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RESEARCH ARTICLE

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Effects of Parkinson's disease on visuomotor adaptation

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Abstract Visuomotor adaptation to a kinematic distortion was investigated in Parkinson's disease (PD) patients and age-matched controls. Participants performed pointing movements in which the visual feedback of hand movement, displayed as a screen cursor, was normal (pre-exposure condition) or rotated by 90° counterclockwise (exposure condition). Aftereffects were assessed in a post-exposure condition in which the visual feedback of hand movement was set back to normal. In pre- and early-exposure trials, both groups showed similar initial directional error (IDE) and movement straightness (RMSE, root mean square error), but the PD group showed reduced movement smoothness (normalized jerk, NJ) and primary submovement to total movement distance ratios (PTR). During late-exposure the PD subjects, compared with controls, showed larger IDE, RMSE, NJ, and smaller PTR scores. Moreover, PD patients showed smaller aftereffects than the controls during the post-exposure condition. Overall, the PD group showed both slower and reduced adaptation compared with the control group. These results are discussed in terms of reduced signal-to-noise ratio in feedback signals related to increased movement variability and/or disordered kinesthesia, deficits in movement initiation, impaired selection of initial movement direction, and deficits in internal model formation in PD patients. We conclude that Parkinson's disease impairs visuomotor adaptation.

Keywords Kinematic distortion · Internal model · Basal ganglia · Sensorimotor learning

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Introduction

Pointing movements to a visual target require the transformation of visual inputs about spatial target locations into motor commands that move the hand in the direction of the target. This spatial direction-to-joint rotation relationship (a type of internal model[1]) must be updated if the visual feedback of movement is altered. The visuomotor relationship can be distorted by artificially rotating and/or scaling visual space via manipulation of the real-time visual feedback of hand movements displayed as a screen cursor on a computer monitor. Under such manipulations, practice is needed to acquire an internal model of the novel environment.

Recent experiments suggest that Parkinson's disease (PD) may impair visuomotor adaptation mechanisms. Teulings et al. (2002) showed that PD patients do not adapt to changes in the gain of handwriting movements displayed in a digitizer-tablet/display, but instead rely strongly on the visual feedback of movement. The lack of visuomotor adaptation was supported by the absence of aftereffects in the PD group compared to the age-matched elderly controls. Stern et al. (1988) compared PD patients and controls in a prism adaptation paradigm, in which visual space was displaced laterally by 11°. Greater spatial errors and smaller aftereffects were observed for the PD group in this study. However, Weiner et al. (1983) reported that PD patients displayed slightly less adaptation and higher variability than controls, but displayed normal aftereffects during prism-induced adaptation. It is difficult to compare the above studies, however, because visuomotor adaptation mechanisms engaged during per-

[1] Generally speaking, "internal models are neural representations of how, for instance, the arm would respond to a neural command, given its current position and velocity" and thus, in the context of this study, they "are expected to represent the altered relationship between the cursor movement and the mouse [or hand] movement (forward and/or inverse kinematics model)" (p 194 of Imamizu et al. 2000). In the context of the present experiment, other researchers have used the term to describe "neural principles which represent positions in such a way that they are accessible by both the sensory and motor system" (Abeele and Bock 2001)

ceptual recalibration (as in most prism adaptation studies) may differ from those employed during visuomotor skill acquisition (as in representational feedback conditions similar to the present task) (Clower and Boussaoud 2000). In addition, the prism adaptation paradigm produces a shift of the entire visual field, including the targets, and it has been noted that prism adaptation may also engage recalibration of the visual system with respect to neck or trunk position (Ingram et al. 2000). In this study, we show that PD patients have deficits in visuomotor adaptation to a novel, rotational transform of screen cursor representation of hand movement. These data suggest that during adaptation to a sudden screen cursor rotation, the basal ganglia may be critical for acquiring the internal model of a kinematic distortion.

Materials and methods

Subjects

Five mild-to-moderate PD patients (mean Hoehn-Yahr score 2.1±0.82; mean MMSE score 24.8±0.45 in the temporal orientation, registration, attention and calculation, recall and language items of the Mini-Mental State Examination test) participated in this study. The PD group had a mean post-diagnosis disease duration of 6.25±5.87 years (range 0.25–16 years), and a mean age of 61.20±12.60 years. In addition, five healthy age-matched control subjects (mean MMSE score 24.6±0.55) were examined. The mean age of the control group was 61.0±14.26 years. All subjects were right-handed, had normal or corrected-to-normal vision, and were naïve as to the purpose of the study. Subjects gave informed written consent prior to their inclusion in the study, and were paid for their participation. All procedures were approved by the Institutional Review Board at the University of Maryland at College Park.

Apparatus

Subjects sat at a table facing a computer monitor (41×30 cm),which was situated in front of them at a distance of 60 cm. A vertical board was placed on the table between the subject's head and right shoulder to occlude vision of the arm and hand. An infrared marker was attached to the tip of the right index finger. The position of this marker was sampled in real time at 100 Hz via a three-dimensional motion measurement system (Optotrack; Northern Digital, Ontario, Canada) connected to a personal computer (Gateway 2000 E-4200). Feedback of the index finger position was presented in the form of a white screen cursor (5-mm diameter). The subjects controlled the movement of the screen cursor by sliding the wrist and forearm across the surface of the table to the right of the occluding board. This constrained the movement to the horizontal plane. Subjects were instructed to make point-to-point movements as fast and as straight as possible, when ready, by moving the screen cursor from a common central starting location to one of four target circles (12-mm diameter, directions of 45°, 135°, 225°, and 315°, at a target distance of 20 cm) displayed on the screen. The start position and all four targets were visible throughout the entire duration of the testing session. Movements were initiated following the presentation of a 400-Hz auditory signal when subjects felt ready to move.

Procedure

The experimental session consisted of three conditions that covered a total of 440 trials. During the pre-exposure condition (40 trials, ten movements per target direction), subjects moved to one of four targets in the absence of any visual feedback distortion. During the exposure condition, trials 41–400 (360 trials, 90 movements per target direction) were performed with a 90° counterclockwise rotation applied to the screen cursor representation of the index finger position. Finally, trials 401–440 (40 trials, ten movements per target direction) were performed with normal visual feedback to test for aftereffects (post-exposure condition). The target directions were randomized within each condition and were consistent between all subjects. Data acquisition was initiated with the acoustic start signal and was manually terminated once the screen cursor reached the pre-specified target. Subjects had a maximum of 10 s in which to complete the trial. If this time constraint was reached, subjects were instructed to immediately terminate the current movement and return to the home position where they awaited commencement of the subsequent trial. These trials (<1% overall) were excluded from analysis. To familiarize them with the experimental setup, subjects were allowed a few practice trials (with normal visual feedback) before testing began.

Data acquisition and statistical analysis

Cartesian position data were low-pass filtered using a dual-pass eighth-order Butterworth filter with a high cutoff of 5 Hz. The Cartesian data were then transformed to a tangential position time-series, and numerical differentiation of the tangential position was used to obtain the velocity time-series for each movement. Additionally, the acceleration and jerk time-series were obtained through numerical differentiation of the velocity and acceleration time-series, respectively. Movement onset was determined by finding the velocity zero-crossing immediately preceding the first point in the velocity time-series that was at least 20% of the peak velocity. The initial directional error (IDE, in degrees) was measured as the angular difference in degrees between a vector from the starting position of the infrared marker at movement onset to the target, and the vector from the starting position to the marker's location at 80 ms after movement onset. Assessment of the directional error 80 ms after movement onset allows the error to be measured before corrections guided by visual feedback are employed. Thus, the IDE represents a behavioral measure of the planned initial movement direction, and hence a measure of acquisition of the 'internal model' of the novel environment. Normalized jerk (NJ, dimensionless) scores were calculated to assess the average movement dysfluency as follows (Kitazawa et al. 1993),

$$NJ = \sqrt{\frac{T^5}{D^2}\int j^2(t)dt} \tag{1}$$

where j(t) is the rate of change of acceleration (i.e., jerk), T is the movement time, and D is the distance covered during the movement. Root mean square error (RMSE, in millimeters) was calculated to assess the average deviation of the spatially re-sampled (to achieve equally-distant data samples) movement trajectory from the 'ideal' straight line connecting the starting-point of the movement and target position (the temporal structure of the ideal trajectory was therefore characterized by a uniform velocity profile), as follows:

$$RMSE\ (\text{in mm}) = \sqrt{\frac{\sum_{i=1}^{N}\left[(x_a - x_i)^2 + (y_a - y_i)^2\right]}{N}} \tag{2}$$

where x_a, y_a and x_i, y_i are corresponding points of the resampled trajectory and the ideal trajectory, respectively, and N is the number of points in the path.

Submovement analysis was also used to assess changes in the ballistic component of the movement during the adaptation period (Pratt et al. 1994). Local maxima and subsequent minima in the velocity profile were paired by detecting consecutive zero-crossings in the acceleration time-series following movement onset. Starting with the first maximum/minimum pair, the minimum from the pair that first satisfied the following criteria was selected as the

primary movement offset: (1) the velocity corresponding to the maximum from that pair had to be ≥20% of the peak velocity, and (2) the velocity minimum of the same pair had to be ≤80% of the paired maximum. The distance covered during the portion of the movement occurring from movement onset to primary movement offset was defined as the primary movement distance. The ratio of primary-to-total movement distance (PTR) was obtained, providing a normalized assessment of the ballistic portion of each movement. A decrease in the ratio suggests an increase in visual feedback control of movement.

Measurements from four consecutive trials were pooled and one block mean was calculated for IDE, RMSE, NJ, and PTR for data fitting and display purposes. Group data were fitted to linear (pre-exposure condition), double exponential (exposure condition; see Krakauer et al. 2000) and single exponential (post-exposure condition) functions and plotted as a function of trial block. For the nonlinear curve-fitting we used optimal nonlinear methods (Nelder-Mead simplex algorithm as implemented in the function *fminsearch* of MATLAB; Mathworks, Inc., Natick, MA, USA) to fit the adaptation data. The residual errors (root mean square errors and the residuals normalized to the mean score) were compared to assess goodness of fit. To avoid over fitting of the post-exposure trials, a penalty factor [(N+P)/(N–P), where N is the number of samples, and P is the number of parameters], which increases with the number of parameters, was used to weight the modeling error. This criterion is similar to the final prediction error (FPE; Manolakis et al. 2000) used in parametric signal modeling.

A Group (2) × Condition (4) repeated measures multivariate analysis of variance (MANOVA) was performed on IDE, RMSE, NJ, and PTR. Between-group comparisons during pre-exposure trials were performed (using *t*-tests for independent samples) to assess differences in baseline levels. Within-group planned comparisons (using *t*-tests for paired samples) were performed to assess differences in adaptation level (i.e., late exposure versus pre-exposure) and aftereffects (i.e., post-exposure versus pre-exposure) for the four dependent measures. Means computed from the last five trials of the pre-exposure, first five trials of the early-exposure, last five trials of the late-exposure, and the first two trials of the post-exposure condition were used in these comparisons. Only two post-exposure trials were used to minimize volitional strategic aspects of adaptation (Weiner et al. 1983), and because of the transient nature of the aftereffects, which is typical of paradigms that use representational feedback of hand movement (Kagerer et al. 1997; Clower and Boussaoud 2000).

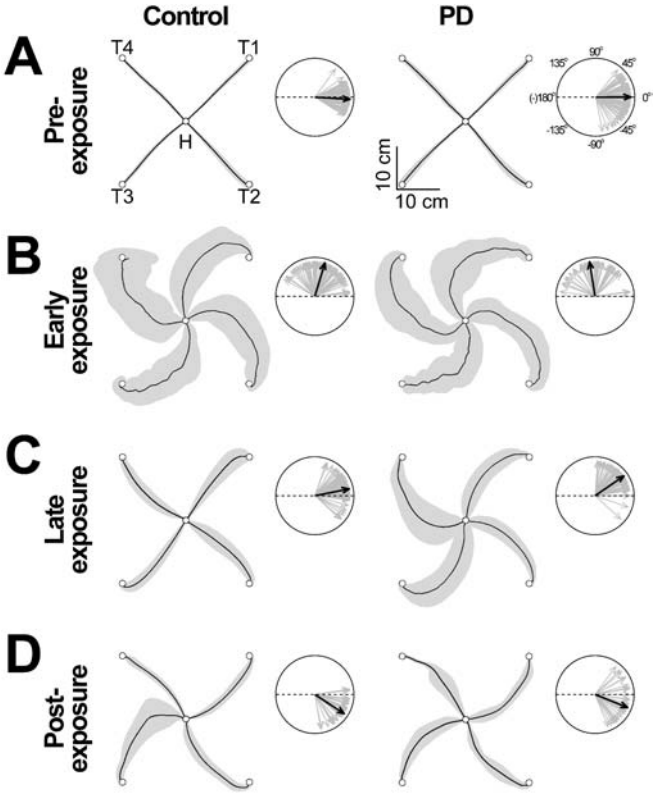

Fig. 1A–D Screen cursor movement paths (mean ±SD) and normalized shifts of initial direction of movement (*insets*) for the age-match controls and the Parkinson's disease (PD) subjects at **A** Pre-exposure, **B** early-exposure and **C** late-exposure to the 90° counterclockwise screen cursor rotation, and **D** post-exposure following removal of the screen cursor rotation. To obtain these plots, individual movement trajectories to each target were first spatially re-sampled and then the group means and SD were computed. *Insets* For pre-exposure (**A**) only, each unlabeled vector represents the initial direction of movement normalized with respect to the corresponding target direction. For the remaining *insets* (**B–D**), each unlabeled vector indicates the relative shift of the initial screen cursor direction (collapsed across targets) from pre-exposure to early-, late- and post-exposure trials, respectively. The relative shift was obtained by normalizing each trial to the mean initial screen cursor direction for the final five pre-exposure trials of the appropriate target. The initial direction of movement for pre-exposure is represented by a *single dashed line*. The *dark vectors* represent median normalized shifts

Results

Screen cursor movement paths (mean ±SD) observed during pre-, early-, late-, and post-exposure conditions for the control and PD groups are depicted in Fig. 1, together with the corresponding normalized shifts of initial screen cursor direction of movement (*insets*). Figure 1A shows that movement paths taken during the pre-exposure condition were similar between groups. Indeed, statistical analysis of the subject means for the last five movements performed during the pre-exposure condition showed no significant differences between groups ($P>0.05$) in terms of the spatial variability (RMSE), the initial directional error (IDE), or movement smoothness (NJ). Normalized jerk (NJ) scores however, showed a practice effect for the PD group (see Fig. 3C) during pre-exposure. In addition, the primary-to-total distance ratio (PTR) was smaller for the PD group than that for the controls ($t=2.49$, $P<0.05$; see Fig. 2D).

When the participants were first exposed to the 90° rotation of the screen cursor, movements deviated from the straight-line trajectories as seen in Fig. 1B. Although all participants became aware of these pronounced deviations upon performing the first early-exposure trial; debriefing by the experimenters indicated that by the end of the experiment none of them were able to recognize the nature and magnitude of the distortion. Moreover, the participants did not report using any specific cognitive strategy to accomplish the task. We noted that through the adaptation trials the corrective actions during exposure to the visual rotation included one or more types of movement trajectories: mostly spiral, sometimes jagged, and rarely slow progression movements (see also, Roby-Brami and Burnod 1995).

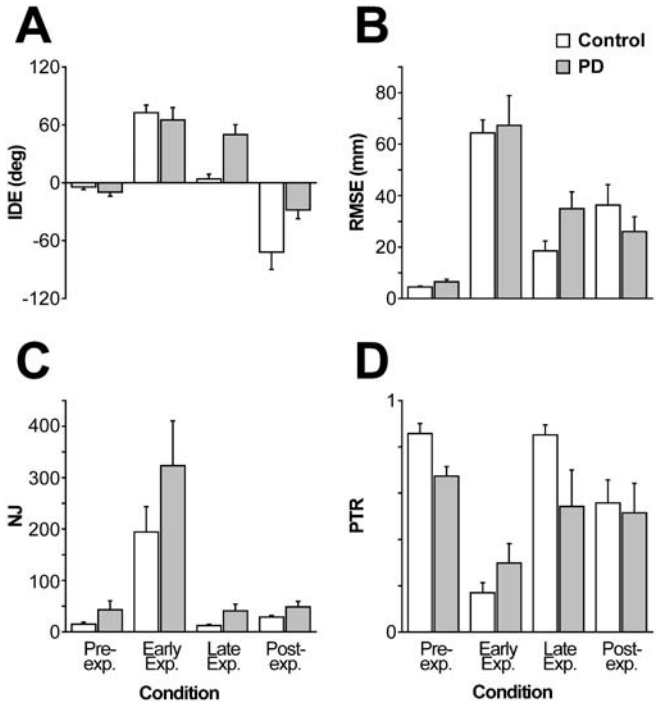

Fig. 2A–D Means and standard error for **A** initial directional errors (IDE in degrees), **B** root mean square errors (RMSE in mm), **C** normalized jerk scores (unit-free NJ) and **D** primary-to-total distance ratios (unit-free PTR) scores during pre-exposure (*Pre-Exp*), early exposure (*Early Exp*), late exposure (*Late Exp*) and post-exposure (*Post-Exp*) conditions for the Parkinson's disease (PD) group and the age-matched control group

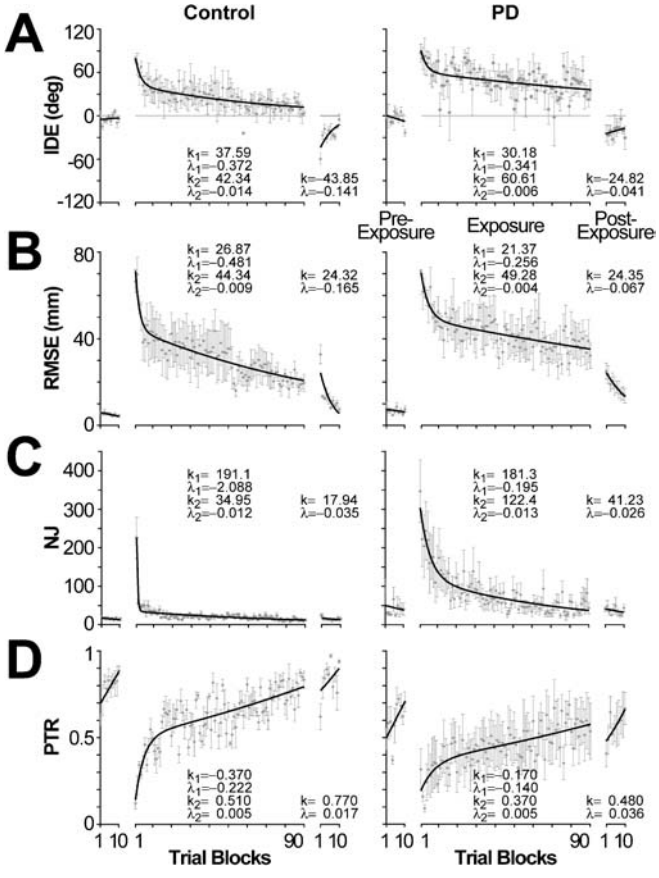

Fig. 3A–D Trial block means (±standard errors) and fitted curves for **A** the initial directional error (IDE), **B** root mean square error (RMSE), **C** normalized jerk (NJ), and **D** primary-to-total distances ratio (PTR) for the control and Parkinson's disease (PD) groups. The group data for each measure has been subdivided into three sections and fit separating the pre-exposure (linear fit), exposure (double exponential fit), and post-exposure (single exponential fit) conditions, as stated by the horizontal axis label in the *right* panel of **A**. Parameters for the double exponential fits ($f(t) = k_1 e^{\lambda_1 t} + k_2 e^{\lambda_2 t}$, where t represents trial block) and single exponential fits ($f(t) = ke^{\lambda t}$, where t represents trial block) for the exposure and post-exposure conditions are included

The *insets* in Fig. 1B show that the median deviation (with respect to the pre-exposure mean) of the initial screen cursor direction was close to 90° counterclockwise for both groups. Early-exposure trials in both groups were best characterized by curved trajectories towards the target (e.g., clockwise "spirals"). The straightness of movements, as measured by the RMSE, in these early trials was affected similarly in both groups (control 62.7±9.67 mm, PD 60.85±14.84 mm; P=0.821, independent samples t-test). With respect to movement smoothness, the PD group displayed a mean NJ score that was 78% greater than that in the control group (control 196±112.9 mm, PD 347±172 mm). However, due to the large variability observed in the NJ scores during the initial response to the perturbation, this difference was not significant (t=−1.65, P=0.14).

During the last five movements performed to each target in the exposure condition (Fig. 1C), control subjects were able to perform relatively straight movements similar to those in the pre-exposure condition, whereas the PD group continued to display clockwise spirals typical of early adaptation, albeit of a smaller magnitude. The smoothness of the PD group spirals did improve with practice, suggesting the patients improved their ability to utilize visual feedback to control movement. Consistent with the above, the shift in the initial cursor direction in the PD group was less than that in the control group (compare the *insets* in Fig. 1C). In post-exposure trials (Fig. 1D), the control group showed more consistent and larger aftereffects than the PD group, suggesting reduced visuomotor adaptation in the patients. This observation was supported by the larger clockwise shift of the initial screen cursor direction in the control group (*insets* in Fig. 1D).

The above findings were supported by a statistically significant Group × Condition interaction found by the repeated measures MANOVA analysis for IDE, RMSE, NJ and PTR ($F_{(12,55.8)}$=2.289, P<0.05). Figure 2 shows the group mean and standard error from each condition for IDE, RMSE, NJ and PTR. Interestingly, the PD patients did not adapt the initial direction of movement to the same extent as the controls (see Fig. 2A, *Late Exp* condition), since pre-exposure and late exposure IDE means differed significantly for the PD group (t=−3.1,

$P<0.05$, paired t-test), but did not for the controls ($t=-1.50$, $P>0.05$).

In terms of RMSE scores, both groups showed a significant difference in pre- versus late-exposure trials (controls $t=-3.68$, $P<0.05$; PD $t=-4.69$, $P<0.01$). However, between-group comparisons of baseline-corrected late-exposure RMSE scores (i.e., late- pre-exposure trials) indicated that this difference was larger for the PD subjects than the controls ($t=-2.024$, $P<0.05$), suggesting a reduction in visuomotor adaptation levels at the end of the exposure condition in the patients with respect to the controls. Surprisingly, both groups were able to increase movement smoothness and primary submovement distance with practice, as the late-exposure NJ (controls $t=0.59$, $P=0.58$; PD $t=0.19$, $P=0.86$) and PTR scores (controls $t=-0.11$, $P=0.91$; PD $t=0.81$, $P=0.46$) were reduced to pre-exposure levels. Following removal of the perturbation, the control group displayed significant differences between pre-exposure and post-exposure means in IDE ($t=3.69$, $P<0.05$, paired t-test), RMSE ($t=-3.9$, $P<0.05$), and PTR ($t=3.6$, $P<0.05$), whereas NJ showed only a trend ($t=-2.38$, $P=0.076$). Conversely, the PD group showed a significant difference for RMSE ($t=-3.37$, $P< 0.05$), but no statistical differences for IDE $t=1.54$, $P=0.19$), NJ ($t=-0.26$, $P=0.81$) or PTR ($t=1.18$, $P=0.3$).

Nonlinear curve fitting analysis supported differences between the control and PD groups in the adaptation levels observed during the exposure condition. Figure 3 displays best fits to trial block means for IDE, RMSE, NJ and PTR for each experimental condition. Both a single exponential with one linear and one nonlinear parameter and a double exponential with two linear and two nonlinear parameters were used to fit the data from the exposure and post-exposure conditions. In agreement with a previous study, a double exponential function was found to best fit the exposure condition (e.g., Krakauer et al. 2000), whereas the post-exposure trials were best fitted with a single exponential function. The latter reflects the transient nature of the aftereffects of exposure. Importantly, the non-linear parameters (i.e., the rate parameters) from the double-exponential fit of the exposure trials were larger for the control group than for the PD group, indicating faster adaptation for the control group. Parameters for the single exponential fitting of post-exposure trials were also larger for the control group. This suggests that at the time of post-exposure, control subjects were more adapted to the screen cursor rotation than the PD subjects, and therefore the controls showed a stronger deterioration of performance in terms of IDE and RMSE (Figs. 2A, B and 3A, B) when confronted with a distinct visuomotor relationship in the post-exposure trials. This is reflected in the larger and more consistent aftereffects in the control group.

Discussion

The main result of this study is that PD patients display impairments in visuomotor adaptation to a 90°-rotated screen cursor, when compared with age-matched controls. While PD subjects continued to produce spiral-shaped trajectories by the end of the late exposure condition, the controls performed relatively straight paths and were able to nearly align the initial screen cursor direction to that of pre-exposure trials (see *insets* of Fig. 1C). Thus, only the control group was able to reduce the IDE score to near pre-exposure levels. Moreover, the controls showed larger IDE aftereffects after removal of the rotation than the PD group.

An intriguing finding was that the PD group showed some adaptation and aftereffects in terms of RMSE scores, although the degree of adaptation was reduced compared with that of controls. Relatively small mean post-exposure IDE scores in the PD group suggest that spatial errors related to erroneous movement direction cannot fully account for post-exposure RMSE scores. In fact, while the control group showed a predominantly clockwise shift in the initial directional vectors in post-exposure, the PD group displayed post-exposure shifts that were distributed along either side of the ideal screen cursor movement direction (i.e., zero degree; see *insets* in Fig. 1D). Thus, increased post-exposure RMSE scores observed in the PD group contain bi-directional errors (which would cause the mean IDE to average closer to zero) and may be more representative of online corrections related to movement execution in a distinct environment. Thus, the spatial errors in the PD group can be accounted for by erroneous movement direction with a less "stable" error than that observed in the controls. The PD subjects were perturbed, but they did not display the more-or-less stereotyped response observed in the controls, that is a uniform directional response that would be expected with implementation of a now inappropriate internal model that was acquired during exposure.

Statistical comparisons of pre- and post-exposure trials showed only significant differences for IDE and PTR scores between the two groups. The IDE score was significantly altered by learning and was fully adapted in the controls, but not in the PD patients. Additionally, the PTR score was reduced at post-exposure in controls, but not in the PD patients. These findings may imply a deficit in movement initiation consistent with the literature on akinesia in PD (Schugens et al. 1993). Indeed, the pre-exposure PTR scores in the PD group were smaller than those in the control group (PTR scores were larger for the PD in early-exposure trials). However, pre-exposure performance in both groups was similar in terms of IDE and RMSE. This is consistent with reports that mildly affected patients show no difficulties in the coding of movement direction (Jones et al. 1993; Klockgether and Dichgans 1994), or in the accuracy of pointing movements (Ghilardi et al. 2000a), whereas both movement speed and the transport phase (analogous to our PTR measure) were reduced in the PD group compared with

those in controls (Ghilardi et al. 2000a). Nevertheless, it could be argued that impaired selection and programming of movement direction based on an inappropriate internal model would result in movement initiation deficits in PD. Thus, this view remains plausible.

The initial rapid change and the later gradual reduction in the mean error scores during exposure to a kinematic distortion in this (see Fig. 3) and other studies suggest that there are two processes operating during the course of adaptation (Krakauer et al. 2000). The rapid exponential portion of the learning curve may be attributed to the initial acquisition and/or selection of a behaviorally appropriate internal model, whereas the latter almost-linear component may involve processes that progressively fine-tune the selected internal model to the specific task conditions. This is compatible with the idea that during gradual distortions (or at late adaptation stages), cortico-cerebellar error-correction mechanisms are critically engaged (Robertson and Miall 1999), whereas during step distortions fronto-striatal networks might be involved in selecting and stabilizing the appropriate internal model. In the present study, the time constants of the rapidly decaying exponential portion of all learning curves were larger in the control group than in the PD group (Fig. 3). Also, the time constants of the slowing decaying exponential portion for IDE and RMSE were larger for controls, while time constants for NJ and PTR were similar across groups. This suggests that adaptation was slower and reduced, but not completely abolished in the PD group, perhaps because the patients were only mildly affected by disease. It also suggests that impairment in the early (fast) stages of adaptation can affect the later, slower adaptation mechanisms.

Adaptation to visual distortions introduced gradually (Kagerer et al. 1997; Robertson and Miall 1999; Ingram et al. 2000) may depend on cerebellar error-correction mechanisms for gradual acquisition of a new internal model. Robertson and Miall (1999) have shown that adaptation to gradual visual distortions is blocked by inactivation of the dentate nucleus, whereas step adaptation is spared in non-human primates. This suggested that the lateral cerebellum may be implicated selectively in adaptation to gradual as opposed to step kinematic distortions. In the case of gradual distortions, the original internal model engaged prior to a gradual distortion can still be employed to help develop the new internal model of the task. Thus, subjects can utilize information regarding the original internal model together with memorization of trial-to-trial error correction signals to be used at the onset of the next movement (Roby-Brami and Burnod 1995). However, in the case of step rotations, the awareness or detection of large, explicit errors may engage different adaptation mechanisms that involve the use of various types of corrective actions.

Recent brain imaging experiments have revealed activation in cortical areas, thalamus, basal ganglia and cerebellum during visually guided finger or hand movements (Grafton et al. 1996). Imamizu et al. (2000) showed that during early stages of learning to use a computer mouse with a novel rotational transformation, large regions in the lateral cerebellum showed activations proportionally related to the magnitude of the error signals. A smaller area near the posterior superior fissure, reflecting the newly acquired internal model, remained activated even after the error levels were equalized. As the imaged area was centered at the cerebellum in this study, no basal ganglia or cortical activations were recorded (H. Imamizu, personal communication). The large, nonspecific cerebellar activation seen early during the step adaptation may be related to the acquisition, evaluation, and discrimination of sensory information generated during the learning of the internal model (Gao et al. 1996).

Using positron emission tomography (PET), Ghilardi et al. (2000b) showed that re-adaptation to a previously learned rotated reference frame, in which the screen cursor motion was rotated by 30–60°, activated the right posterior parietal cortex. Because subjects in that study were previously trained in the task, it is likely that they had already consolidated their internal model of the task, and therefore no basal ganglia activation was seen. Thus, the new and old internal models may have coexisted and thus re-adaptation during the imaging stage had the role of behaviorally selecting the correct internal model. This is consistent with the proposal of Kawato and Wolpert (1998) that multiple internal models exist in the central nervous system and that these models compete to learn new environments.

The poor adaptation observed in PD may be the result of reduced signal-to-noise ratio in feedback signals used for learning. This is suggested by the poorer performance of the PD group during exposure, which shows larger variability in all measures compared with that of controls, particularly in terms of NJ scores (see Fig. 3C). Because visuomotor adaptation requires the integration of visual and proprioceptive inputs (van Beers et al. 1999), it is possible that disordered kinesthesia in PD contributes to impaired adaptation. Rickards and Cody (1997) have found that kinesthetic illusions elicited through tendon vibration are significantly reduced in PD. This abnormal response has been attributed in part to evidence of reduced selectivity of pallidal neurons to striatal microstimulation (Tremblay et al. 1989), or to passive joint movement observed in 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP)-treated monkeys (Boraud et al. 2000; Filion et al. 1988). These data suggest that nigrostriatal degeneration may compromise the ability of the basal ganglia to select appropriate actions in response to peripheral or central inputs.

Soft cognitive deficits in PD may have also affected adaptation mechanisms. The present study used a 90° rotation in conjunction with targets separated by 90°, which remained visible throughout the testing. Thus, it is possible that controls learned to point not to the current target but to the next one to achieve the task, whereas the PD patients did not (or could not) use such a cognitive strategy to speed up learning. However, the PD group consisted of mildly affected patients who showed no

cognitive deficits relative to the controls (MMSE scores were similar for both groups). Moreover, none of the subjects verbally reported using such a strategy, nor were they able to report the type and magnitude of the distortion. Furthermore, if we assume that such a cognitive strategy played a role in the performance of the control subjects, then it would be reasonable to expect that these subjects would have learned the task very rapidly (i.e., as soon as they "discovered" the 90° rotation) and shown very small aftereffects of the first post-exposure trial, if any at all. The present data do not support this view. Also, there was no need for storing visual target locations, and feedback of cursor movement was available at all times. Moreover, as subjects were asked to move 'when ready', any loads placed on visual processing capacity or programming time were minimal.

Falkenstein et al. (2001) reported that compared with age-matched controls, PD patients show reduced error negativity (N_e) that may indicate a deficit in online error correction due to basal ganglia dysfunction. However, Carter et al. (1998) showed that the N_e better reflects the detection of response competition rather than detection of errors per se, since N_e (in both controls and PD) is present not only during erroneous responses, but also during correct responses (albeit of a smaller magnitude). In fact, this peak negativity increases under conditions of increased response competition (Carter et al. 1998). Thus, the findings of Falkenstein et al. (2001) could reflect a reduction of response competition in PD. This is consistent with the view that the PD patients have problems in selecting appropriate responses (e.g., movement direction) through trial-and-error mechanisms. In this regard, Touge et al. (1995) showed that prior to random selection of the direction in which subjects were to move a joystick, movement-related cortical potentials did not scale in PD patients as in controls, suggesting that neural mechanisms engaged in self-selection of movement direction are abnormal in PD – a finding consistent with the present study.

Our proposal is consistent with the view that the basal ganglia may be involved in the selection of appropriate movements and/or control strategies based on external cues, whereas the cerebellum may be involved in the recalibration of motor commands through the adjustment and optimization of movement parameters (Jueptner and Weiller 1998). Thus, it appears that functional basal ganglia engagement is crucial in tasks that are initially effortful (e.g., a large visuomotor distortion) and in which correct responses are self-selected through trial-and-error. However, once the appropriate action has been found and stabilized, the cerebellum can fine-tune the internal model through practice until the task can be performed automatically.

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