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Interlimb coordination in patients with Parkinson's disease: motor learning deficits and the importance of augmented information feedback

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Abstract The basal ganglia have traditionally been associated with motor control functions and this view has prevailed since the late nineteenth century. Recent experimental studies suggest that this neuroanatomical system is also critically involved in motor learning. In the present study, motor learning/transfer capabilities were compared between patients with Parkinson's disease and a group of normal elderly people. Subjects practiced a bimanual coordination task that required continuous flexion-extension movements in the transverse plane with a 90° phase offset between the forearms. During acquisition, augmented visual feedback of the relative motions was provided in real time. The findings revealed improvements in the bimanual coordination pattern across practice in both groups when the augmented concurrent feedback was present. However, when transferred to performance conditions in which the augmented information was withheld, performance deteriorated (relative to the augmented condition) and this effect was more prevalent in the Parkinson patients. More specifically, no improvement in interlimb coordination was observed under nonaugmented feedback conditions across practice. Instead, a drift toward the preferred in-phase and antiphase coordination patterns was evident. The present findings suggest that Parkinson patients can improve their performance on a new motor task, but they remain strongly dependent on augmented visual information to guide these newly acquired movements. The apparent adoption of a closed-loop control mode is accompanied with decreases in movement speed in order to use the feedback to ensure accuracy. When the augmented feedback is withheld and the movement pattern is to be controlled by means of intrinsic information feedback sources, performance is severely hampered. The findings are hypothesized to indicate that learning/transfer is affected in Parkinson patients who apparently prefer some constancy in the environmental contingencies under which practice takes place. The present findings are consistent with the notion that the basal ganglia form a critical neuroanatomical substrate for motor learning.

Key words Parkinson's disease · Motor learning · Interlimb coordination · Basal ganglia · Human

Introduction

Of all central neurological movement disorders, Parkinson's disease has perhaps been studied most intensively. This work has contributed to a better understanding of the effects of degenerative diseases of the basal ganglia. Patients with Parkinson's disease show clear disorders in the organization and control of movement. Deficits in movement initiation and movement speed have been observed during the production of simple movements. These problems become even more prevalent when complex sequential or simultaneous movements are to be performed (Benecke et al. 1986; Schwab et al. 1954).

Until recently, few studies have addressed the possible effects of practice on those motor impairments, even though this matter appears of critical importance for improving movement control in Parkinson patients. The existing body of knowledge concerning learning capabilities in these patients is scarce and inconclusive. Some experiments have focused on the effect of practice on the ballistic, preprogrammed part of a tracking task (Flowers 1976; Frith et al. 1986; Worringham and Stelmach 1990). According to Woodworth (1899), such tasks involve a preprogrammed part that brings the arm near the goal, followed by a corrective part that is slow-

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er and under continuous control. Flowers (1976) concluded that Parkinson patients were not able to perform the fast ballistic movement but were forced to move slowly to allow continuous monitoring. In other words, these patients had a problem with open-loop control of movement. Moreover, they could not improve their performance after 2 min of practice: the patients failed to learn to anticipate the movement of a target but followed it instead. Frith et al. (1986), however, found that Parkinson patients were able to learn to make anticipatory movements during a particular task, but they experienced difficulties in deploying already existing programs in novel situations. Similarly, Worringham and Stelmach (1990) found that patients could use advance information to initiate their movements faster following sufficient practice, suggesting that preprogrammed actions could be acquired.

Robertson and Flowers (1990) tested the ability of Parkinson patients to learn and generate movement sequences and to switch between alternative sequences at will. They found that patients could learn individual patterns of movement normally but experienced difficulty in switching spontaneously from one to another acquired sequence within a trial. In other words, the patients exhibited difficulties in executing a designated sequence while at the same time suppressing the alternative, currently unwanted, sequence.

Studies using the pursuit rotor task showed that only demented patients or patients with more advanced symptoms of the disease showed impairments in the acquisition of the task (Harrington et al. 1990; Heindel et al. 1989). Soliveri et al. (1992) also demonstrated improvements during practice of a “doing up buttons” task.

It appears from the aforementioned overview that the evidence in favor of the viewpoint that the basal ganglia are involved in motor learning is largely inconclusive, at least when relying on evidence from studies with Parkinson patients. Moreover, three serious drawbacks characterize past learning research and underscore the need for additional experiments. First, the tasks used in previous studies often imposed more cognitive than motor demands. Secondly, they entailed only limited levels of complexity and few (if any) addressed the acquisition of new spatiotemporal topologies. Third, the practice sessions were usually short. These limitations provided the major incentive for the present experiment in which subjects learned a complex bimanual coordination pattern over a longer period of practice. This represents one of the first studies that addresses the learning of new coordination skills in diseased groups.

Recent work on bimanual coordination has resulted in the identification of two elementary and preferred modes of movement coordination, called in-phase and anti-phase patterns (Heuer 1991; Kelso 1984; Turvey 1990; Yamanishi et al. 1980). In-phase coordination refers to the simultaneous contraction of homologous muscles (e.g., flexing or extending the arms simultaneously). Anti-phase (or 180° out-of-phase) coordination refers to the simultaneous activation of nonhomologous muscle groups. Against the background of these preferred modes of coordination, new tasks can be designed that are not intrinsic to the human motor repertoire and that require practice. In the present study, subjects produced a bimanual coordination pattern with a phase offset of 90° between the limbs, located between the aforementioned in-phase and anti-phase modes. The difficulty with learning such a pattern is that a strong tendency emerges to be drawn to the preexisting or preferred coordination modes. Previous experiments using young adults demonstrated this bias for bimanual finger movements (Zanone and Kelso 1992) as well as for arm movements (Lee et al. 1995).

In view of the difficulty associated with overcoming the aforementioned preferred coordination modes, the new coordination pattern was practiced with the help of augmented visual information feedback of the produced relative motions in real time. Based on the general contention that visual information is important in the control of movement in Parkinson patients, it was predicted that the augmented information would constitute an invaluable source of information for acquiring the new task. However, performance was also assessed in the absence of augmented feedback, because it has previously been shown that various sources of feedback (particularly concurrent feedback) have a strong influence on performance when available, but their effect may decrease or disappear when the feedback is withheld (Salmoni et al. 1984; Schmidt 1988; Swinnen 1996). Therefore, transfer of performance to feedback withdrawal conditions was investigated at regular intervals during practice. An additional benefit of this procedure is that it enabled the evaluation of performance under externally guided and internally cued environmental circumstances.

Materials and methods

Subjects

Subjects were seven patients with idiopathic Parkinson’s disease. Clinical characteristics of these patients were obtained at the time of testing and are shown in Table 1. All patients were declared free of cognitive deficits by a neurologist. Seven subjects without any neurological problem formed the control group. The mean age of the patient group was 73 years (SD 2.38), that of the control group 69 years (SD 2.44). None of the subjects had previous experience of the task. All subjects were tested between 3 and 6 p.m.

Apparatus and task

The apparatus consisted of two horizontal metal levers (43 cm long and attached to virtually frictionless vertical axles) which could be moved toward and away from the body midline. An adjustable handle was located at the distal end of each lever (see Fig. 1). Incremental shaft encoders (4096 counts/revolution) were mounted at the base of the axles to determine elbow displacement, sampled at 150 Hz. The subject was seated on a height-adjustable chair behind the apparatus in such a way that the body was centered between the levers. Movements were made while resting the forearms on each lever and by grasping the handle at the distal end. The handle could be adjusted to accommodate different fore-

Table 1 Clinical characteristics of the patients with Parkinson's disease

Subject	Age	Time since onset (year's)	Stage[a]	Rigidity[b]	Bradykinesia[b]	Tremor[b]	Medication	Dose
1	66	7	2	1 R>L	1	2 R>L	Eldepryl Sinemet	2×5 mg 3×1/2 tablet
2	66	12	3	0	2	1	Permax Prolopa Apomorphin Eldepryl Akineton	3×0.5 mg 5×125 2 mg, 1–2/day 2×1 2–3×1/2
3	83	10	3	1 L>R	2 L>R	0	Sinemet Parlodel	3×250 mg 2.5mg, 3×1/2
4	75	6	1	1 L>R	2 L>R	3	Sinemet	4×1/2 tablet
5	67	3	3	L>R	3 L>R	1	Amantan Sinemet	2×100 mg 250 mg, 3×1/2
6	79	5	2	1 L>R	1	0	Sinemet	250 mg, 3×1/2
7	75	7	2	2 R wrist	1	3 R hand	Parlodel	10+5+5 mg

[a] Hoehn and Yahr scale
[b] Unified Parkinson-rating scale

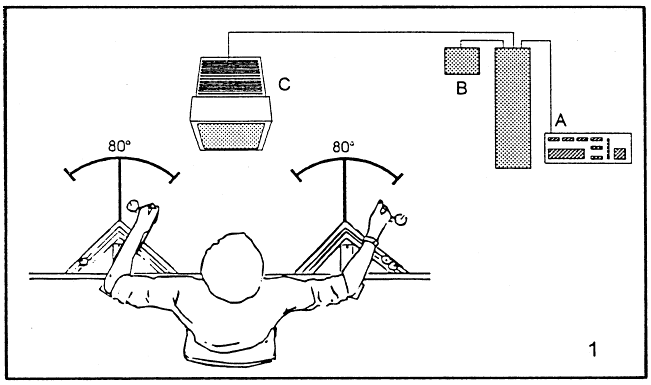

Fig. 1 Schematic view of the experimental apparatus. **A** Personal computer; **B** Terminal for experimenter; **C** Terminal for subject

arm lengths. The elbow was positioned just above the lever's axis of rotation. Table height was 75 cm and the levers were positioned 6 cm above the table surface.

Subjects were instructed to make cyclical, bimanual movements coincident with the beating of an electronic metronome (KORG DTM-12), such that one complete movement cycle (flexion-extension) was performed on every beat. Subjects were required to produce oscillations of each limb with the same frequency (0.83 Hz) and amplitude (±40°, or 80° peak-to-peak displacement) but with a phase offset between the limbs of 90°. The duration of each trial was 20 s. The limbs always started in mid-position prior to movement initiation. The reversals in direction at peak flexion and peak extension were made within indicated vertical targets (width 4°), located behind the movement path. A 80486 microcomputer was used to sample and record data, to signal the start and end of the trial, and to control the onset and offset of the metronome.

The main goal of this motor skill is to develop a new spatiotemporal relationship between the limbs. When one limb is reversing direction at peak position, the other limb is located midway between peak extension and flexion. This is exemplified in Fig. 2, showing the upper limbs' angular displacement-time profiles for a successful 90° out-of-phase movement (left side). The orthogonal plot of the angular displacement patterns (also called a Lissajous figure) results in a circular configuration (right side). Thus, an internal spatiotemporal structure is to be developed within the confines of an imposed overall time frame (the metronome) and against the backdrop of preferred preexisting coordination tendencies (i.e., the in-phase and anti-phase modes).

Procedure

Subjects were instructed to produce cyclical limb movements for a duration of 20 s per trial at the pace of the metronome (0.83 Hz).

Acquisition

Two blocks of 20 acquisition trials were performed within a single experimental session. Augmented visual feedback of the relative motions was provided during all 40 acquisition trials. This information was shown with the aid of a computer monitor that was positioned just beyond the movement apparatus, 10 cm above the surface of the table. The monitor provided feedback of the displacement-displacement angles, with the left limb represented in the ordinate and the right limb in the abscissa (the Lissajous figure). When produced correctly, the movement resulted in a Lissajous plot with the configuration of a circle. Provision of this visual information occurred in real time. Previous work showed this to be a powerful source of information for the acquisition of new bimanual coordination patterns (Lee et al. 1995; Swinnen et al. 1991b, 1996). The Lissajous figures remained on the screen until the trial was completed.

In addition to concurrent information feedback during each trial, posttrial feedback was also provided during the acquisition phase: Following every fifth trial, subjects were shown information of the last trial produced in the set: the right and left limb movements were plotted orthogonally on top of a representation of the ideal movement template (a circle). This template was obtained through generation of two pure sine waves with equal frequencies (0.83 Hz) and amplitudes (±40°) and with a phase offset of 90°. The experimenter explained the displayed information to the subject and aided in interpreting this feedback. The plot of the movement template on the computer screen on top of the subject's own trial enabled a quick comparison of both patterns.

Prior to and during the acquisition phase, subjects were given three test blocks: prior to practice (a test of initial skill level, block 1), and following completion of 20 (middle test, block 2) and 40 acquisition trials (final test, block 3). During these test blocks, performance was assessed under three different feedback conditions. In order, the movement was produced while the subject was blind-

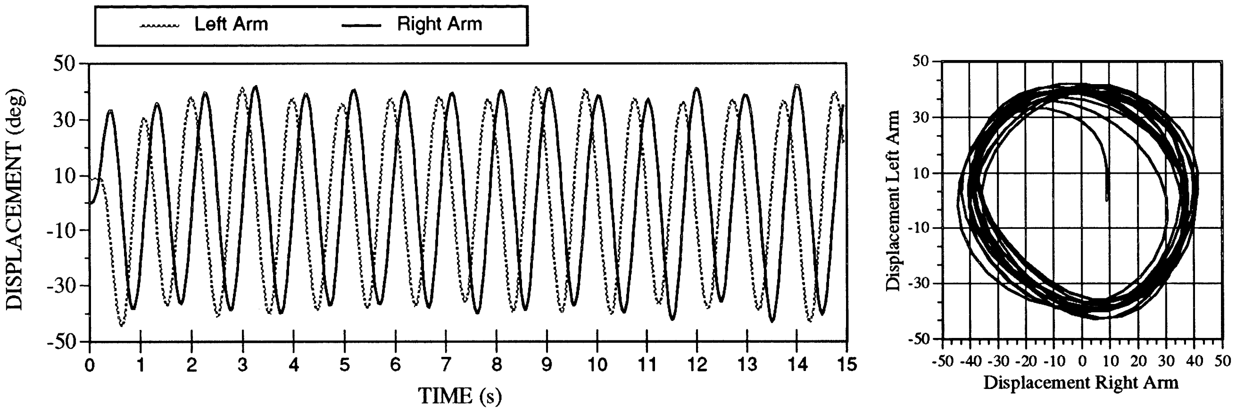

Fig. 2 Displacement-time profiles of the left and right limb movement (*left side*) and relative motion plot of a successful 90° out-of-phase movement (*right side*)

folded (reduced vision condition), with normal vision (normal vision condition), and in the presence of concurrent information feedback (augmented vision condition). This order was maintained across all three test occasions to minimize the effect of one test upon the next. These tests enabled the evaluation of performance under augmented feedback conditions as well as under feedback withdrawal conditions, i.e., learning and transfer of learning were assessed:

Acquisition

1. Test block 1 – pretest:
One trial – reduced vision condition
One trial – normal vision condition
One trial – augmented vision condition

(Practice phase 1: 20 trials under augmented vision conditions)

2. Test block 2:
One trial – reduced vision condition
One trial – normal vision condition
One trial – augmented vision condition

(Practice phase 2: 20 trials under augmented vision conditions)

3. Test block 3:
One trial – reduced vision condition
One trial – normal vision condition
One trial – augmented vision condition

Retention

Five minutes after completion of the practice session, a retention test was given. Subjects were again tested under the aforementioned three different feedback conditions:

1. One trial – reduced vision condition
2. One trial – normal vision condition
3. One trial – augmented vision condition

The data analysis focused on performance obtained during the three test blocks of acquisition as well as during the retention test.

Data analysis

The data analysis focused on (a) the spatiotemporal features of the individual limb motions by means of cycle duration and amplitude measures and (b) a quantification of the new coordination pattern that evolved between the limbs through relative phase measures. Through subtraction of the phase angles of two signals (or limb motions) occurring simultaneously, insights are obtained into the way these signals relate to each other. This difference in phase angle, also referred to as relative phase, provides a signature of the coordination pattern that is observed between the limbs as well as its stability (Haken et al. 1985; Turvey 1990).

The phase angle of each arm oscillation was calculated for each sample of the displacement time series, using a formula adapted from Kelso et al. (1986):

$$\phi=\theta_R-\theta_L=\tan^{-1}[(dX_R/dt)/X_R]-\tan^{-1}[(dX_L/dt)/X_L]$$

whereby θ_R refers to the phase of the right limb movement at each sample, X_R is the position of the right limb after rescaling to the interval [–1, +1] for each cycle of oscillation, and dX_R/dt is the normalized instantaneous velocity. The same notation applies to the left limb (L). The relative phase between the arms was subsequently determined through subtraction of the phase angle of the limbs, $\theta_R-\theta_L$. Amplitude rescaling was done for each half-cycle: the positive amplitudes were divided by their peak positive amplitude and the negative amplitudes by their respective peak negative amplitude score. A similar procedure was applied for normalization of velocity. This allowed a conversion from the Cartesian coordinates to sine and cosine functions of the unit circle (ranging from 1 to –1).

Briefly, the reasoning underlying this procedure is as follows. The relevant variables to describe the state of an arm movement or any other system with oscillatory features are its momentary position and velocity (the state variables). In graphical terms, these variables can be considered as coordinates of a point in a two-dimensional Cartesian coordinate system, with position being represented in the *x*-axis and velocity in the *y*-axis (a phase-plane). When the oscillations are harmonic, the phase-plane represents a circular trajectory. If position and velocity are rescaled to the interval [–1, +1], these Cartesian coordinates are equivalent to the cosine and sine values of the phase angle, which are then used for computation of the tangent of that angle. It is therefore possible to represent the state of that system by polar coordinates (0°–360°) as described by the phase angle.

Following computation of the continuous estimate of relative phase with the formula shown above and with a remapping of the unit circle to the range 0–180 and –180 to 0, the absolute difference in phase angle (ranging from 0–180°) was extracted at two peak position landmarks of the reference (right, R) limb and for each oscillation cycle. Accordingly, the program routine provided two sets of absolute phase differences, one at peak elbow flexion and one at peak elbow extension. These data were subsequently averaged to provide an estimate of relative phase accuracy. The SD around the mean relative phase was used as a measure of variability in relative phase.

In addition to relative phase measures, temporal and spatial parameters of the left and right limb motions were quantified, i.e., cycle duration and amplitude. Cycle duration was defined as the time that elapsed between successive peak extension positions. The mean cycle duration was computed across the 20-s trial, and within-trial standard deviations were computed to assess temporal variability. The spatial measure consisted of the absolute value of the peak-positive to peak-negative amplitude for each individual cycle. This measure was averaged across each trial and the within-trial SD was computed to estimate variability.

The analysis of relative phase, timing, and amplitude, which is reported next, focused on the three test blocks (start, middle, and end) obtained during acquisition as well as on retention performance.

Results

Relative phase

Relative phase accuracy

Acquisition. Figure 3 shows the mean absolute error in relative phase, as determined during the three test blocks administered at the start, middle, and end of acquisition. These error scores denote the absolute deviation between the observed relative phase and the required 90° phase offset.

The graph illustrates two major findings of interest. First, a considerable improvement in the performance of the circle task was made in the presence of augmented visual feedback as a result of practice. Error scores decreased sharply, particularly between the first and second test block. Both groups showed a comparable progress. Second, performance was much worse in the absence of augmented visual information (normal vision and blindfolded conditions).

Data were analyzed using a 2×3×3 (Group×Test block×Feedback condition) ANOVA with repeated measures on the last two factors (see Table 2). The variable denoted as Test block referred to the administration of performance at the beginning, the middle, and the end of acquisition. The variable called Feedback condition included evaluation of performance under blindfolded, normal vision, and augmented visual feedback conditions. The results of the statistical analyses are presented in Table 2.

A significant decrease in error was observed during acquisition, resulting in a significant Test block effect. Significant differences were also observed across Feedback conditions. Mean error was lower during the augmented feedback condition (*M*=53°) than during the normal vision (*M*=63°) and blindfolded performance conditions (*M*=64°). The main effect for Group was not significant. However, the interaction between Group and Feedback condition was significant (see Fig. 3A). Whereas the Parkinson and elderly group performed similarly in the presence of augmented visual feedback, the former were less successful than the latter during the normal vision and blindfolded conditions. The interaction effect between the variables Test block and Feedback condition also reached significance. During the first test block (before initiation of practice), no distinction was found among the three feedback conditions. Differences emerged in the middle and at the end of acquisition where performance was more successful during the augmented feedback condition than during the blindfolded and normal vision conditions. Finally, a significant three-way interaction between the variables Group, Test block, and Feedback condition was observed. The aforementioned different performance patterns of both groups during the three feedback conditions (see Group×Feedback condition interaction) also differed across the three test blocks.

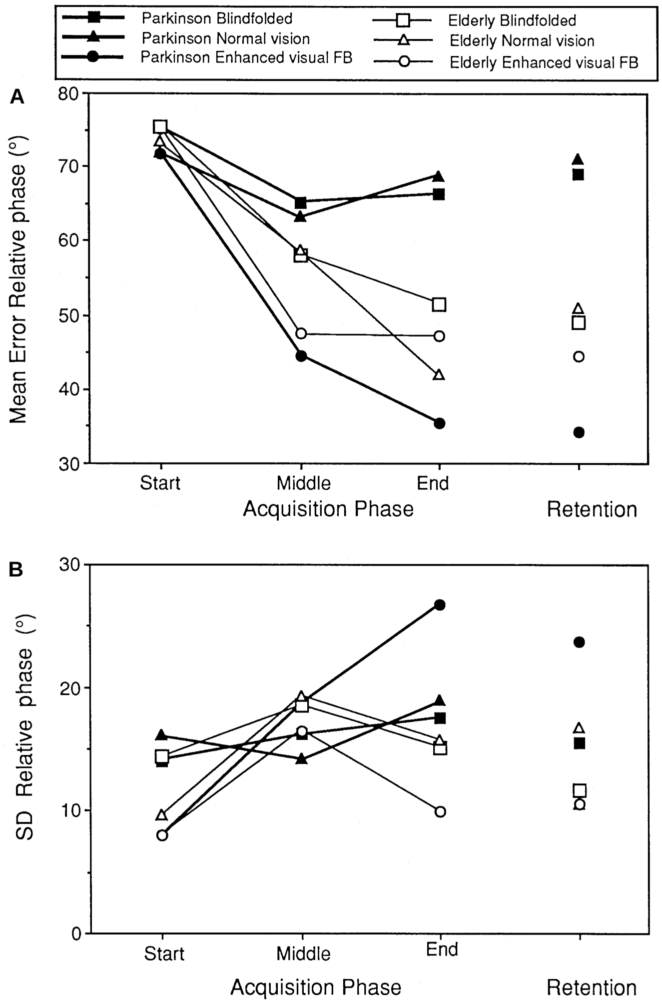

Fig. 3A, B Relative phase accuracy and variability for the Parkinson group and elderly group across the different feedback (FB) conditions during acquisition and retention

Retention. The performance pattern found at the end of acquisition was essentially confirmed at retention (see Fig. 3A). The 2×3 (Group×Feedback condition) ANOVA with repeated measures on the last factor supported these observations (see Table 2). The Group effect was not significant. The Feedback condition effect was significant: Lower error scores were observed in the condition with augmented visual feedback (*M*=39°) than in the remaining two conditions (blindfolded *M*=59° and normal vision *M*=61°). The interaction between both variables was also significant. Figure 3A shows that the elderly subjects performed very similarly across the three feedback conditions, whereas the Parkinson group performed well in the presence of augmented feedback but poorly during the normal vision and blindfolded conditions. In fact, when comparing retention performance under the latter two feedback conditions with pretest performance (Test

Table 2 Results of the statistical analyses with respect to relative phase, movement amplitude, and cycle duration (*FB* Feedback condition, *Gr*, Group, *Bl.* block)

	df	Relative phase		Amplitude		Cycle duration	
		Mean	SD	Mean	SD	Mean	SD
Acquisition							
Group	1, 12	<1	1.46	3.7	4.15	2.96	5.73*
Test block	2, 24	10.22**	2.37	2.6	<1	11.66**	6.68**
Feedback condition	2, 24	9.6**	<1	2.24	1.33	5.37**	3.74*
Limb	1, 12	–	–	2.42	7.82*	<1	1.71
Gr.×Test Bl.	2, 24	<1	1.24	1.95	<1	<1	1.27
Gr.×FB	2, 24	4.63*	1.09	1.35	<1	5.06*	7.2**
Gr.×Limb	1, 12	–	–	<1	4.33	1.22	<1
Test Bl.×FB	4, 48	3.63*	<1	<1	<1	2.72*	3.88**
Test Bl.×Limb	2, 24	–	–	4.36	<1	1.7	2.8
FB×Limb	2, 24	–	–	1,41	1.05	2.43	1.36
Gr.×Test Bl.×FB	4, 48	3.61*	<1	1.11	<1	3.28*	2.93*
Gr.×Test Bl.×Limb	2, 24	–	–	<1	<1	2.44	1.11
Test Bl.×FB×Limb	4, 48	–	–	1.72	1.67	3.99**	<1
Gr.×Test Bl.×FB×Limb	4, 48	–	–	1.27	<1	2.41	<1
Retention							
Group	1, 12	1.05	1.54	2.79	10.57**	1.41	<1
Feedback condition	2, 24	14.76**	1.14	<1	<1	5.94**	<1
Limb	1, 12	–	–	1.45	11.09**	3.93	1.26
Gr.×FB	2, 24	8.01**	6.4**	<1	1.93	9.23**	2.89
Gr.×Limb	1, 12	–	–	<1	4.75*	8.12*	4.14
FB×Limb	2, 24	–	–	<1	<1	10.24**	1.8
Gr×FB×Limb	2, 24	–	–	1.42	<1	10.4**	2.56

* $P<0.05$
** $P<0.01$

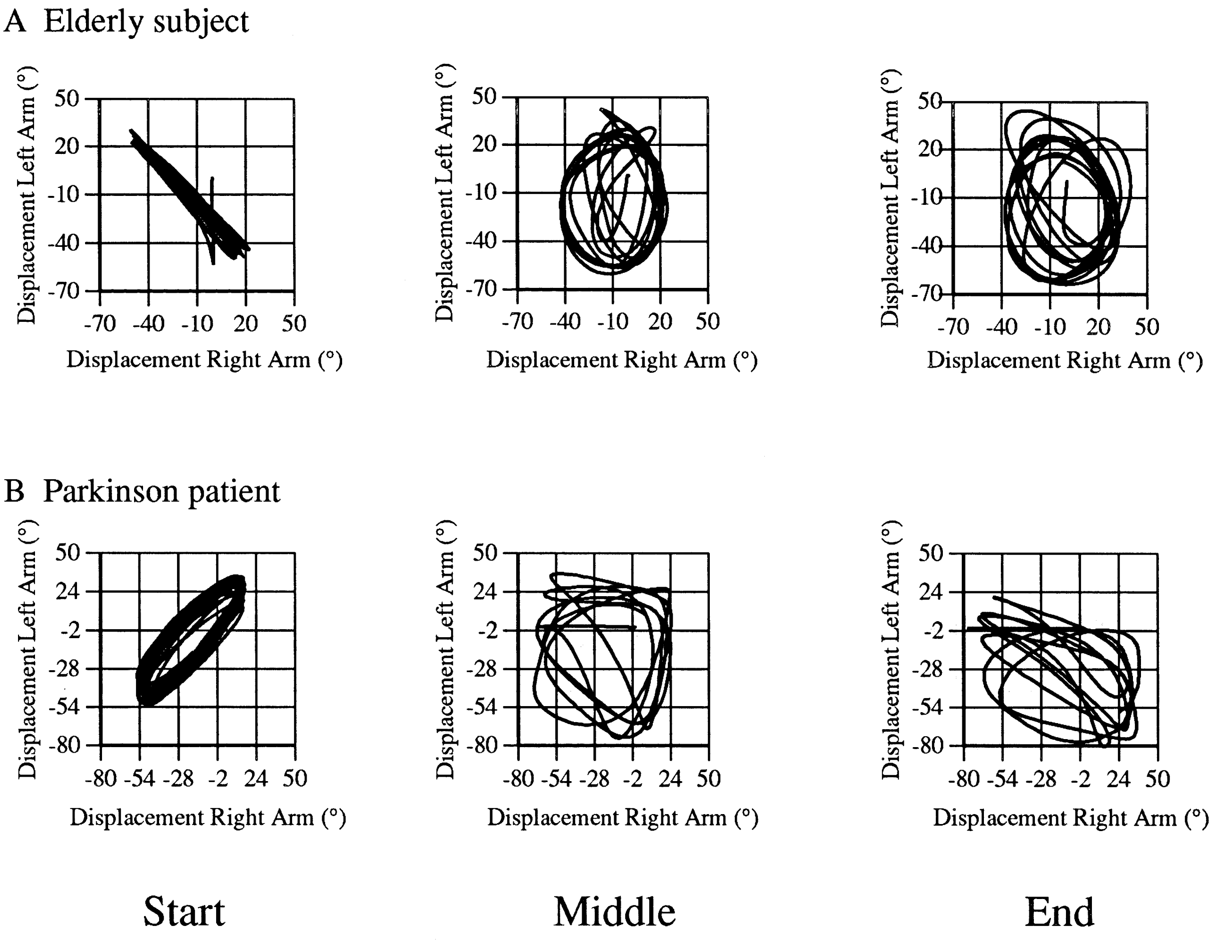

Fig. 4 Example of the evolution of the coordination pattern across acquisition in the presence of augmented visual feedback for an elderly subject (**A**), and a Parkinson patient (**B**)

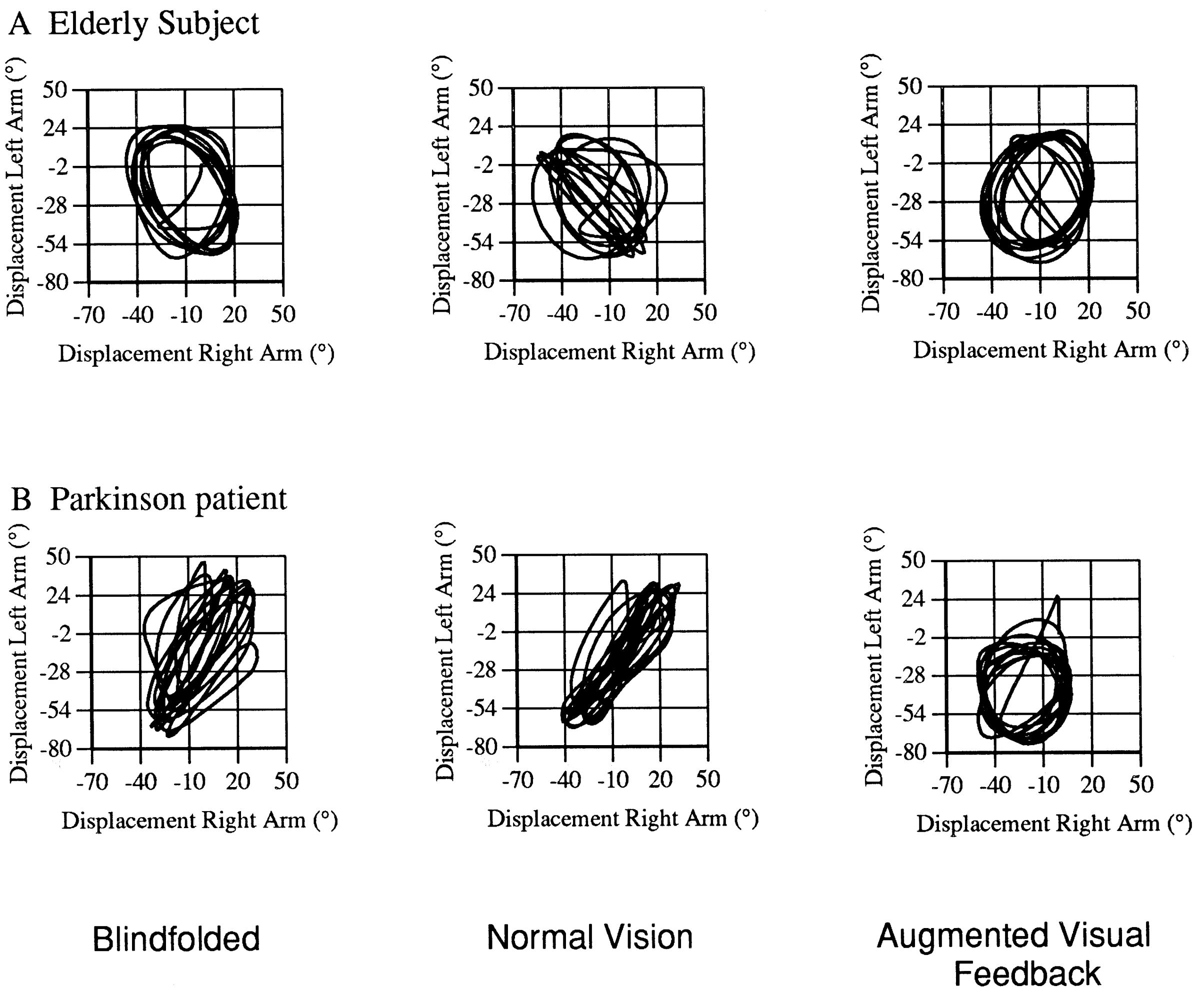

Fig. 5 Example of the coordination pattern of a typical elderly subject (**A**) and Parkinson patient (**B**) as produced at retention under the three different feedback conditions

block 1), it appears that no improvement on the coordination pattern had taken place.

One additional note is in order here. The successful performance of the Parkinson patients during the augmented feedback condition should be evaluated in combination with the cycle duration data (as discussed later).

Relative phase variability

Acquisition. Before initiation of practice, differences in SD between both groups were small (See Fig. 3B). Variability appeared to increase from the first to the second test block. At the end of acquisition, relative phase was slightly more variable in Parkinson patients, particularly in the condition with augmented visual information.

However, the aforementioned observations were not statistically supported (see Table 2). The ANOVA did not reveal any significant main effects. The interaction effects also failed to reach significance.

Retention. The main effects for Group and Feedback condition failed to reach significance (see Table 2). The interaction effect between both variables was significant and suggests a divergence in variability scores for both groups across the three feedback conditions. A posteriori tests revealed that relative phase variability was significantly higher in the Parkinson group (SD 24°) than in the elderly group (SD 11°) when augmented visual information was present ($P<0.01$). No significant differences were observed with respect to the remaining two performance conditions ($P>0.05$; see Fig. 3B, right side).

Example of improvements in the coordination pattern during the acquisition phase

Figure 4 shows the evolution of the coordination pattern across practice with augmented feedback for an elderly and Parkinson subject. The displacement pattern of the left arm is plotted against that of the right arm (Lissajous figure). These plots need to be compared with the correct performance of the 90° out-of-phase pattern which is characterized by a circular configuration (see Fig. 2).

In the elderly subject, a strong tendency to perform the intrinsic antiphase coordination mode is evident before initiation of practice (Fig. 4, upper left). After 20 trials, the circular configuration (gradually) appears (Fig. 4, upper middle) and this pattern is further improved after 40 trials of practice (Fig. 4, upper right). The pattern still shows variations from cycle to cycle.

In the Parkinson patient, a tendency toward the in-phase pattern is initially evident (Fig. 4, lower left). After 20 and 40 practice trials, features of the required coordination mode emerge (Fig. 4, lower middle and right). Variability in coordination remains evident as well as a tendencies to regress toward the antiphase coordination mode, as shown by an occupation of the diagonal (Fig. 4, upper left/lower right) in the second and third plot.

Example of performance under the three feedback conditions administered during the retention test

Figure 5 shows an example of retention performance under the three different feedback conditions, i.e., blindfolded, with normal vision, and with augmented visual information. It is evident that the elderly person is capable of producing the required coordination pattern across the three feedback conditions. In other words, the subject succeeds in transferring what was learned during practice trials with augmented feedback to other conditions. Nevertheless, the diagrams representing performance under blindfolded and normal vision conditions (Fig. 5, upper left and middle) lean slightly to the left, indicative of tendencies toward the antiphase (or 180° out-of-phase) pattern. Small problems in breaking away from the antiphase pattern are also encountered at the start of the trial, but the pattern improves toward the end. With augmented visual feedback (Fig. 5, upper right), the required coordination pattern emerges during the majority of the cycles.

The example of the Parkinson patient demonstrates that the 90° pattern is lost during blindfolded (Fig. 5, lower left) and normal vision (Fig. 5, lower middle) conditions. Without augmented visual information, performance breaks down and leans toward the in-phase pattern. In general, the Parkinson patient is less successful in transferring the skill level, established under augmented feedback conditions, to conditions where this information is withheld. Apparently, the patient strongly relies on the augmented visual information to produce the correct pattern. This is evident in Fig. 5 at the lower right, where the required coordination pattern reappears when augmented feedback is again available.

Amplitude

In addition to the imposed relative phase mode of 90°, a peak-to-peak amplitude of 80° was required in both arms. The data for acquisition were analyzed by means of a 2×2×3×3 (Group×Limb×Test block×Feedback condition) ANOVA with repeated measures on the last three factors. Separate analyses were conducted on the mean and SD scores. Retention data were analyzed by means of a 2×2×3 (Group×Limb×Feedback condition) ANOVA with repeated measures on the last two factors. The results of the statistical analysis are reported in Table 2.

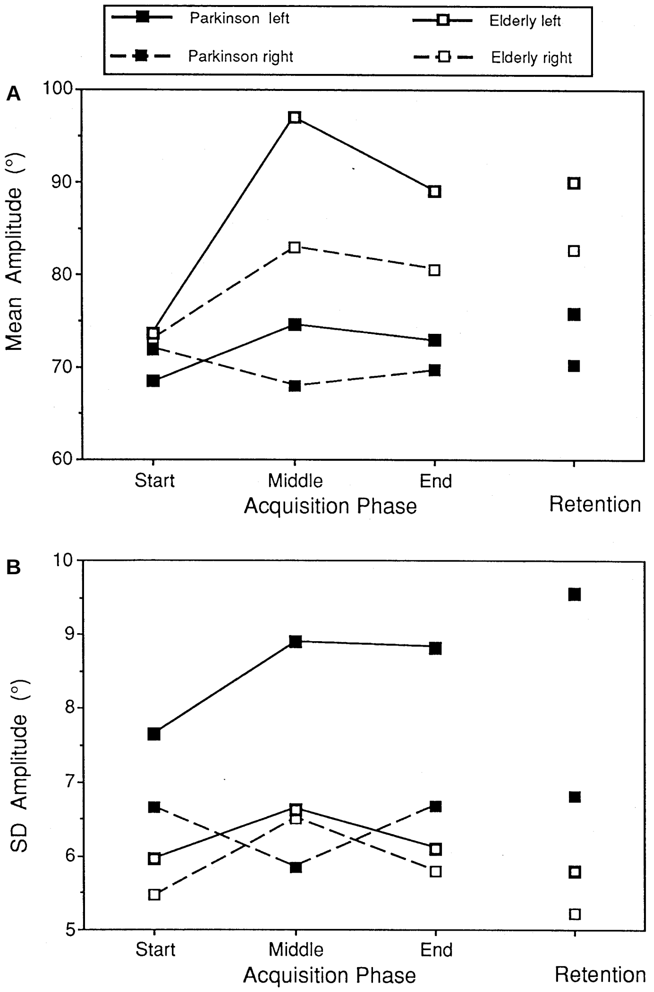

Fig. 6A, B Mean amplitude and variability of the left and right limb motion for the elderly group and Parkinson group during practice and retention

Mean amplitude

Acquisition. No significant main or interaction effects were identified. Even though mean amplitudes were generally higher in the elderly group than in the Parkinson group (see Fig. 6A), the Group effect did not quite reach significance (P=0.078). Left arm amplitudes were not significantly different from right arm amplitudes. The Test block and Feedback condition effect also failed to reach significance.

Retention. The ANOVA did not reveal significant main effects for Group, Limb, and Feedback condition. The interaction effects also failed to reach significance (see Table 2).

Variability of amplitude

Acquisition. Variability of the amplitudes was significantly larger in the left than in the right limb (see Fig. 6B). The main effect for Group was not significant, neither was the effect for Test block and Feedback condition. None of the interaction effects were significant.

Retention. The trends observed during the acquisition phase were confirmed at retention (see Table 2). The ANOVA revealed that the SD scores were significantly smaller in the elderly group than in the Parkinson group, M=5.5° and M=8.2°, respectively. The larger variability of the left arm (M=7.6°) as compared to the right arm (M=6.0°) was also statistically confirmed. The Feedback condition effect failed to reach significance. The differences between both arms were more clearly apparent in the Parkinson patients than in the control group. This resulted in a significant Group×Limb interaction (see Fig. 6B).

Cycle duration

The ANOVAs applied to the cycle duration means and SDs were similar to those used for analysis of the movement amplitudes.

Mean cycle duration

Acquisition. In the present experiment, the target cycle duration was set at 1200 ms. The main effect for Group and Limb failed to reach significance (see Fig. 7A, Table 2). A significant increase in cycle duration was observed across practice: mean cycle duration was 1715 ms, 2573 ms, and 2772 ms, at the start, middle, and end of practice, respectively. Significant differences in cycle duration were also observed across the three feedback conditions. Cycle duration was generally higher in the presence of augmented visual information (M=2572 ms) as compared to the remaining two conditions (blindfolded M=2310 ms, normal vision M=2189 ms). The Group×Feedback condition interaction was significant. It is apparent from Fig. 7A that mean cycle duration diverged more across feedback conditions in the Parkinson group than in the group of elderly persons. The latter group showed only small timing differences among the feedback conditions (P>0.05). Conversely, the Parkinson group showed significantly slower movements in the presence of augmented visual information than the remaining two performance conditions (P<0.05).

The Test block×Feedback condition interaction was significant, suggesting that the increase in cycle duration across the three test blocks was more pronounced in the augmented feedback condition than in the remaining conditions. Finally, two three-factor interactions were significant and invite a reinterpretation of the previous effects: Group×Test block×Feedback condition and Test block×Feedback condition×Limb. The former interaction indicated that the extra increase in cycle duration during the augmented feedback condition, relative to the other conditions, was mainly due to the Parkinson group. The latter interaction indicated that the increase in cycle duration across test blocks was more pronounced in the right than in the left limb.

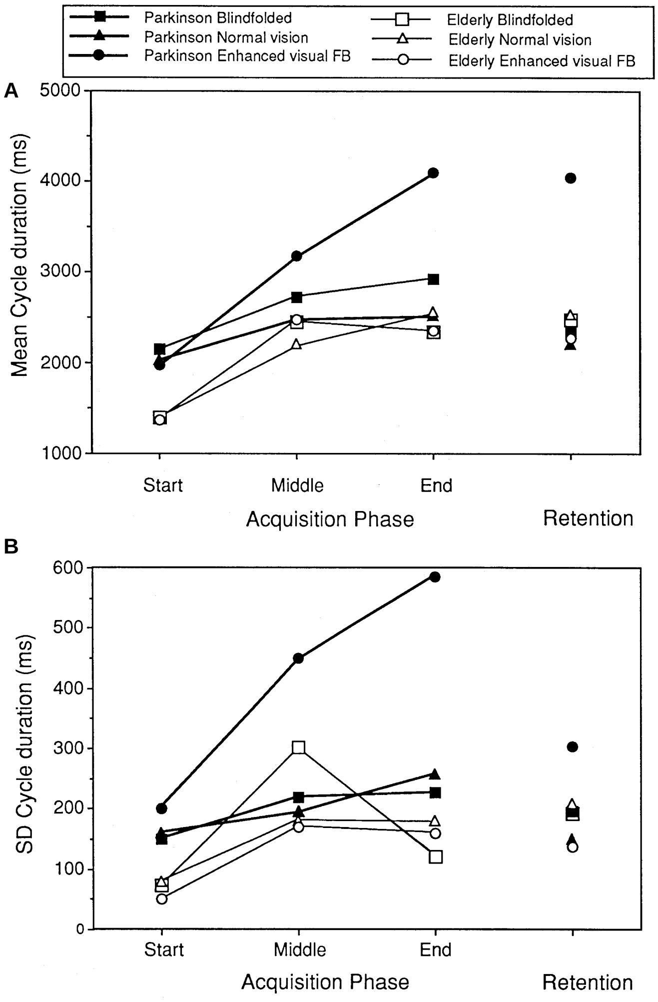

Fig. 7A, B Mean and SD of cycle duration for the elderly and Parkinson group with respect to the three feedback conditions as observed during practice and retention

Retention. The only significant main effect was observed for Feedback condition. All interaction effects were found significant (see Table 2). The significant Group×Feedback condition interaction can be interpreted as follows: whereas no differences in cycle duration among the three feedback conditions were observed in the elderly group (P>0.05), the Parkinson group showed higher cycle duration scores during the augmented feedback condition than during the remaining two conditions (P<0.01 for both). The Limb×Group interaction was also significant. Whereas the left arm was slightly slower than the right arm in the elderly group (M=2432 ms and M=2411 ms), the converse effect was found in the Parkinson group (M=2801 ms and M=2923 ms). The Feedback condition×Limb interaction also reached significance. Whereas no differences in cycle duration between the left and right limb were observed during the blindfolded and normal vision conditions, the left arm moved faster than the right arm during the augmented feedback condition. In order, means for the left and right limb were 2422 ms and 2389 ms during the blindfolded condition, 2375 ms and 2358 ms during the normal vision condition, and 3053 ms and 3253 ms during the augmented feedback condition. Finally, the Feedback condition×Group×Limb interaction was significant. As stated previously, the elderly group did not show major differences in cycle duration among the three feedback conditions and this effect was similar in both limbs. On the other hand, the Parkinson group moved slower during the augmented feedback condition than during the remaining conditions and this effect was more prevalent in the right than in the left limb.

Variability of cycle duration

Acquisition. Figure 7B shows that cycle duration was more variable in the Parkinson patients than in the control group. The ANOVA confirmed this observation, revealing a significant main effect for Group (see Table 2). SD scores for the elderly and Parkinson group were 147 ms and 263 ms, respectively. Variability scores differed significantly across the three test blocks: variability increased from the start (SD 105 ms) to the middle of practice (SD 258 ms) and remained at the same level toward the end of practice (SD 256 ms). The main effect for Feedback condition was also significant. The SD scores were larger during the augmented feedback condition (256 ms) than during the blindfolded (182 ms) and normal vision conditions (176 ms). The effect of Limb failed to reach significance.

The aforementioned main effects for Group and Feedback condition need to be reinterpreted in view of the significant Group×Feedback Condition interaction. As is evident from Fig. 7B, the elderly group only showed small differences among the three feedback conditions. In the Parkinson group, however, the SD scores were larger during performance with augmented feedback than during the normal vision and blindfolded conditions ($P<0.01$). The interpretation of the remaining significant interaction effects bears similarities with the mean cycle duration effects.

Retention. No significant main or interaction effects were identified (Table 2).

Discussion

In the present study, two research issues were combined that have received limited attention in the literature on Parkinson’s disease: the learning/transfer of movements and coordination between the limbs. The study of interlimb coordination has become a dominant focus of attention in current motor neuroscience (for an overview of this work, see Swinnen et al. 1994). When more than one limb or segment is involved in movement production, interactions become evident that reflect constraints in controlling the intrinsically high number of degrees of freedom that characterizes the human motor apparatus. These interactions have been studied extensively in the upper limbs and they have become particularly evident when human performers are confronted with performing different tasks with both arms simultaneously (Heuer 1991; Kelso et al. 1979; Swinnen et al. 1991b, 1993).

With respect to cyclical bimanual movement, two coordination modes have been characterized as intrinsically stable patterns that normally belong to the preexisting motor repertoire of the human performer: in-phase, requiring the simultaneous activation of homologous muscle groups, and antiphase (180° relative phase), which is characterized by the simultaneous contraction of nonhomologous muscle groups. In the present study, subjects acquired a 90° out-of-phase task, located in between the previously identified in-phase and antiphase modes. This task has the advantage that its goal can be specified in exact mathematical terms. Because this new skill is not normally part of the intrinsic motor repertoire, difficulties in performing the skill are initially experienced and practice is required to attain accurate and stable performance. Accordingly, the present task was considered a valuable tool with which to address the acquisition of new skills.

Previous experiments on the acquisition of a 90° out-of-phase task revealed that performance was constrained by the in-phase and antiphase modes at the start of practice (Lee et al. 1995; Zanone and Kelso 1992). This also became evident in the present experiment, giving rise to large deviations from the intended relative phase of 90° at the start of practice. However, as practice with augmented feedback continued, the elderly as well as the Parkinson subjects became gradually more successful in reducing the influence of these preferred coordination modes. In spite of the major improvements made in the accuracy of the coordination pattern, variability of relative phase remained high and was not reduced across practice in the Parkinson subjects. In fact, variability tended to increase in those conditions where the coordination pattern was produced most successfully. The increase in variability was perhaps due to attempts to overcome the preferred in-phase and antiphase coordination modes that have an intrinsically higher degree of stability. Inspection of the relative motion plots also revealed that some Parkinson patients tended to perform the limb motions sequentially instead of simultaneously. As practice continued, sequencing disappeared and true coordination of the limbs emerged. Similar difficulties in producing movements simultaneously have also been underscored in previous work, albeit not within the context of motor learning (Benecke et al. 1986; Schwab et al. 1954).

Even though the Parkinson patients seemed to succeed reasonably well in the presence of concurrent, visual relative motion feedback (but with higher relative phase variability and increased cycle duration), they showed marked deficits when transferring to performance conditions in which this augmented feedback was withheld. During normal vision and blindfolded conditions, performance deteriorated, relative to the augmented feedback condition. No indications of improvement in the coordination pattern across practice were evident in the Parkinson patients during the former conditions. This is in marked contrast with the elderly group, who showed clear improvements in transfer performance across practice, almost reaching the skill levels attained under augmented feedback conditions. On the one hand, these observations may reflect the difficulty that Parkinson patients experienced in shifting their attention from one performance condition to another. On the other hand, we entertain the hypothesis that the movement representation established by the Parkinson patients as a result of practice appeared to be rather specific to the conditions in which practice took place, i.e., generalizability of learning was hampered.

The performance deterioration observed under blindfolded and normal vision conditions predominantly resulted from a regression to the preferred in-phase and antiphase coordination patterns (see Fig. 5). It appears, therefore, that the presentation of relative motion information in real time allowed the patients to establish a perception-action link for guiding their movements. The present observations support and extend earlier contentions that Parkinson patients prefer to adopt a closed-loop control mode, adjusting their movements continuously on the basis of available visual information (Flowers 1976). Apparently they experience difficulties in generating movements from an internal action plan. These observations bear a remarkable resemblance to animal research. Saint-Cyr et al. (1995) have remarked that animal research indicated relatively early that “damage to the caudate nuclei led to a condition in which animals had difficulty formulating internally (i.e., subjectively) driven response strategies, relying instead on environmental (i.e., external) cues and previously established, somewhat stereotypical, response tendencies”. Similarly, Goldberg (1985) has noted that Parkinson patients have difficulty initiating motor programs that are not directly linked to exteroceptive information and he has suggested that nigrostriatal dopaminergic function is particularly important in this respect. The present findings are in agreement with this viewpoint. In particular, the observed regression toward in-phase and antiphase coordination modes in the absence of augmented information feedback suggests that Parkinson patients converged upon stereotypical response tendencies and/or were unable to sufficiently suppress these unwanted patterns.

No clear improvements in other features of movement were observed. Instead, subjects appeared to focus predominantly on the required relative phasing of the limbs at the expense of timing and amplitude. Higher variability in the specification of movement amplitude was observed in Parkinson patients than in the elderly subjects (significant at retention), and this is a typical sign of the disease (Phillips and Stelmach 1992). This effect was particularly evident in the nondominant limb, suggestive of a differential impairment of simultaneous movement scaling between the limbs.

With respect to movement timing, the findings showed that Parkinson patients moved almost as fast as the control subjects during the nonaugmented performance conditions. However, the former group slowed down considerably during the augmented feedback condition. Previous studies have also shown considerable slowing in Parkinson patients in comparison with normal people, particularly when simultaneous movements are to be produced (Benecke et al. 1986; Berardelli et al. 1986; Flowers 1976; Hallet and Koshbin 1980; Schwab et al. 1954). Furthermore, the observed decrease in movement speed during the augmented visual feedback condition is consistent with the findings of Inzelberg and coworkers (1990), who also described a similar effect in association with the presence of visual feedback. They concluded that Parkinson patients are forced to verify their movement progression continuously according to the available visual information. It is then reasonable to propose that bradykinesia is not only a consequence of an intrinsic movement speed deficit but also reflects a control strategy associated with the processing and use of (augmented) visual feedback, resulting in slower but more accurate behavior. Reducing movement speed allows the patients to establish a closed-loop control mode or perception-action link.

The apparent discrepancy in performance under augmented and nonaugmented feedback conditions may also tentatively suggest the involvement of different brain areas or network systems that are differentially affected in Parkinson’s disease, even though additional research is mandatory to further validate this judgment. Deficits in internally generated movements have been linked with disruption of the basal ganglia and supplementary motor area circuits (Deiber et al. 1991; Goldberg 1985; Marsden 1989). On the other hand, externally cued or closed-loop movements are argued to rely upon the sensory and premotor cortex with less involvement from the basal ganglia (Marsden 1989).

In summary, the present findings suggest that Parkinson patients are able to improve performance on a new bimanual coordination pattern if augmented visual information about the crucial features of the task is provided. Performance is nevertheless more variable and slower. However, virtually no improvement in coordination is observed when the augmented feedback is withdrawn, i.e., patients are hampered when they have to rely on their own intrinsic feedback sources. Even though it cannot be excluded that problems with shifting attention may have contributed to this effect, we hypothesize that this lack of transfer to feedback withdrawal conditions suggests limited generalizability of learning.

In spite of the fact that the cerebellum has traditionally been denoted as a principal learning device, the learning/transfer deficits established in the present experiment suggest that the basal ganglia play an equally important role in certain forms of motor learning. Accordingly, future work on the neurobiological bases of motor learning should focus on the relative contribution of the basal ganglia and cerebellum as well as on the interactions among various other brain regions that are involved in this process. The present findings support the hypothesis that motor (and more general procedural) learning is impaired in Parkinson patients (Butters et al. 1994; Saint-Cyr et al. 1995; Salmon and Butters 1995). The relation between basal ganglia dysfunction and motor learning impairment has also been supported in recent animal research (Aosaki et al. 1994; Whishaw et al. 1994).

The observed lack of transfer of learning has clinical relevance as well in that it suggests that skill improvement, obtained with augmented sources of feedback or extra cues in the environment, does not necessarily transfer to conditions where these extra aids are withheld. It remains to be seen whether practice with a greater variety of environmental conditions (including conditions with removal of augmented feedback) provides a more fertile ground for provoking generalizability of learning.

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