulty regardless of the performer or the environmental circumstances. Thus, it includes such factors as perceptual and motor requirements for the task. For example, when spatial accuracy is controlled, a movement with a short movement time (MT) goal would have a higher level of nominal task difficulty than a movement with a longer MT goal. In this study, a 1500 ms MT goal was used for the low level of nominal task difficulty, whereas a 900 ms MT goal was used for the high level of nominal task difficulty. In contrast to nominal task difficulty, the level of functional task difficulty is influenced by several factors including the conditions of practice. For example, when a task with low nominal difficulty (ie, 1500 ms MT goal) is being performed under a low-demand practice condition (ie, blocked order and 100% KR), the task is considered to pose “low functional task difficulty.” In contrast, when a task with high nominal difficulty (ie, 900 ms MT goal) is being performed under a high-demand practice condition (ie, random order and 60% KR), the task is considered to possess “high functional task difficulty.” Finally, when a task with low nominal task difficulty is being performed under a high-demand practice condition or when a task with high nominal task difficulty is being performed under a low-demand practice condition, the task is considered to possess “intermediate functional task difficulty.”

The purpose of this study was to test the predictions of the CPF for motor learning in individuals with PD by manipulating nominal task difficulty and the conditions of practice. To our knowledge, this study is the first to explore motor learning through a systematic manipulation of 3 important factors: the learner’s skill level (ie, PD, controls), the conditions of practice that include practice order (ie, blocked, random) and feedback frequency (ie, 100% KR, 60% KR), and nominal task difficulty (ie, low and high). We tested the hypothesis that participants with PD will demonstrate comparable learning to that of age-matched, nondisabled controls when functional task difficulty is low. In contrast, participants with PD will demonstrate poorer motor learning relative to nondisabled controls when functional task difficulty is high.

METHODS

Participants

Twenty adults with PD and 20 nondisabled, age-matched volunteers were enrolled. Participants with PD were recruited if they had moderate illness classified by the modified Hoehn and Yahr stage II or III35 and were optimally medicated for PD. They participated in the investigation during the “on” medication cycle. To ensure homogeneity within PD subgroups and to control for relevant confounding factors, all participants were screened for dementia (scores ≥ 28 on the Mini-Mental State Examination [MMSE]),36 depression (score < 10 on the Center for Epidemiologic Studies Depression [CES-D] short form scale),37 and hand-dominance (right-handed with 80% cutoff on the Edinburgh Handedness Inventory).38 All participants gave written informed consent and participated in the study under a protocol approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Instrumentation and Task

A lightweight lever affixed to a frictionless vertical axle was attached to a table and positioned parallel to
the floor. A handle at the end of the lever was adjusted to accommodate the participant’s forearm. A linear potentiometer was attached to the transducer at the base of the vertical axle. Signals from the transducer were converted to a digital signal by an A-D board of a Dell 466v computer and sampled at 200 Hz. The Template software program was used to manipulate the movement trajectory and the interval duration and to store data from each trial for further analyses.

The task was to grasp the handle of a lever and move it horizontally at the correct speed and distance to replicate a goal movement trajectory, which was displayed on the computer monitor before each trial. The goal was to learn a continuous movement with 2 elbow extension-flexion reversal actions. This goal movement was to be performed under 3 different movement times (ie, 900, 1200, and 1500 ms; Figure 1A). During acquisition, after each trial, the participant was presented with either the trial number together with 2 types of feedback or the trial number alone. The 2 types of feedback were (1) an overall error score, the root mean square error (RMSE), representing the difference between the goal movement task and the participant’s response, and (2) a graphic representation of the response superimposed with the goal movement task (Figure 1B).

**Experimental Design and Procedure**

A 2 Group (control [Con], PD) × 2 Practice condition (low-demand practice condition, high-demand practice condition) between-factor design was implemented. This overall design resulted in 4 experimental groups: Con-low demand, Con-high demand, PD-low demand, and PD-high demand. The 3 movement time goals (900, 1200, and 1500 ms) were constant under both conditions of practice (ie, within factor design).

The experimental protocol included an acquisition phase (days 1 and 2) and delayed retention phase (day 3). During acquisition, participants in the low-demand condition practiced the tasks under blocked order and received 100% KR frequency, whereas those in the high-demand condition practiced the tasks under random order and received 60% KR frequency. The 60% KR was scheduled as follows: 100% for trials 1 to 15, 60% for trials 16 to 30, and 20% for trials 31 to 45 in each trial set. All participants practiced 6 sets of 45 trials during acquisition (3 sets each day), resulting in a total of 270 trials. There were 2 retention test conditions (blocked and random retention). The order of the retention tests was counterbalanced across participants. During the retention test, participants performed the same movements (ie, recall test) they practiced the day before but without any KR feedback.

**Outcome Measures and Statistical Analyses**

Global performance accuracy (RMSE) was quantified across acquisition and delayed retention phases. RMSE is the average difference between goal movement trajectory and the participant’s response calculated over the participant’s total movement time. Individual RMSE data were grouped into 9-trial blocks for the acquisition phase (blocks 1-10) and 5-trial blocks for the retention (blocks 11-12) phase.

Although 3 movement time goals were used to grade nominal task difficulty, we were particularly interested in the 2 extreme nominal task difficulty levels, 1500 ms (low) MT goal and 900 ms (high) MT goal. The 1200 ms MT goal was included in the design to reduce the number of repetitive representations of the same trajectory in the random practice condition. Therefore, only data from the 900 ms and 1500 ms MT goals were included in the analyses.

A 2 Group (Con, PD) × 2 Practice condition (low demand, high demand) × 2 Nominal task difficulty (low, high) × 10 Block analysis of variance (ANOVA) with repeated measures on the last factor was conducted on the acquisition data to provide an overall description of the performance for the 2 groups. Performance during the retention test was used to assess motor learning. Retention data from each practice condition were analyzed separately to
accommodate inclusion of the 2 retention tests (random, blocked) as a within-factor. Therefore, retention data for the PD-low demand subgroup were compared to the Con-low demand subgroup and those for the PD-high demand subgroup were compared to the Con-high demand subgroup. Two separate 2 Group (Con, PD) × 2 Nominal task difficulty (low, high) × 2 Retention test (blocked, random) ANOVA were conducted on mean RMSE to address our questions regarding the motor learning capability of individuals with PD compared to nondisabled controls. Post hoc analyses of any significant main effects and interactions were conducted using pairwise comparisons with a Bonferroni correction. A partial eta squared statistic was used to index the strength of association (ie, effect size, ES).41 Independent 2-sample t tests were conducted to assess differences in demographic characteristics between PD and nondisabled groups. For all statistical tests, significance level was set at \( P < .05 \).

RESULTS

Participant Demographic Characteristics

Group mean comparisons for the demographic characteristics are summarized in Table 1. Group comparisons were made separately within the same practice condition. For the low-demand practice condition, there were no differences between groups for age, education, or MMSE score. For the high-demand practice condition, there was no difference between groups for age. However, participants with PD had a higher education level but lower MMSE score than the nondisabled controls. None of the participants had clinical signs of dementia or depression. Mean score on the CES-D was, however, higher for the PD group than the control group for both practice conditions. The disease severity was similar for the 2 PD subgroups (mean Hoehn and Yahr stage: PD-low demand = 2.6, PD-high demand = 2.5). For all participants with PD, their PD-related symptoms presented bilaterally with some postural instability. However, they were physically independent. Average PD duration was 7.3 years (range, 3-15 years) for the PD-low demand subgroup and 10.2 years (range, 4-20 years) for the PD-high demand subgroup.

Acquisition Performance

RMSE block means for each group by condition of practice and motor task during acquisition are displayed in Figure 2. All participants improved their performance with practice (Block Effect; \( P < .001 \)). Overall, performance was not different between the 2 groups (Group Effect; \( P = .07 \)). Participants who practiced in blocked order with 100% KR frequency (ie, Con-low demand and PD-low demand, top row) were generally more accurate than those who practiced in random order with 60% KR frequency (ie, Con-high demand and PD-high demand, bottom row) (Practice Condition Effect; \( P < .001 \)). Similarly, all participants were more accurate in reproducing the low nominal task difficulty (ie, 1500 ms trajectory, right column) than that of the relatively higher nominal task difficulty (ie, 900 ms trajectory, left column) (Nominal task difficulty Effect; \( P < .001 \)). Across the 2 conditions of practice, individuals with PD had higher error than nondisabled controls for the high but not for the low nominal task difficulty (Group × Nominal task difficulty interaction; \( P < .05 \)). The estimated effect size for this interaction was large (ES = .41).42 This group difference for the high nominal task difficulty was due primarily to the high error of the PD-low demand subgroup during the first half of practice (Block 2-5, Figure 2 top left). The Group × Practice condition interaction was not significant (\( P = .64 \)), suggesting that during acquisition,
participants with PD benefited from practice order and feedback frequency as nondisabled controls.

Retention Performance

Low-demand practice condition subgroups (con-low demand, PD-low demand). For participants who practiced under blocked order and received 100% KR frequency, the PD group was as accurate as the nondisabled, control group in reproducing the low nominal difficulty task (1500 ms trajectory) either when tested in blocked retention or random retention (Figure 3, top right). However, when nominal task difficulty was high (900 ms trajectory), the PD group performed with significantly greater error than the control group for both blocked and random retention tests (Figure 3, top left). This Group × Nominal task difficulty interaction was significant ($P < .02, ES = .22$).

High-demand practice condition subgroups (con-high demand, PD-high demand). For participants who practiced under random order and received 60% faded KR frequency, retention data showed that the context of the retention test (whether it is the same as or different from the practice condition) primarily affected the learning capability of the PD group. Individuals with PD exhibited greater error than controls when tested in blocked retention for both low and high nominal task difficulty conditions (1500 ms and 900 ms trajectories). Conversely, individuals with PD were as accurate as nondisabled controls when tested in random retention, again for both low and high nominal task difficulty conditions (Figure 3, bottom row). These findings resulted in a significant Group × Retention Test interaction; $P < .01$, $ES = .33$. Findings that the PD-high demand subgroup performed relatively well compared to controls in the random retention but not in the blocked retention test suggest that practice under the random order together with receiving
60% KR frequency evoked context-specific learning in individuals with PD. This context-specific learning effect in the PD-high demand subgroup was evident independent of the order of the retention test condition (ie, participants performed the random retention before or after the blocked retention). This effect is illustrated for 2 exemplar participants who had different retention test orders (PD-01, PD-05) in Figure 4.

The context-dependent learning effect in adults with PD is illustrated in Figure 5. The retention data (averaged across the 2 nominal task difficulties) for each practice condition were compared within each subgroup. For the control group (Figure 5A), both Con-low demand and Con-high demand subgroups showed a smaller error in the blocked relative to random retention. In contrast, the PD-low demand subgroup showed a smaller error in the random relative to blocked retention (Figure 5B). This resulted in a significant Practice condition × Retention condition interaction ($P < .004$, ES = .39). Post hoc analyses identified a significant difference between blocked and random retention for the PD-high demand subgroup ($P < .02$, ES = .50) but not the PD-low demand subgroup ($P = .07$, ES = .40).

Statistical analysis revealed no significant Practice Condition main effect or interaction, suggesting that the 2 practice conditions (low, high) had similar effects on retention performance of nondisabled controls. Unlike the control groups, the pattern of findings was different between the 2 PD subgroups. Specifically, the PD-low demand subgroup showed a smaller error in the blocked relative to random retention. In contrast, the PD-high demand subgroup showed a smaller error in the random relative to blocked retention (Figure 5B). This resulted in a significant Practice condition × Retention condition interaction ($P < .004$, ES = .39). Post hoc analyses identified a significant difference between blocked and random retention for the PD-high demand subgroup ($P < .02$, ES = .50) but not the PD-low demand subgroup ($P = .07$, ES = .40).
DISCUSSION

The aim of the present study was to test the predictions of the Challenge Point Framework for motor learning in individuals with PD by manipulating nominal task difficulty and the cognitive demand inherent in the practice condition. The CPF offered useful scaffolding for understanding the importance of the motor task and conditions of practice for the information processing capability of this population.

This study appears to be the first to manipulate the conditions of practice (feedback frequency, practice schedule), nominal task difficulty (movement time), and retention test condition (blocked, random) within the same experiment. Thus, there is no definitive information from previous work that would allow us to accurately predict the expected results. When averaged across the 2 nominal task difficulties, our findings show that the 2 practice conditions (low, high) had similar effects on retention performance only for the nondisabled controls. Of particular interest, the results showed context-specific learning characteristics only for the adults with moderately severe PD.

Our findings showed that the level of nominal difficulty of the to-be-learned task and information processing demands inherent in the practice conditions do interact and play a critical role in determining motor learning capability for the PD group. Under a low-demand practice condition, individuals with moderately severe PD demonstrated comparable learning to nondisabled, age-matched participants when nominal task difficulty was also low but demonstrated learning deficits when nominal task difficulty was high. However, in contrast to the predictions of CPF, and in comparison to the nondisabled group, under the high-demand practice condition, individuals with moderately severe PD demonstrated comparable learning to nondisabled, age-matched participants when nominal task difficulty was also low but demonstrated learning deficits when nominal task difficulty was high. However, in contrast to the predictions of CPF, and in comparison to the nondisabled group, under the high-demand practice condition, individuals with PD demonstrated comparable motor learning, but only when the context of the recall test was the same as that during practice (ie, random retention). This context-specific effect is not a new concept in the PD literature and has variously been referred to as a deficit in “task-switching,”“43-46 stuck-in-set-perseveration,“47 and “motor set inflexibility.”“48,49 The context-specific learning effect does suggest that the nature of the transfer/retention test is important for future motor learning research, especially for understanding the learning capability in adults with PD.
Discussion of Methods and Experimental Design

The Challenge Point Framework led us to speculate that some of the discrepancies in previous studies of motor learning capability in adults with PD were due to differences in the level of nominal task difficulty, the practice conditions employed, and the severity level of the disease that is well known to affect information processing capability. Therefore, we included only individuals with moderate severity (modified Hoehn and Yahr stage II-III) and systematically manipulated the cognitive demand through scheduling of the motor tasks and the frequency of performance feedback, along with the level of nominal task difficulty. In addition and to account for the well-known temporary performance effects induced during practice, motor learning was assessed by performance during no feedback, delayed recall (ie, a transfer test design). We deliberately chose 2 retention conditions, blocked and random, to examine the generalizability and context-specific nature of motor learning in this group. This was done because there is some evidence that motor set inflexibility is one characteristic of PD that would predict context-specific learning.

Effects of Low-Demand Practice Condition and 2 Levels of Nominal Task Difficulty on Motor Learning in Individuals With PD

In the low-demand practice condition, participants practiced the same task throughout the practice set and received feedback after every trial. It is well established that although a low contextual interference and a high frequency of feedback usually enhance acquisition performance, this combination would likely degrade learning, at least for nondisabled young adults. However, because of the alterations in cognitive processing, this may not be the case for older adults or individuals with PD. For example, recent work has shown that a condition with high-frequency KR is superior to one with a low frequency of KR for motor learning in PD, and similarly, a blocked order practice condition is superior to a random-order practice condition for motor learning in PD. Consistent with these findings and our hypothesis, the PD group showed comparable learning to the nondisabled control group when functional task demand was high. The CPF predicted that high cognitive demand induced through practice together with a high motor demand task would be detrimental for learning in individuals with PD, in part due to an already compromised cognitive and motor processing capability. In contrast, our findings showed that the added cognitive demand induced from high contextual interference and reduced feedback resulted in comparable motor learning. The mechanism underlying this learning effect is unclear and may be different from that of nondisabled controls. The basal ganglia are known to have a role in task-switching, and the cortico-striatal feedback loop is important for internal cueing of motor execution. Thus, the random practice order and reduced feedback frequency may directly challenge the task-switching and internal cueing deficits.

Effects of High-Demand Practice Condition and 2 Levels of Nominal Task Difficulty on Motor Learning in Individuals With PD

Our results from the low-demand practice condition described above support the hypothesis that when functional task demand is low, motor learning is preserved in individuals with moderately severe PD. In contrast, when the practice condition evokes a high cognitive demand and functional task demand varies (either high or intermediate), the results depend on the specific retention test used to assess learning. This finding had a medium strength effect size (Group × Retention interaction, ES = .33). The significant interaction between retention test condition and group highlights the context-specific learning allowed through the unique experimental design, discussed further in the next section.

Contrary to expectations, participants with PD showed comparable learning to nondisabled controls when functional task demand was high. The CPF predicted that high cognitive demand induced through practice together with a high motor demand task would be detrimental for learning in individuals with PD, in large part due to an already compromised cognitive and motor processing capability. In contrast, our findings showed that the added cognitive demand induced from high contextual interference and reduced feedback resulted in comparable motor learning. The mechanism underlying this learning effect is unclear and may be different from that of nondisabled controls. The basal ganglia are known to have a role in task-switching, and the cortico-striatal feedback loop is important for internal cueing of motor execution. Thus, the random practice order and reduced feedback frequency may directly challenge the task-switching and internal cueing deficits.
of PD. It may be possible that by forcing individuals with moderately severe PD to practice task-switching over a sufficient number of practice trials, they eventually habituate and overcome these known deficits. It should be noted that for each practice set, feedback was given at 100% for the first 15 trials, then 60% for trials 16 to 30, and 20% for trials 31 to 45. This faded feedback frequency may have allowed individuals with PD to use external information during early practice to improve their performance and then to gradually adjust to the reduced feedback by engaging the appropriate cognitive processes necessary to learn the task.

Context-Specific Learning in Individuals With PD

For the high-demand practice conditions, the context of the recall test was critical for demonstrating comparable motor learning capability to that of the nondisabled age-matched control group. This significant group effect had a large effect size (ES = .50). The evidence of context-specific learning, exclusively for the PD group, is indicative of a dysfunction of the basal ganglia. Set-shifting deficits or stuck-in-set-perseveration, a characteristic that has long been identified in PD, may mediate the less flexible learning capability identified here.43-48 The set-shifting deficit is thought to be due to impairment of the dorsolateral prefrontal circuit in selection mechanisms, necessary for disengaging from a previous task set and engaging a new one.43,58 Evidence presented here that individuals with PD showed preserved learning only when practiced under the high cognitive demand condition and only when learning was assessed in the same context underscores the importance of exploring the optimal challenge point for the learner. Even under a high functional task difficulty condition, adults with PD demonstrated comparable motor learning to that of controls (ie, 900 ms movement). This has important implications for designing rehabilitation programs.

IMPLICATIONS AND LIMITATIONS

Our experimental design allowed us to uncover a significant interplay between nominal task difficulty and the conditions of practice for determining motor learning capability and to reveal the context-specific learning that is characteristic of adults with moderately severe PD. Had we manipulated only a single dimension (ie, conditions of practice or nominal task difficulty or retention test condition) in our design, we might have arrived at a far different conclusion. We suggest that a combination of factors including the conditions of practice, nominal task difficulty, learner characteristics, and recall/retention test condition should be considered when designing rehabilitation programs for motor skill learning.

Our findings of motor learning under conditions of high contextual interference even with reduced levels of feedback suggest that adults with moderately severe PD can overcome the known task-switching deficits if tested in the same context as that of the practice phase. Commonly, individuals with PD are not sufficiently challenged in the rehabilitation settings, in part because of known motor and cognitive deficits. We have demonstrated that, in fact, the challenge itself may be what benefits motor learning. The beneficial effect from a high-demand practice condition is similar to activity-dependent neuroplasticity that has recently been identified in individuals with PD who undergo intensive exercise programs.59 Training programs for individuals with PD that use high contextual interference conditions may not only facilitate learning but also translate to the real-world situation where normally responses must be adapted to the environmental context. Similar suggestions have been offered for this population.60 Together, our results suggest that motor rehabilitation programs for adults with moderately severe PD should be designed to be challenging with a relatively high cognitive demand and to exploit the context specificity of learning through recall tests that are similar in nature to the practice condition.

Although these results are promising for application to the neurorehabilitation setting, there are a few limitations that need to be considered. First, generalizability should be demonstrated using functional activities of daily living in place of our laboratory-based motor tasks. Second, little is known about the “dose” of practice needed to overcome the learning deficits commonly attributed to individuals with PD. Acquiring motor skills under a high-demand practice condition may require extended practice compared to that under a low-demand condition. Indeed, previous work has shown that extended practice was beneficial for motor learning in adults with PD.16,61

REFERENCES

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