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Interlimb coordination: Learning and transfer under different feedback conditions

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Abstract

The role of intrinsic and extrinsic information feedback in learning a new bimanual coordination pattern was investigated. The pattern required continuous flexion–extension movements of the upper limbs with a 90° phase offset. Separate groups practiced the task under one of the following visual feedback conditions: (a) blindfolded (reduced FB group), (b) with normal vision (normal FB group), or (c) with concurrent relative motion information (enhanced FB group). All groups were subjected to three different transfer test conditions at regular intervals during practice. These tests included reduced, normal vision, and enhanced vision conditions. Experiment 1 showed that the group receiving augmented information feedback about its relative motions in real-time produced the required coordination pattern more successfully than the remaining two groups, irrespective of the transfer conditions under which performance was evaluated. Experiment 2 replicated and extended the superiority of the enhanced feedback group during acquisition and retention. Experiment 3 demonstrated that successful transfer to various transfer test conditions was not a result of test-trial effects. Overall, the data suggest that the conditions that optimized performance of the coordination pattern during acquisition also optimized transfer performance. © 1997 Elsevier Science B.V.

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1. Introduction

Research on motor learning has predominantly been concerned with the acquisition of movement parameters, such as overall timing or force. This implies that an already available movement pattern is to be scaled in accordance with externally imposed requirements. This perspective has considerable limitations in that the true learning of skills often requires the development of a new movement form that was not available before practice, in addition to fine tuning of movement parameters. In the past years, the study of complex skills has gained momentum through a renewed interest for the study of patterns of interlimb coordination. Isolated attempts to unravel the processes underlying interlimb coordination were made during the post-war period when a strong link became established with the human factors involved in pilot training (Fleishman and Rich, 1963). Subsequently, research on coordination became almost dormant even though most batteries of motor proficiency included some tests for assessing coordinative capabilities in children or adults. This indirectly implies that interlimb coordination has always been considered an important dimension of human motor functioning.

Recently, the study of the principles of learning discrete (Swinnen et al., 1988, 1993) and cyclical interlimb coordination tasks (Lee et al., 1995; Schöner, 1989; Schöner et al., 1992; Zanone and Kelso, 1992, 1994) has received increasing attention. These principles are being examined relative to the advances made in the study of interlimb *control* since the early eighties (see Swinnen et al., 1994 for a sample of this work).

Studies on interlimb coordination in biological systems have resulted in the identification of two elementary modes of movement coordination, called in-phase and anti-phase patterns (Kelso, 1984; Kelso and Jeka, 1992; Yamanishi et al., 1980). With respect to upper-limb movements, 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 less intrinsic to, or embedded in the human motor system, and whose accurate and consistent performance requires practice.

In the present study, subjects produced bimanual oscillations with a 1:1 frequency ratio and the same amplitudes, but with a phase offset of 90° between the limbs. This pattern is located between the aforementioned in-phase and anti-phase modes. The difficulty with learning such a pattern – and presumably many other motor skills – is the strong initial tendency to be drawn to the pre-existing or preferred motor patterns (Swinnen and Walter, 1988; Schöner et al., 1992; Zanone and Kelso, 1992). This gives rise to interference that needs to be gradually overcome with practice. Previous experiments with a similar forearm task exemplified the strong bias to in-phase and anti-phase coordination while subjects attempted the 90° out-of-phase pattern (Lee et al., 1995).

The present series of studies was designed to examine the role of augmented extrinsic feedback on the acquisition and retention of the 90° out-of-phase task. Augmented feedback refers to information that is provided in addition to the intrinsic feedback that is normally available to the performer. Whereas certain forms of augmented feedback (such as knowledge of results) have been studied intensively, investigations on the effect of other types of feedback that may be more appropriate for the acquisition of coordination skills, are conspicuous by their absence. In the present experiments, our purposes were to examine: (1) the relative importance of augmented relative motion feedback on the acquisition of this task, and (2) the effect on transfer when the feedback conditions were either the same or different from the learning context (i.e., the conditions available during the acquisition trials).

Regarding the first purpose, we hypothesized that augmented relative motion feedback would be critical to the acquisition of the 90° out-of-phase task. Anecdotal evidence from our previous studies on augmented real-time information feedback (Lee et al., 1995; Swinnen et al., 1991a) suggested that subjects tended to learn the task in two stages. The first stage was to acquire a rudimentary idea of the movement pattern to match the task constraints. Once the "idea of the movement" (Gentile, 1972) had been acquired, the second stage was to refine the movement pattern (Adams, 1971; Fitts, 1964). It has been argued that the feedback provided during learning should match the degrees of freedom (in the present case: joint motions) to be controlled in the task (Fowler and Turvey, 1978). In this respect, the critical role of relative motion information during the learning of coordination tasks has been underscored (Newell et al., 1985).

Relative to the second purpose, evidence from the learning of unimanual discrete tasks suggests that the relation between the feedback conditions available during practice and the conditions at transfer have a critical impact on performance. Proteau and colleagues have provided evidence to support a specificity of learning hypothesis regarding the learning of a unimanual aimed timing task (Proteau et al., 1987). Their observations have culminated in the proposal that learning results in building a specific sensorimotor representation, based on the available information feedback sources. Withdrawal of information would therefore lead to a decrement in performance. It is unknown, however, whether such specificity of augmented feedback effects would also be evident when learning a cyclical coordination task. The three studies reported in this paper address related questions.

2. Experiment 1

2.1. Method

2.1.1. Subjects

The subjects were thirty-three 18–20-year-old male students from the Katholieke Universiteit Leuven. All were right-handed and had no previous experience with the task.

2.1.2. Apparatus and task

The apparatus consisted of two horizontal metal levers (43 cm long), attached to virtually frictionless vertical axles, that could be moved toward and away from the body midline. An adjustable handle and a 350 g weight were located at the distal end of each lever. The weight was added to increase the force requirements of the task. Incremental shaft encoders (4096 counts per 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 such that the body was aligned between the levers. Movements were made by resting the forearms on each lever and grasping the handle at the distal end. The handle could be adjusted to accommodate different forearm 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.

The 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 was performed on every beat. Subjects were required to produce oscillations of each limb with the same frequency (1 Hz) and amplitude (±40°, or 80° peak-to-peak displacement) but with a phase offset of 90° between the limbs. The duration of each trial was 15 s. The limbs always started in mid-position prior to movement initiation. The reversals in direction at peak flexion and peak extension were made at vertical targets (width = 4°), located behind the movement path. These markers served only as general indicators to reverse the movements, and accuracy in reversing was neither stressed nor directly communicated to the subjects. A computer 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 data were saved on optical disk and analyzed later.

The essence of this motor skill is the development of a spatiotemporal relationship between the limbs. When one limb is reversing direction at peak position, the other limb is located mid-way between peak extension and flexion. This is exemplified in Fig. 1, showing the upper limbs' angular displacement–time profiles for a successful 90° out-of-phase movement. The orthogonal plot of both angular displacement patterns results in a circle configuration (see Fig. 1, right plot). Thus, an internal spatiotemporal structure is to be developed within the confines of an external timer (the metronome) and against the backdrop of preferred pre-existing coordination tendencies.

2.1.3. Procedure

Subjects were instructed to move both limbs continuously with a phase offset of 90° and for a duration of 15 s at the pace of the metronome (1 Hz). Fifty acquisition trials were performed on each of three different days across

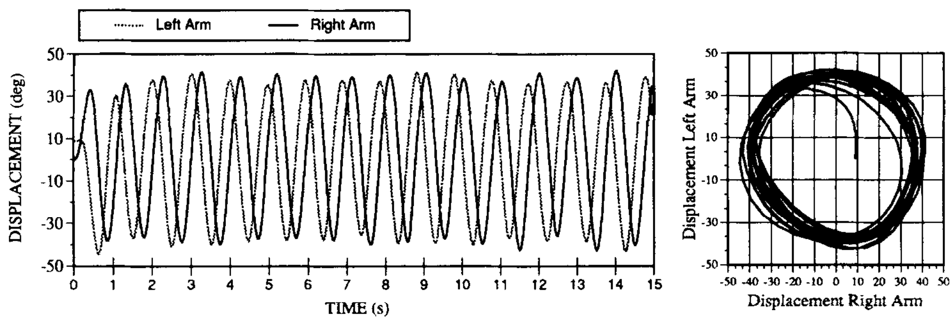

Fig. 1. Displacement–time profiles of the left and right arm movement (left) and relative motion plot of a successful 90° out-of-phase movement (right).

a two-week period. There were three experimental groups: Subjects of Group 1 were blindfolded (*reduced feedback group*), Group 2 subjects were allowed normal vision across all practice trials (*normal feedback group*). Group 3 was provided concurrent information feedback of the relative motions during the performance of a trial (*enhanced feedback group*). The augmented information was illustrated by a computer monitor which was positioned just beyond the movement apparatus and 10 cm above the surface of the table. The terminal provided feedback of the displacement–displacement angles with the left limb represented in the ordinate and the right limb in the abscissa (referred to as a Lissajous figure [1]). When produced correctly, the task resulted in a figure with a circle configuration. Provision of this visual information occurred in real time: The delay was only limited by the screen refresh rate (60 Hz). Previous work showed this concurrent feedback (FB) to be a powerful source of information for the acquisition of new bimanual coordination patterns (Lee et al., 1995; Swinnen et al., 1991a). The Lissajous figures remained on the screen until the trial was completed.

Three transfer test trials were administered prior to, in the middle, and at the end of each practice day. [2] Subjects reproduced the movement while blindfolded (reduced vision transfer condition), with normal vision (normal vision transfer condition), and in the presence of concurrent information feedback (enhanced vision transfer condition), respectively. This order was maintained across all transfer tests so as to minimize the effect of one criterion test upon the next, i.e., feedback sources became progressively available across the three transfer trials. In addition, subjects produced one trial of the in-phase and anti-phase coordination pattern prior to the first acquisition session and at the end of each practice day. The goal of assessing performance on these patterns was to examine potential chan¿;ges in the stability of these preferred coordination modes as a result of learning the new 90° out-of-phase mode. This was inspired by previous work in which these preferred modes were shown to destabilize during the acquisition of a new coordination mode (Zanone and Kelso, 1992).

[1] Lissajous figures are plane curves formed by the composition of two sinusoidal waveforms in perpendicular direction.

[2] Strictly speaking, transfer applies to the performance of a different movement or of the same movement under different experimental conditions. Moreover, transfer occurs after practice has taken place and this was not the case with respect to the first transfer test which was administered before acquisition started (day 1: pre-test).

Following every fifth trial, subjects of all three groups received terminal relative motion information of the last trial produced in the set: The right and left limb movements were plotted orthogonally on top of the movement template (a circle). This template was obtained through generation of two pure sine waves with equal frequencies (1 Hz) and amplitudes (±40°), but with a phase offset of 90°. The experimenter explained the displayed information to the subject and aided in interpreting this feedback. This feedback allowed subjects of all three groups to acquire information about the produced movement amplitudes as well as their relative phasing.

2.1.4. Data analysis

The data analysis focused on the spatiotemporal features of the individual limb motions by means of cycle duration and amplitude measures and on a quantification, through relative phase analyses, of the new coordination pattern that evolved between the limbs. Phase refers to a description of the stage that a periodic motion has reached, i.e., the point of advancement of a signal within its cycle. The subtraction of the phase angles of two signals (or limbs) occurring simultaneously is referred to as relative phase and 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 the formula proposed by Kelso et al., 1986:

$$\theta_R = \tan^{-1}[(\mathrm{d}X_R/\mathrm{d}t)/X_R],$$

where θ_R refers to the phase of the right arm movement at each sample, X_R is the position of the right forearm after rescaling to the interval $[-1, 1]$ for each cycle of oscillation, and $\mathrm{d}X_R/\mathrm{d}t$ is the normalized instantaneous velocity. The relative phase between the arms was subsequently determined through subtraction of the phase angle of both limbs, $\phi = \theta_R - \theta_L$. 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. This allowed a conversion from the Cartesian coordinates to sine and cosine functions of the polar coordinate system (ranging from 1 to −1). Velocity was obtained by differentiation of the displacement data.

Following computation of the continuous estimate of relative phase with the formula shown above, the absolute difference in phase angle (ranging from 0 to 180°) was extracted at two peak position landmarks of the reference (right) 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. Finally, absolute differences were computed between the obtained and target relative phase measure (i.e. 90°), similar to absolute error. The standard deviation (SD) around the mean relative phase was computed to obtain an estimate of the variability in relative phase. [3]

In addition to relative phase measures, temporal and spatial parameters of the left and right limb motions, i.e., cycle duration and amplitude were quantified. Cycle duration was defined as the time that elapsed between successive peak extension positions. The average cycle duration was computed across the 15 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 standard deviation was computed to estimate variability.

2.2. Results

2.2.1. Relative phase

2.2.1.1. Performance on the 90° out-of-phase task

2.2.1.1.1. Acquisition.

Relative phase accuracy. Fig. 2 shows the evolution of relative phase performance across three practice days. All three groups showed decreases in absolute error across days, with the largest decrease observed during the first day. The enhanced FB group performed with the least error, the reduced FB group with the most error. The group with normal vision of the limbs was positioned in between the former two groups. The performance difference among groups was largest on the first day of practice and decreased on the second and third day. The order among the groups remained evident until

[3] Based on the reviewers' suggestions, we made comparisons between our current procedure for computation of relative phase and the procedure based on circular statistics (as proposed by Batschelet, 1981). Even though we believe that the latter procedure can be generally recommended, we observed only very minor differences between both computational procedures. Even when initial practice of the 90° out-of-phase pattern gave rise to highly variable relative phase patterns, including the adoption of the in-phase and anti-phase mode, differences between both computational procedures were very small.

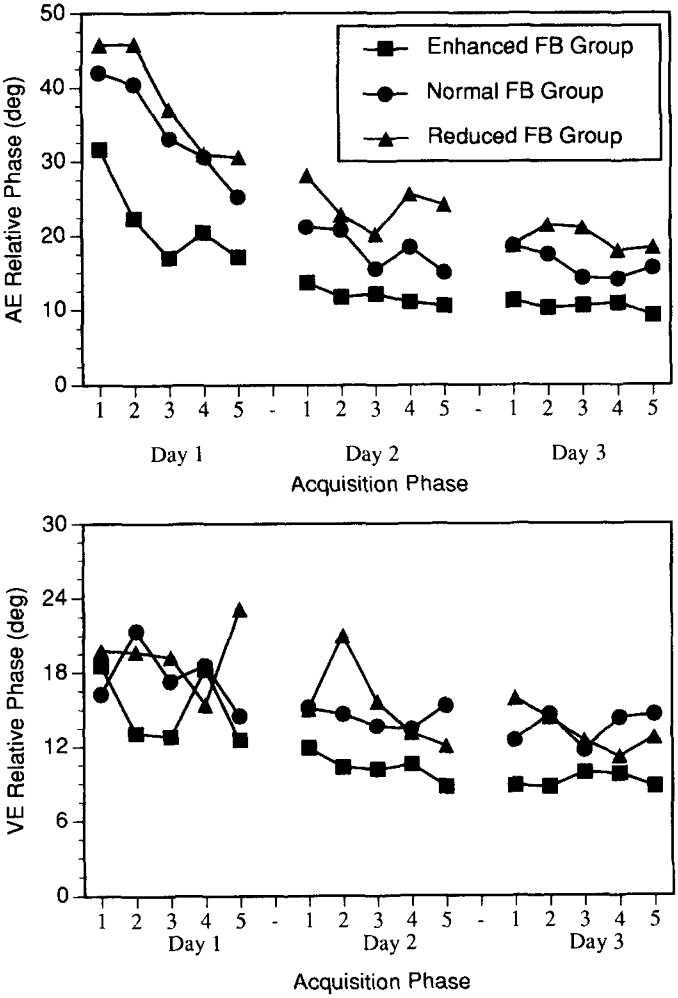

Fig. 2. Relative phase accuracy and variability for the reduced, normal, and enhanced FB group during the acquisition phase (Experiment 1).

the end of acquisition. Relative phase error was analyzed by means of a $3 \times 3 \times 5$ (Group × Day × Block) analysis of variance (ANOVA) with repeated measures on the last two factors. The group effect was significant, $F(2,30) = 4.32$, $p < 0.05$ (MSE = 1559.84). Tukey a posteriori tests revealed that performance of the enhanced FB group differed significantly from the reduced FB group (critical value of studentized range statistic = 3.49, minimum significant difference = 10.72, $p < 0.05$) but not from the normal FB group ($p > 0.05$). Mean error scores for the reduced FB group, the normal vision FB group, and enhanced FB group were 27.24, 22.83, and 14.64°, respectively. Error decreased significantly across blocks within days as well as across days, $F(4,120) = 13.45$, $p < 0.01$ (MSE = 65.41) and $F(2,60) = 37.11$, $p < 0.01$ (MSE = 325.92). The interaction between both effects was also significant, indicative of a differential evolution of performance across blocks among the three days of practice, $F(8,240) = 3.8$, $p < 0.01$ (MSE = 85.62). The remaining interactions were not significant ($p > 0.05$).

Relative phase variability. The SD data showed some fluctuation, particularly during the first day of practice. The scores gradually decreased on the second and third day except for the reduced FB group who demonstrated a large increase in variability on the second block of Day 2. The increases in variability that were observed during the first day are possibly a consequence of abandoning the highly consistent preferred coordination modes. The enhanced FB group performed with the lowest relative phase variability, followed by the normal FB and reduced FB groups. The statistical analysis revealed a significant group effect, $F(2,30) = 9.15$, $p < 0.01$ (MSE = 104.76). Means for the reduced FB, normal vision and enhanced FB groups were 16.04, 15.21, and 11.51°, respectively. Tukey tests indicated that the enhanced FB group differed significantly from the other groups ($p < 0.05$), which themselves were not different ($p > 0.05$). Variability decreased significantly across the three practice days, $F(2,60) = 21.38$, $p < 0.01$ (MSE = 59.29). The block effect was not significant, $F(4,120) = 1.87$, $p > 0.05$ (MSE = 32.98), but its interaction with group was significant, $F(8,120) = 2.3$, $p < 0.01$. The remaining interaction effects were not significant ($p > 0.05$).

2.2.1.1.2. Transfer.

Relative phase accuracy. Three trends are clearly evident from Fig. 3. First, mean relative phase error decreased across days. Second, the groups differed from each other: the enhanced FB group performed with the least error, the reduced FB group with most error, and the normal FB group with intermediate error. Third, the size of the group differences was not altered by the transfer test conditions. Data were analyzed using a $3 \times 3 \times 3 \times 3$ (Group × Transfer Test × Day × Block) ANOVA with repeated measures on the last three factors. The group variable included the reduced, normal, and enhanced FB groups. The transfer test variable referred to assessment of transfer performance under reduced, normal vision, and enhanced vision conditions. There were three testing days with three test blocks administered

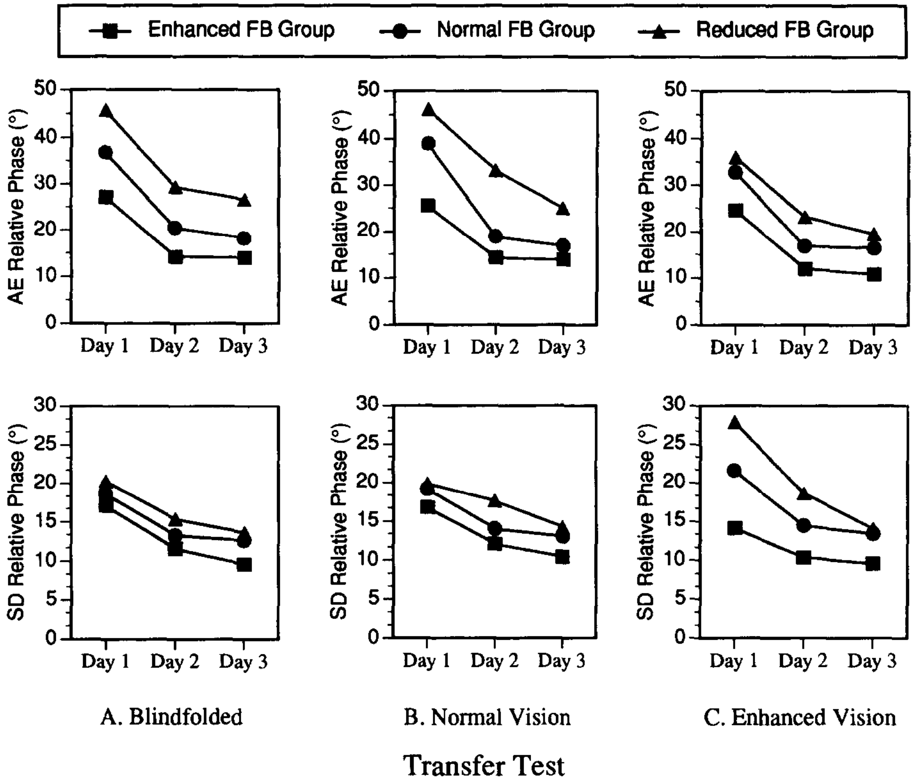

Fig. 3. Relative phase accuracy and variability for the reduced, normal, and enhanced FB group under reduced feedback (A), normal vision (B), and augmented vision (C) transfer test conditions (Experiment 1).

on each day. The figure shows only the mean scores per day, averaged across the three blocks.

The group effect was significant, $F(2,30) = 8.74, p < 0.01$ (MSE = 1731.69). In comparison with the reduced FB group ($M = 31.6°$), the enhanced FB group ($M = 17.35°$) maintained a better performance level across days. The normal feedback group was positioned in between the remaining two groups and largely maintained that position across practice ($M = 24°$). A posteriori tests revealed a significant difference in performance between the enhanced FB and reduced FB groups ($p < 0.01$), whereas the other pairwise comparisons did not reach significance ($p > 0.05$). No significant interactions involving the group effect were observed ($p > 0.05$).

Significant differences were also observed among the transfer conditions, $F(2,60) = 13, p < 0.01$ (MSE = 155.39). Irrespective of the differential performance among groups, the lowest error scores were observed under enhanced vision transfer conditions ($M = 21.5°$), followed by the normal vision ($M = 25.84°$) and reduced transfer test conditions ($M = 25.83°$). A posteriori tests revealed significant differences between the enhanced vision and reduced vision transfer tests ($p < 0.01$) and between the enhanced vision and normal vision tests ($p < 0.01$), but not between the reduced and normal vision transfer tests ($p > 0.05$).

The effect for day was significant, $F(2,60) = 49.91$, $p < 0.01$ (MSE = 500.01), as it was for the block effect, $F(2,60) = 55.26$, $p < 0.01$, (MSE = 184.44). Of the interaction effects, only the Day × Block interaction reached the conventional levels of significance, $F(4,120) = 6.75$, $p < 0.01$ (MSE = 228.09). Although large decreases in error across blocks were observed on the first day of practice, the changes were much smaller on the remaining two days.

Relative phase variability. Fig. 3 shows that the smallest variability scores were observed for the enhanced FB group across the three transfer test conditions ($M = 12.37°$). The reduced FB group performed with the highest variability ($M = 18°$), with the normal FB group occupying an intermediate position ($M = 15.6°$). Significant group differences were observed, $F(2,30) = 10.04$, $p < 0.01$ (MSE = 235.01). Tukey tests revealed significant differences between the enhanced FB and the normal and reduced FB groups ($p < 0.05$), but not between both latter groups ($p > 0.05$).

Similar to the absolute error scores, the variability scores decreased significantly across practice days, resulting in a significant day effect, $F(2,60) = 64.56$, $p < 0.01$ (MSE = 64.75) (see Fig. 3). The block effect was also significant, $F(2,60) = 10.43$, $p < 0.01$ (MSE = 46.92). No significant differences were observed among the three transfer test conditions, $F(2,60) = 2.20$, $p > 0.05$ (MSE = 50.43). However, the transfer test condition interacted with group, $F(4,60) = 3.87$, $p < 0.01$. The reduced FB group showed higher variability scores with an increase in the availability of information feedback during transfer test performance whereas this data pattern was less predominant for the enhanced FB and normal FB group. Subsequent analyses revealed that the group effect was significant under each of the three transfer test conditions. However, the differences were much larger under enhanced vision transfer test conditions in comparison with the remaining two conditions: reduced ($F(2,30) = 4.35$, $p = 0.022$, MSE = 86.31), normal vision ($F(2,30) = 4.47$, $p = 0.02$, MSE = 94.9), and enhanced vision ($F(2,30) = 12.61$, $p = 0.0001$, MSE = 154.6). The variability of relative phase under reduced, normal vision, and enhanced vision transfer test conditions was 12.93°, 13.07°, and 11.42°, respectively, for the enhanced FB group, 14.6°, 15.8°, and 16.4° for the normal FB group, and 16.1°, 17.78°, and 20.34° for the reduced FB group.

2.2.1.2. Performance on the in-phase and anti-phase tasks

2.2.1.2.1. Relative phase accuracy. Overall, the in-phase and anti-phase coordination modes were produced with higher accuracy than the 90° out-of-phase mode. In addition, the in-phase mode ($M = 7.65°$) was produced more accurately than the anti-phase mode ($M = 12.7°$) and this effect reached significance, $F(1,30)$ 82.15, $p < 0.01$ (MSE = 20.47). No significant differences between groups were identified, $F(2,30) = 1.01, p > 0.05$, (MSE = 45.71). Values for the reduced FB, normal FB, and enhanced FB group were 11.01°, 9.69°, and 9.84°, respectively. The scores obtained at pre-test and following each day of practice did not differ much from each other. There was only a small tendency for accuracy to decrease for the in-phase task following practice on the 90° out-of-phase task but this effect failed to reach significance, $F(3,90) < 1$. Means at pre-test and at the end of each of the three practice days were 9.65°, 10.68°, 10.11°, and 10.26°, respectively. None of the interaction effects reached the conventional level of significance ($p > 0.05$).

2.2.1.2.2. Relative phase variability. The effects with respect to variability of relative phase were similar to those observed for accuracy. The main finding was that in-phase coordination ($M = 4.4°$) was produced more consistently than anti-phase coordination ($M = 6.87°$), $F(1,30) = 52.54$, $p < 0.01$ (MSE 7.7). No significant differences were observed among the three groups, $F(2,30) < 1$. Variability scores for the reduced FB, normal FB, and enhanced FB group were 5.75°, 5.71°, and 5.45°, respectively. No significant differences were observed among the four tests administered, $F(3,90) = 1.04$, $p > 0.05$ (MSE = 6.36). Mean variability scores at pre-test and at the end of each of the three practice days were 5.24°, 5.96°, 5.54°, and 5.8°, respectively. None of the interaction effects reached significance.

2.2.1.3. Example of improvements in the coordination pattern at three transfer test conditions during acquisition. Fig. 4 shows an example of the evolution of the coordination pattern across transfer tests for a subject in the enhanced FB group. The displacement pattern of the left arm is plotted against that of the right arm (Lissajous figure). A correct performance of the 90° out-of-phase pattern is characterized by a 'circular' configuration. Transfer test

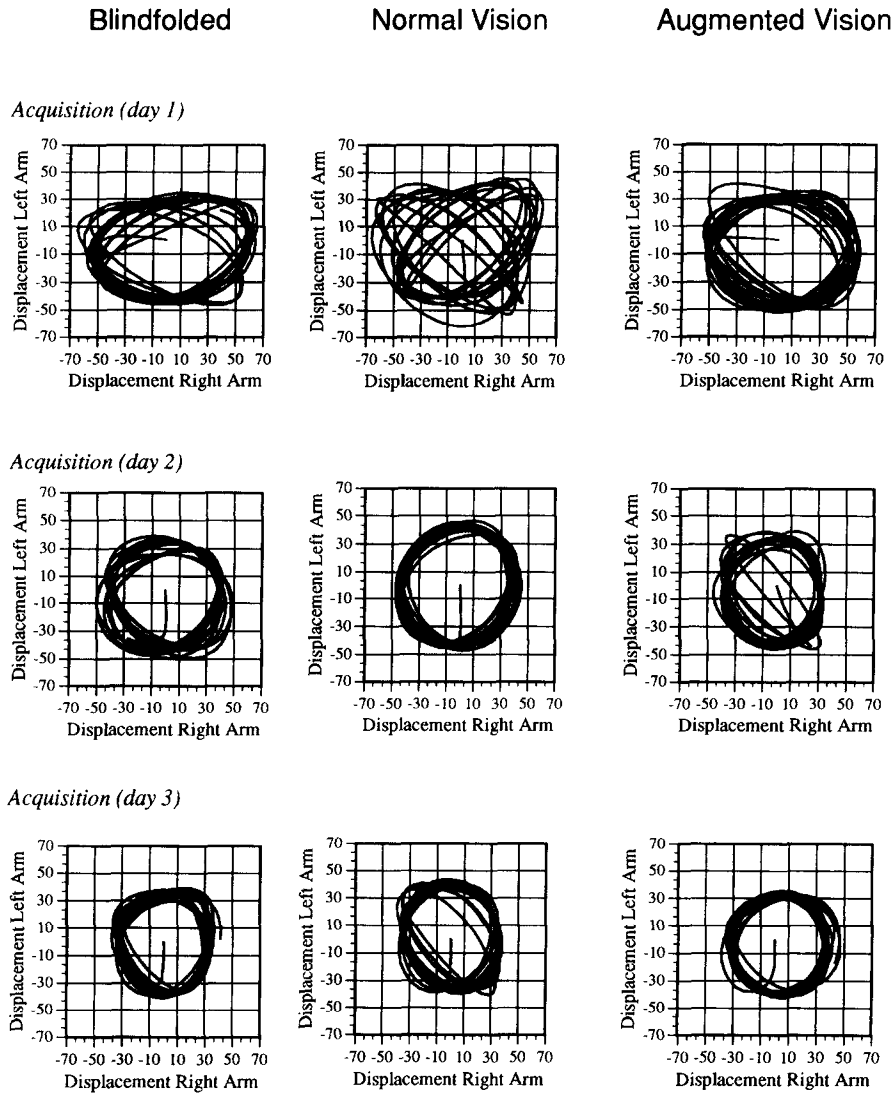

Fig. 4. Evolution of the performance pattern of a subject of the enhanced FB group during transfer to reduced feedback, normal vision, and augmented vision test conditions (Experiment 1).

performance at the end of each practice day (rows 1–3) is shown for the three test conditions: reduced (first column), normal vision (second column), and enhanced vision (third column). The tendency to perform preferred coordination modes is still evident at the end of the first practice day: in the test with reduced and normal vision feedback, and to a smaller extent during the enhanced transfer test, the occupation of the diagonals is indicative of in-phase and anti-phase performance. On the remaining days, the circular configuration gradually appears even though the remnants of in-phase and anti-phase performance remain evident on some of the cycles. It is predominantly pattern consistency that improves on the final two days of practice.

2.2.2. Cycle duration

2.2.2.1. Mean cycle duration. As shown in Fig. 5, cycle duration decreased across practice toward the target score of 1000 ms. This decrease was evident for all three groups and across the three transfer conditions and occurred simultaneously in both limbs. A 3 × 3 × 3 × 3 × 2 (Group × Transfer Test × Day × Blocks × Limb) ANOVA with repeated measures on the last four factors confirmed these observations. The group effect was not significant, $F(2,30) < 1$. However, three of the four remaining main effects were significant. First, there were differences in cycle duration across the three transfer test conditions, $F(2,60) = 23.02$, $p < 0.01$ (MSE = 14 768.6). Cycle duration was the most during reduced conditions (M = 1076 ms) and the least during enhanced vision conditions (M = 1028 ms), with the normal vision condition positioned in between (M = 1048 ms). Cycle duration decreased across the three practice days and also within each day, resulting in a significant effect for day and block, $F(2,60) = 3.25$, $p < 0.05$ (MSE = 48 250.13), and $F(2,60) = 22.75$, $p < 0.01$ (MSE = 31 394.63). No significant differences in cycle duration were found between the left (M = 1050 ms) and right limb (M = 1051 ms), $F(1,30) < 1$. The interactions will not be discussed here because they are not of direct interest, except for the group and transfer test condition interaction which was not significant, $F(4,60) < 1$.

2.2.2.2. Variability of cycle duration. Across the three days of practice, variability scores decreased and this was evident across all three transfer test conditions (see Fig. 5). The improvements were largest between the first and second day. In addition, the enhanced FB group demonstrated the most variability and the reduced FB group the least. The group effect was significant, $F(2,30) = 9.92$, $p < 0.01$ (MSE = 8379.27). In comparison with the reduced FB group (M = 41.39 ms) and the normal FB group (M = 50.09 ms), the enhanced FB group showed larger within-trial SD scores (M = 64.8 ms). A posteriori tests revealed significant differences between the reduced FB group and both remaining groups ($p < 0.01$) which did not differ from each other

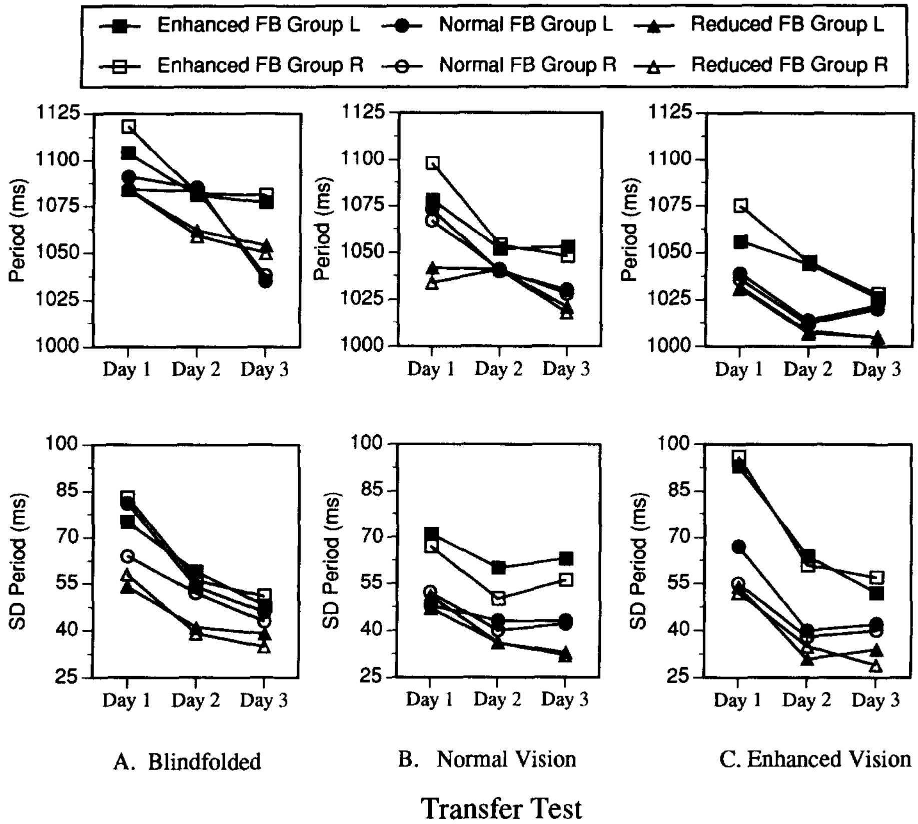

Fig. 5. Mean cycle duration and its variability for the reduced, normal, and enhanced FB group under reduced (A), normal vision (B), and augmented vision (C) transfer test conditions (Experiment 1).

($p > 0.05$). In addition, variability scores tended to be highest during transfer test conditions with reduced feedback ($M = 54.88$ ms), followed by the enhanced vision ($M = 52.71$ ms) and normal vision transfer test conditions ($M = 48.69$ ms). This resulted in a significant effect for transfer test condition, $F(2,60) = 3.91$, $p < 0.05$ (MSE = 1495.17). The effect for day was significant, $F(2,60) = 37.55$, $p < 0.01$ (MSE = 2159.91), just as for the block effect, $F(2,60) = 38.17$, $p < 0.01$ (MSE = 1180.88). Even though there was a tendency for the right limb to move with smaller temporal variability than the left limb ($M = 51.03$ versus 53.16 ms), the limb effect just failed to reach significance, $F(1,30) = 2.99$, $p > 0.05$.

In contrast with the analysis of mean cycle duration, variability of cycle duration demonstrated an interaction between group and transfer test conditions, $F(4,60) = 3.59$, $p < 0.05$. While the reduced FB and normal FB group showed a decrease in temporal variability from the reduced to the normal vision condition and a stagnation or very small increase under enhanced vision conditions, the enhanced FB group showed similar scores in the former two conditions but showed a large increase in temporal variability under enhanced vision transfer test conditions.

2.2.3. Amplitude

2.2.3.1. Mean amplitude. Fig. 6 illustrates that mean amplitudes decreased for all the three groups and that this effect was evident across all the three transfer test conditions. The largest decrease was observed during the first two days of practice. The ANOVA did not reveal significant differences in mean amplitude among the three groups, $F(2,30) = 2.16$, $p > 0.05$ (MSE = 1980.79). The means for the reduced, normal, and enhanced FB groups were 81.72, 76.72, and 80.92°, respectively. Performance under enhanced vision ($M = 77.73°$) and reduced feedback transfer test conditions ($M = 76.89°$) was accompanied with smaller amplitudes than under normal vision conditions ($M = 82.39°$), resulting in a significant effect for transfer test, $F(2,60) = 19.21$, $p < 0.01$ (MSE = 175.12). Post hoc tests demonstrated that the transfer tests with enhanced and reduced feedback differed from the normal vision test condition ($p < 0.01$). The decreases in amplitude across practice were statistically supported by a significant effect for day and block, $F(2,60) = 9.81$, $p < 0.01$ (MSE = 495.49), and, $F(2,60) = 74.76$, $p < 0.01$, (MSE = 237.82). Smaller amplitudes were observed in the right arm ($M = 78.16°$) as compared to the left arm ($M = 81.41°$), resulting in a significant effect for limb, $F(1,30) = 5.32$, $p < 0.05$ (MSE = 884.13). The Group × Transfer Test interaction was not significant, $F(4,60) = 1.65$, $p > 0.05$.

2.2.3.2. Variability of amplitude. Fig. 6 shows that variability decreased across practice days. The largest decreases were found under enhanced vision transfer test conditions. Variability under enhanced vision conditions was highest at the start of practice and lowest by the third day of practice. With respect to the three feedback groups, spatial variability scores of the enhanced FB group largely exceeded those of the other groups, particularly with respect to the left limb. The group effect was significant, $F(2,30) = 4.74$, $p < 0.05$ (MSE = 72.44). Tukey a posteriori tests revealed that the enhanced FB group performed with significantly higher variability scores

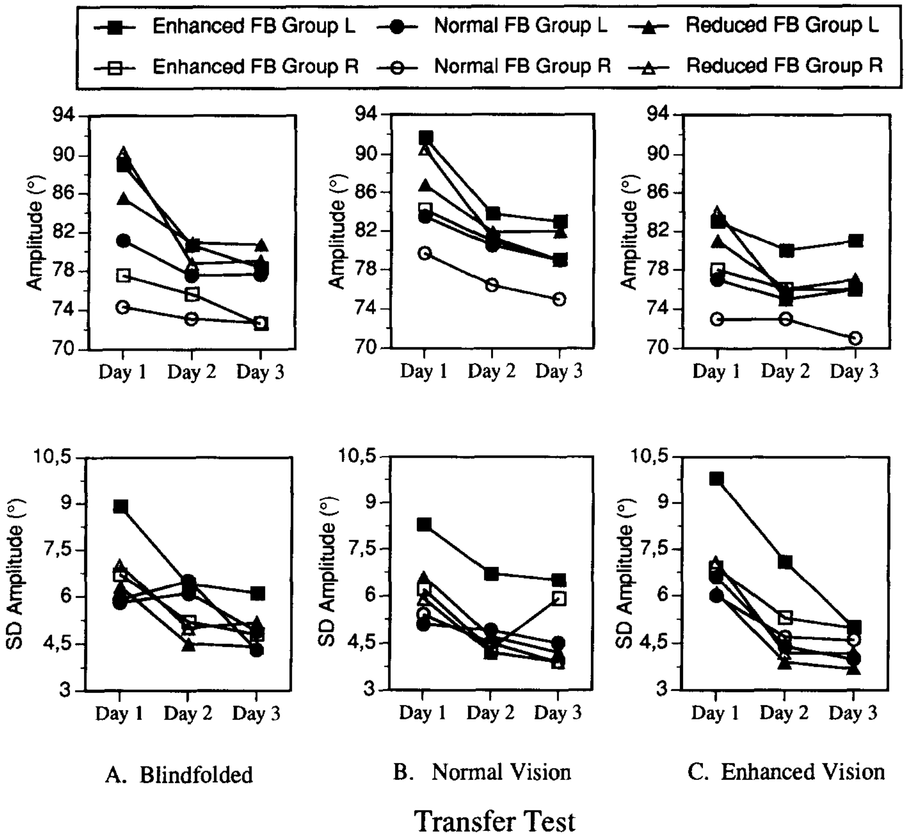

Fig. 6. Mean amplitude and its variability for the reduced, normal, and enhanced FB group under reduced (A), normal vision (B), and augmented vision (C) transfer test conditions (Experiment 1).

($p > 0.05$) than the remaining two groups which did not differ significantly from each other ($p > 0.05$). SD's for the enhanced FB, normal FB, and reduced FB group were 6.45, 5.15, and 5.12°, respectively.

Significant differences were also observed among the three transfer test conditions, $F(2,60) = 3.63$, $p < 0.05$ (MSE = 9). The smallest variability scores were observed during normal vision conditions ($M = 5.37°$), the highest during reduced feedback conditions ($M = 5.83°$); intermediate scores were obtained during enhanced vision transfer test conditions ($M = 5.52°$). Only the difference between the normal vision transfer test and the test with reduced feedback was significant ($p < 0.05$).

Across the three days of practice as well as the three blocks within each day, major decreases in variability were observed, $F(2,60) = 27.72$, $p < 0.01$

(MSE = 23.37), and $F(2,60) = 24.10$, $p < 0.01$ (MSE = 11.7). The limb effect was also significant, $F(1,30) = 4.3$, $p < 0.05$ (MSE = 24.48). Variability was generally larger in the left arm (5.81°) than in the right arm (5.33°). The Group × Transfer Test interaction was not significant, $F(4,60) = 1.44$, $p > 0.05$. The remaining interaction effects will not be discussed because they are of marginal importance.

2.3. Discussion

The present study provided some insights into transfer of learning across various information feedback conditions. Success in producing the required coordination pattern between the upper limbs, as determined through relative phase measures, was a function of the available information feedback. During acquisition, the enhanced FB group performed the pattern most accurately and consistently, followed by the normal vision and reduced FB groups. During transfer, the main effects for group and transfer test condition reached significance. Both effects converged with the notion that the quality of interlimb coordination improved with increasing availability of information feedback. The enhanced FB group produced the 90° out-of-phase pattern most successfully, the reduced FB group was least successful, and the group with normal vision was positioned in between the former two groups. On the other hand, transfer test performance was optimized when the concurrent information feedback was present, irrespective of the feedback sources that were made available to the subjects during practice of the task. No significant differences were found between the reduced feedback and normal vision transfer test conditions. Apparently, the augmented visual feedback (provided in real time) aided accuracy and consistency in interlimb coordination, irrespective of whether subjects were made familiar with this information during practice or not. Overall, performance during transfer test conditions was not a function of the similarity with the conditions that prevailed during practice. No support for the specificity of learning hypothesis could be found in those data.

In view of the serious concerns that have arisen about the negative side-effects of the frequent information feedback that guides subjects during practice but results in detrimental transfer performance in the absence of this feedback (Salmoni et al., 1984), we expected a severe performance deterioration for the enhanced FB group during transfer to feedback withdrawal conditions because the subjects of the latter group were guided extensively by the real-time information during each practice trial. Indeed, the on-line perception-action link that was established during practice could be used to monitor ongoing performance continuously. However, the superior performance of the enhanced feedback group under *all* three transfer test conditions did not provide evidence for these performance decrements. Even though this group showed some decreases in performance under reduced feedback and normal vision transfer test conditions, relative to the enhanced transfer condition, its performance still exceeded that of the groups which were familiar with such practice conditions.

Previous research on left and right finger coordination has characterized the in-phase and anti-phase modes as preferred patterns of interlimb coordination. In subsequent studies on the acquisition of a 90° out-of-phase pattern, Zanone and Kelso (1992) scanned the full range of relative phase modes at regular intervals during practice to assess the effect of acquisition of this new pattern on the total array of possible relative phase patterns. The findings showed that as learning on the 90° out-of-phase task proceeded, the anti-phase coordination pattern was destabilized. In the present experiment, only the in- and anti-phase modes were scanned at regular intervals during practice. No evidence was found for the destabilization of these preferred coordination modes: The differences between pre-test in-phase and anti-phase performance and performance measured at the end of each practice day were small and failed to reach significance.

In addition to improvements in relative phase, the spatiotemporal characteristics of the component limb movements were studied through analyses of cycle duration and amplitude and their within-trial variability. Consistency in both timing and amplitude improved considerably across the three days of practice even though these aspects of performance were not primary learning goals. Whereas the enhanced FB group was most successful in producing the required relative phasing pattern, spatiotemporal consistency of the component movements was lower than in the other two groups. The reduced feedback group showed the highest consistency in cycle duration and amplitude. Apparently, subjects of the enhanced FB group traded spatiotemporal consistency for success in producing the required coordination pattern. It is possible that the lower spatiotemporal consistency is a consequence of the abandoning of pre-existing relative phase patterns with the goal of developing a new less preferred (and therefore more variable) coordination pattern.

In view of the specificity of learning hypothesis, the final question to be dealt with is how the similarity between the performance conditions during acquisition and transfer affected the consistency in cycle duration and amplitude. In this respect, the reduced FB group was found to show its spatiotemporal superiority across all transfer test conditions and not only during the reduced vision conditions. Again, this does not comply with a specificity of learning perspective but supports the idea that subjects were able to generalize their performance capabilities across various test conditions.

3. Experiment 2

Experiment 1 generated evidence that transfer of a new bimanual coordination pattern generalized across various information feedback conditions. To substantiate this effect, a replication of this finding was pursued using the two most extreme practice conditions of the previous experiment, i.e., the reduced FB and enhanced FB groups. In particular, we were encouraged to partially replicate the experiment because the enhanced FB group in Experiment 1 already showed evidence of more successful performance under reduced and normal vision transfer test conditions before the start of practice (e.g., see Fig. 2). Thus, the concern was raised that the enhanced FB group might have consisted of intrinsically better performers than those of the other groups, even though all subjects were randomly assigned to the different experimental groups. The data analysis was focused on relative phase accuracy and consistency.

Recent research on motor learning has frequently demonstrated considerable differences in the pattern of results between an immediate and delayed retention test, administered respectively, some minutes and one or more days following the end of practice (Swinnen, 1990; Swinnen et al., 1990a; Winstein and Schmidt, 1990). Therefore, a delayed retention test was added to assess the capability to transfer the learned coordination pattern after a longer rest period (2 days later).

3.1. Method

3.1.1. Subjects

The subjects were 18 right-handed, 18–20-year-old students enrolled at the Katholieke Universiteit Leuven. None had previous experience with the task. All were right-handed. They were randomly assigned to two experimental groups ($n = 9$). The reduced FB group consisted of six male and three female subjects, the enhanced FB group of eight male and one female subject.

3.1.2. Apparatus and task

The experimental setup as well as the general task requirements were similar to the previous experiment.

3.1.3. Procedure

Subjects practiced the bimanual skill on three separate days within an eight day period, with 50 trials of 15 s duration administered on each day. The reduced FB group was blindfolded during all practice trials whereas the enhanced FB group was provided concurrent information feedback of the relative motions during each trial. Following every fifth trial, both groups were shown the relative motion plot of the last trial performed in the set, superimposed over the template. Subjects performed all three transfer test conditions at the beginning, the middle, and at the end of each day of practice. The final test was held five min following the end of the third practice day and served as the immediate retention test. The delayed retention test was administered two days later: subjects performed the coordination pattern under all three transfer test conditions. To prevent carry-over effects among transfer tests, each test condition was preceded by a warm-up trial, consisting of the same feedback condition as the transfer test.

Because learning the new coordination pattern was not found to substantially disrupt the in-phase and anti-phase coordination modes in Experiment 1, performance of these tasks was not assessed in the present experiment. Data analyses were focused on transfer test performance during acquisition and retention.

3.2. Results

3.2.1. Relative phase accuracy

A $2 \times 3 \times 3 \times 3$ (Group $\times$ Transfer Test $\times$ Day $\times$ Block) ANOVA with repeated measures on the latter three variables was applied. As Fig. 7 demonstrates, absolute deviations from the intended relative phase were generally smaller in the enhanced FB group than in the reduced FB group, $F(1,16) = 10.31$, $p < 0.01$ (MSE = 395.23). The remaining main effects also reached significance: transfer test, $F(2,32) = 3.44$, $p < 0.05$ (MSE = 54.1), day, $F(2,32) = 63.45$, $p < 0.01$ (MSE = 244.21), and block, $F(2,32) = 33.73$, $p < 0.01$ (MSE = 181.66). A posteriori tests revealed that performance under reduced and normal vision transfer conditions did not differ significantly ($p > 0.05$), but both demonstrated higher error scores than the enhanced vision transfer test condition ($p = 0.05$). Two interaction effects reached significance: the Day $\times$ Block and the Transfer Test Condition $\times$ Block interaction, $F(4,64) = 42.18$, $p < 0.01$ (MSE = 92.02) and $F(4,64) = 3.47$, $p < 0.05$ (MSE = 50.48), respectively. These effects are not discussed here in further detail because they are only of marginal importance.

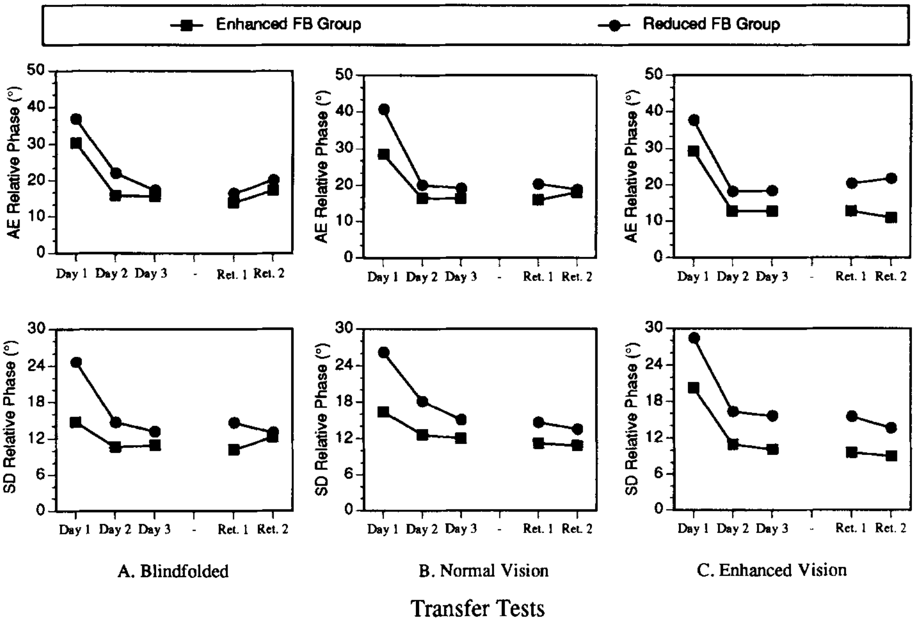

Fig. 7. Relative phase accuracy and variability for the reduced and enhanced FB group under reduced feedback (A), normal vision (B), and augmented vision (C) transfer test conditions during the acquisition and retention phase (Experiment 2).

Retention data were subjected to a $2 \times 3 \times 2$ (Group $\times$ Transfer Test $\times$ Retention Level) ANOVA with repeated measures on the last two variables. The retention level consisted of the final test administered at the end of the third practice day and two days later. The enhanced FB group maintained its superiority over the reduced FB group across retention tests and this effect was significant, $F(1,16) = 5.71$, $p < 0.05$ (MSE = 95.53). Performance deteriorated somewhat across two days of no practice, but this effect was not strong enough to reach significance, $F(1,16) = 2.96$, $p > 0.05$ (MSE = 23.26). The differences among the three transfer test conditions were no longer significant, $F(2,32) = 1.19$, $p > 0.05$ (MSE = 41.93). None of the interaction effects were significant ($p > 0.05$).

3.2.2. Relative phase variability

Analysis of the variability scores obtained in the various transfer test conditions across acquisition resulted in the identification of significant differences between both groups, with the reduced FB group showing higher variability scores than the enhanced FB group, $F(1,16) = 14.78$, $p < 0.01$

(MSE = 290.57) (see Fig. 7). No significant differences among the three transfer test conditions were found, $F(2,32) = 2.28$, $p > 0.05$ (MSE = 98.86). The main effect for day was significant, $F(2,32) = 18.5$, $p < 0.01$ (MSE = 209.37), whereas the block effect was not, $F(2,32) < 1$. Two, two-factor interactions were significant: the Transfer Test Condition × Day and the Transfer Test Condition × Block interaction, $F(4,64) = 2.55$, $p < 0.05$ (MSE = 40.82), and $F(4,64) = 2.53$, $p < 0.05$ (MSE = 44.86), respectively. The Transfer Test Condition × Day × Block interaction was significant, as well as the highest order interaction including all the four variables, $F(8,128) = 6.42$, $p < 0.01$ (MSE = 34.04), and $F(8,128) = 3.02$, $p < 0.01$, respectively. Because these effects are beyond the scope of our interest, they are not discussed further.

The analysis of retention performance resulted in the identification of a significant group effect, $F(1,16) = 4.99$, $p < 0.05$ (MSE = 71.11). The enhanced FB group was more consistent in relative phase than the reduced FB group. No significant deterioration across retention intervals was found, $F(1,16) < 1$. Moreover, no significant differences in variability were found among the three transfer test conditions, $F(2,32) < 1$. None of the interaction effects were significant ($p > 0.05$).

3.3. Discussion

The findings of the present experiment supported the superiority of the enhanced FB group over the reduced FB group across all transfer test conditions. Sampling error, which might have influenced the results in Experiment 1, could be excluded to explain these group effects since they were more balanced at the start of practice than in Experiment 1. Relative phase accuracy and consistency differed between both groups during acquisition and retention. The enhanced FB group's superiority was predominantly evident under enhanced vision transfer test conditions whereas the differences under normal vision and reduced feedback conditions gradually diminished across practice. The effect for transfer test condition no longer reached significance at retention, suggesting that the subjects were largely successful in transferring the acquired skill level to the three different feedback conditions.

A question that remains, however, is whether the successful transfer performance of the groups, in particular the enhanced FB group, was a result of regular experience with the transfer test conditions during practice. Indeed, these transfer test conditions were administered three times per practice day, allowing subjects to attain proficiency in transferring to alternative performance conditions. Studies, using both verbal and motor tasks, have shown that repeated test trials are themselves quite beneficial to learning (e.g., see Hagman, 1983; Schmidt and Bjork, 1992). This possibility for test-trial effects provided the incentive for a third experiment.

4. Experiment 3

The purpose of Experiment 3 was to determine whether the successful transfer performance of the enhanced FB group to the three criterion tests was a result of regular experience with these tests during practice (test-trial effects), or whether it was a consequence of a general sensory-motor representation that was built up with practice. Therefore, the present experiment used two groups, both of which received augmented feedback of their relative motions in real-time during acquisition. The groups differed from each other in the amount of experience received with the transfer test conditions while practicing the 90° out-of-phase task. A possibility is that the previously observed successful transfer performance was mediated by the multiple transfer tests (9 in total) to which subjects had been subjected during practice (in Experiments 1 and 2). The decision to concentrate on the enhanced FB group was motivated by the fact that their transfer performance was found to be most successful. Briefly, two enhanced feedback groups were used in the present experiment, one of which was the same as in Experiments 1 and 2 (with 9 transfer test occasions) while the other group was subjected to the transfer tests only after practice was completed, and never during practice.

4.1. Method

4.1.1. Subjects

The subjects were 20, right-handed, 18–19-year-old students enrolled at the Katholieke Universiteit Leuven. None had previous experience with the task. They were randomly assigned to the two experimental groups ($n = 10$). Each group consisted of eight male and two female subjects.

4.1.2. Apparatus and task

The experimental setup as well as the general task requirements were similar to the previous experiments.

4.1.3. Procedure

Subjects practiced the 90° out-of-phase task across three days within a two week period, with fifty, 15 s trials completed on each day. There were two experimental groups: a transfer and a no-transfer test group. Both groups received augmented information about their relative motions in real-time during each practice trial. In addition, following every fifth trial, the relative motion plot of the last trial performed in the set was shown on a computer terminal, superimposed over the template (similar to the previous experiments). Subjects of the transfer group were subjected to the three transfer test conditions at the start, the middle, and at the end of each day of practice. These criterion test conditions were identical to the transfer tests used in Experiments 1 and 2. Subjects in the no-transfer group were not allowed any experience with the transfer test trials during the acquisition phase. Instead, these trials were replaced by three regular practice trials. Thus, the total number of trials performed across the three practice days was equated between groups.

Subjects in both groups performed the 90° task under three transfer test conditions (reduced feedback, normal and enhanced vision) during an immediate and a delayed retention test, held 5 min and two days following the end of practice.

4.2. Results

4.2.1. Relative phase accuracy

The retention data were analyzed using a $2 \times 2 \times 3$ (Group $\times$ Retention Level $\times$ Transfer Test) ANOVA with repeated measures on the last two factors. Despite the differences in the amount of experience with each of the three transfer tests during the acquisition phase, the group effect was not significant, $F(1,18) < 1$. Means for the transfer and no-transfer test group were 15.94 and 15.48, respectively. Absolute error in relative phase increased from the immediate ($M = 14.52°$) to the delayed retention interval ($M = 16.9°$), but this effect was not significant, $F(1,18) = 2.76, p > 0.05$ (MSE = 61.87). Performance under enhanced vision transfer test conditions was more successful than under the remaining two conditions which did not differ much from each other, and this resulted in a significant effect for transfer test condition $F(2,36) = 6.07, p < 0.01$ (MSE = 54.85). The means for the reduced feedback, normal vision, and enhanced vision conditions were 17.66°, 17.07°, and 12.39°, respectively. A posteriori tests revealed that performance during enhanced vision transfer test conditions was superior to the reduced feedback and normal vision conditions ($p < 0.01$) which did not differ from each other ($p > 0.05$). None of the interaction effects reached the conventional levels of significance ($p > 0.05$).

4.2.2. Relative phase variability

Similar to the observations for relative phase accuracy, the variability scores did not differ significantly between groups, $F(1,18) = 1.78$, $p > 0.05$ ($MSE = 62.95$). Mean scores for the transfer test and no-transfer test group were 12.33° and 10.3°, respectively. The effect for retention levels was not significant either, $F(1,18) < 1$. Values for the immediate and the delayed retention test were 10.94° and 11.59°, respectively. The lowest variability scores were obtained in the enhanced vision condition ($M = 9.44°$), followed by the reduced feedback ($M = 11.85°$) and normal vision transfer test conditions ($M = 12.5°$). These differences among the transfer test conditions were significant, $F(2,36) = 4.55$, $p < 0.05$ ($MSE = 22.84$). Pairwise comparisons revealed that only the difference between the enhanced vision and normal vision condition reached significance ($p < 0.05$). None of the interaction effects reached significance ($p > 0.05$).

4.3. Discussion

The present experiment provided convincing evidence that the successful transfer capability of the enhanced FB group did not result from regular exposure to the transfer test conditions during practice. No significant differences in relative phase accuracy and consistency were observed between the group that was regularly subjected to the transfer tests during learning and the group that was not. Accordingly, no evidence for test trial effects could be found. Instead, performance at retention and transfer was a function of the amount of available information feedback during movement execution. The skill level, determined two days following the end of practice, was not significantly different from that established immediately after practice, suggesting that the relative phase characteristics were well retained.

5. General discussion

5.1. Learning coordinative skills: Coping with pre-existing preferred coordination modes

When dealing with the generation of new movement forms, a primary question concerns the background of available or pre-existing motor patterns from which these new patterns emerge. In this respect, experimental studies on interlimb coordination have drawn attention to the existence of preferred coordination modes that play a dominant (often limiting) role in the learning of new coordination patterns. More specifically, the in-phase and anti-phase coordination modes have been characterized as intrinsically stable patterns that normally belong to the existing motor repertoire of the human performer. With respect to upper-limb coordination, the in-phase mode refers to the simultaneous activation of homologous muscles and the anti-phase mode (180° relative phase) to the simultaneous activation of nonhomologous muscle groups. Attempts to produce alternative modes of coordination are often accompanied with a tendency to fall back into these modes, resulting in performance instabilities. In addition, compared to the anti-phase pattern, the in-phase pattern has been characterized as the most stable mode during bimanual finger coordination (Kelso et al., 1986, 1988). This observation was extended to forearm coordination in Experiment 1: The in-phase pattern was produced with higher degrees of accuracy and stability than the anti-phase pattern. However, more important for improving our understanding of motor learning is to focus on the effects of these preferred patterns on the acquisition of new skills.

In the present study, subjects acquired a 90° out-of-phase task, located in between the previously discussed in- and anti-phase 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 of subjects, they initially experienced difficulties in performing the task. Previous experiments on the acquisition of a 90° out-of-phase task revealed that performance was constrained by the in- and anti-phase modes at the start of practice (Lee et al., 1995; Schöner et al., 1992; Zanone and Kelso, 1992). This also became evident in the present experiments (even though these data are not reported here in detail) and gave rise to deviations from the intended relative phase of 90° during the first practice day (for an extensive discussion of individual data patterns, see Lee et al., 1995). As practice continued, subjects became gradually more successful in defying these preferred coordination modes, and, in attaining stability at the new mode. In contrast to the earlier observations made by Zanone and Kelso (1992) on bimanual finger coordination, learning the 90° out-of-phase task was not accompanied by a significant destabilization of the in-phase or anti-phase modes. Two related studies also failed to support Zanone and Kelso's observations (Lee et al., 1995, in press). Substantial differences in experimental methodology may account for this discrepancy, e.g., task differences, the number of patterns scanned, and the continuous or discrete nature of the scanning technique. Furthermore, Lee et al. (in press) have suggested that perceptual carry-over effects may have confounded Zanone's and Kelso's results because the scanning of the in- and anti-phase modes was embedded in other modes. In view of the aforementioned data, it appears that conclusive evidence for the destabilization of intrinsic patterns while learning new ones is currently lacking. We contend that pre-existing preferred coordination modes will not easily be disrupted when building a new coordination mode through practice.

Traditional theories of motor learning have largely left unanswered the question of how new movement patterns emerge and how they are constrained by the repertoire of pre-existing patterns (Adams, 1971; Schmidt, 1975). This is, however, an important issue to address if we wish to improve our understanding of motor learning. The present study has provided only one example of how pre-existing patterns can affect the learning of a new task, thereby supporting the earlier studies inspired by the dynamic pattern theory (Schöner et al., 1992; Zanone and Kelso, 1992). Obviously, there exist numerous other synergies or preestablished patterns that can affect performance (Walter and Swinnen, 1994). Actions do not occur 'de novo'. Instead, they are built up against the background of pre-existing modes. Converging evidence for this viewpoint has also been provided in previous work on the acquisition of a discrete bimanual skill in which subjects were required to produce a flexion movement in the nondominant limb together with a flexion–extension–flexion movement in the dominant limb. A strong tendency was initially evident to synchronize the patterns of motor output, i.e., to move in-phase. As practice continued, subjects learned to gradually overcome the synchronization tendency, allowing differentiated patterns of activity to emerge (Swinnen et al., 1990a, b, 1991a, b, 1993; Walter and Swinnen, 1992, 1994).

5.2. *The role of augmented information feedback*

A central issue in motor control and learning concerns the feedback sources that are important for performing and learning a skill. Given the great diversity of motor tasks performed in everyday life and in recreational and sports settings, it is rather unlikely that general answers can be provided to this question. In the present set of experiments, the role of information feedback for interlimb coordination was investigated by manipulating the amount of visual information provided during practice: (a) no visual information (blindfolded performance), (b) normal vision of the moving limbs, and (c) augmented concurrent visual information about the relative motions produced.

The use of concurrent information feedback needs some additional clarification. First, provided in real-time during movement production, this information facilitated on-line control through establishment of a direct link between action and perception. Secondly, even though this form of feedback was of low dimensionality (a moving dot on the screen representing two limb motions), it provided detailed information about the spatiotemporal relation between the limbs (e.g., relative phase). The use of relative motion information has been recommended when new spatiotemporal movement forms or topologies are to be acquired (Newell et al., 1985). The theoretical rationale is that the information provided during learning should match the degrees of freedom to be controlled by the subject (Fowler and Turvey, 1978). Within the current framework, degrees of freedom refers to the number of joints moved simultaneously.

Experiments 1 and 2 demonstrated that concurrent relative motion information was beneficial to acquiring the coordination pattern in comparison to normal vision conditions and practice conditions with reduced feedback, as exemplified by the overall superiority of the enhanced feedback group. More importantly, the acquired skill level transferred successfully to other transfer test conditions (with which this group was not familiar), relative to the other groups. These observations suggest that the augmented feedback did not make subjects vulnerable during transfer conditions without the augmented feedback. This is rather striking in view of recent reports that an excess of information feedback may (under certain conditions) be detrimental to retention and transfer performance because the learner becomes too dependent on this information for successful performance (Salmoni et al., 1984; Schmidt, 1991; Swinnen, 1996; Swinnen et al., 1990a; Winstein and Schmidt, 1990). This has particularly been supported in experiments studying the effects of concurrent information feedback sources (Annett, 1969; Lintern, 1991; Vander Linden et al., 1993). For that reason, severe performance detriments were expected in the enhanced feedback group during the transfer conditions because this information evidently *guided* subjects towards correct performance. First, the augmented information was available in real-time such that the evolving trace on the computer screen could be used to correct the ongoing movements. Second, the concurrent information was provided during each trial and for the total duration of the trial. In spite of the excessive availability of this information, subjects were capable of producing the movement successfully in the absence of this information. Apparently, the availability of extrinsic information feedback during acquisition did not prevent the enhanced feedback group to pay attention to the intrinsic information sources. Instead, their equal or even superior performance under reduced feedback and normal vision transfer conditions may suggest that they used the extrinsic concurrent information feedback to update and refine the processing of the intrinsic information feedback sources, allowing a more successful visual and/or kinesthetic guidance of movement as practice continued. These findings lead us to believe that augmented feedback is not always associated with performance deterioration under information withdrawal conditions. Task features such as the amount and type of available intrinsic information feedback and their discrete versus continuous nature are potentially important factors to be considered when assessing the merits and potential pitfalls of augmented information feedback.

5.3. Specificity versus generality of learning: Transfer across different information feedback conditions

For a long time, motor behavior scientists have maintained an interest in the design of the practice environment in relation to criterion task performance. The question has been asked whether the performance conditions in the acquisition phase should match with those of the criterion conditions in which the learning will ultimately be applied (Schmidt, 1988). Earlier discussions on the specificity hypothesis were based on Henry's viewpoint (Henry, 1968) that motor abilities are specific to a particular task. As a consequence, changing the task would change the particular collection of abilities underlying performance in order to meet the new task demands. This argued for matching the practice and transfer test conditions. Recently, the specificity of learning hypothesis has (re)appeared within a feedback perspective. More specifically, questions have been raised about the consequences of withdrawing extrinsic or intrinsic information feedback during transfer test conditions following practice with this form of feedback available (Proteau et al., 1987; Schmidt et al., 1990).

A major drawback of the specificity of learning hypothesis is that a general theoretical framework is currently lacking which clearly specifies the conditions under which specificity effects should be expected. Therefore, some conceptual clarification is required. Specificity and transfer of learning are two sides of the same coin. Specificity indirectly refers to lack of transfer. When focusing on transfer capabilities, a distinction can be made between intra-task and inter-task transfer. Intra-task transfer can be assessed when a task is performed under modified environmental or information feedback conditions or when a new parameter specification is applied. Inter-task transfer refers to the effect of learning one task on the performance or learning of another task. Even though the dividing line between intra- and inter-task transfer may sometimes be obscure, the current framework is helpful in classifying research that deals with specificity versus generality of learning.

In the present study, the specificity of learning hypothesis was operationalized in terms of the availability of intrinsic and extrinsic information feedback sources and thus refers to intra-task transfer. The prediction that transfer performance would be optimized by closely matching it with the practice conditions (the acquisition phase) was not supported. Instead, the main effects for both group and transfer test conditions were significant, suggesting that the amount of available information feedback was the primary determinant of success in producing the required pattern of interlimb coordination during acquisition and transfer. For example, the reduced feedback group was surpassed by the enhanced feedback group in the transfer test conditions with reduced feedback. On the other hand, the enhanced feedback group was most successful in producing the required relative phase pattern, irrespective of the transfer conditions to which it was subjected. This is not to deny that performance tended to decline when all groups transferred from the enhanced to reduced feedback transfer test conditions. However, the reason for this decrement is to be sought in the reduction of the amount of information available for steering performance, and is not to be conceived as a consequence of over-reliance on extrinsic information feedback when it was available. In other words, performance was primarily dependent upon the information feedback available at the time of testing: the more information was accessible to the learner, the more successful the coordination pattern (applicable to all groups, regardless of the practice conditions). In addition, Experiment 3 demonstrated that the successful transfer performance of the enhanced feedback group was not a result of test-trial effects. Subjects learned an action plan that generalized to various transfer test conditions. As such, the findings support theoretical positions that argue for general, rather abstract movement representations or programs (see Schmidt, 1975).

The use of various transfer test conditions may provide indirect insights into the nature of the *intrinsic* information that is used by the performer to produce the skill, i.e., the role of kinesthetic and visual information. In this respect, Experiment 1 revealed that the reduced and the normal feedback groups did not differ significantly from each other. In addition, performance did not differ under reduced feedback and normal vision transfer test conditions. This possibly suggests that kinesthetic information was a primary source of information feedback for performing this bimanual coordination task and that normal vision contributed only to a small extent, except at the start of practice. Indeed, transfer test performance of the reduced and the normal feedback groups of Experiment 1 appeared to diverge during the initial stage of practice (three transfer tests of day 1, not shown in Fig. 3). This lends indirect support to earlier hypotheses that have underscored the importance of visual information at the beginning of practice (Fitts and Posner, 1967; Fleishman and Hempel, 1956; Fleishman and Rich, 1963). On the other hand, *augmented extrinsic* visual information feedback resulted in a significant improvement of the coordination pattern, relative to the intrinsic information feedback groups. Furthermore, the enhanced feedback group exceeded the reduced feedback group under reduced feedback transfer test conditions (Experiments 1 and 2). This may imply that the extra concurrent visual information feedback was used to refine the kinesthetic monitoring of movement through provision of the coordinative relation between the limbs in a direct manner.

The present observations deviate from those of Proteau and collaborators who found that performance was most successful when the transfer test conditions complied with the conditions that prevailed during acquisition (Proteau et al., 1987). In their experiments, changes in the performance conditions – irrespective of whether information was added or withdrawn – resulted in a performance deterioration. In contrast, the present experiments demonstrated that performance during acquisition and transfer was a function of the amount of information available at the time of testing. In addition, while Proteau and collaborators demonstrated larger degrees of performance deterioration during transfer to new conditions with greater amounts of practice, our studies showed that transfer performance improved as subjects became more skillful.

The potential reasons for this discrepancy between our results and those of Proteau and collaborators are many but are most likely to be sought in the different tasks that were investigated. Proteau and collaborators investigated the precise parameterization of a visual aiming task where the goal was to minimize target error. We made use of a bimanual task in which a new coordination pattern was to be acquired whereby the spatiotemporal consistency of the component limb motions was subordinate to the coordination between the limbs. In addition to parameterization, this required the development of a new movement form. Moreover, the role of kinesthetic afferences was probably of greater importance in the bimanual coordination skill. There is mounting evidence in the literature that proprioception is a crucial source of information for the production of patterns of inter-limb coordination

(Baldissera et al., 1991, 1994; Buchanan and Kelso, 1993; Kelso et al., 1991; Kots et al., 1971; Preilowski, 1975; Swinnen et al., 1995). Additional experimental support has been provided in studies demonstrating inter-limb (Teasdale et al., 1994) and intra-limb (inter-segmental) (Ghez et al., 1995; Sainburg et al., 1993) coordination deficits in de-afferented patients, deprived of normal kinesthetic sensations.

Even though the present findings do not support the specificity of learning hypothesis, neither do they totally invalidate it. What is to be learned from the present series of experiments is that the type of information feedback required for performance is task dependent and so, possibly, will be our laws of motor skill learning. The current hypotheses of motor learning are clearly in need of further validation. With a shift from the study of fine tuning to the acquisition of new forms of movement (in particular inter-segmental and inter-limb coordination), a new round of investigations is probably required to verify the current principles of motor learning, even the ones we felt most comfortable with until recently.

A final issue that we wish to address concerns the variables that are used by the CNS to control patterns of interlimb coordination. The present studies can only provide indirect hints toward resolving this question. Given the importance of feedback variables that directly confer the coordinative relation between the limbs, it appears that the relative motion information is a primary variable that is picked up by the perceptual system and that enters the production of coordinated movement. This concurrent relative motion feedback along with the relative phasing pattern it conveys, may be a very important learning aid in the study of complex skill acquisition, allowing the experimenter to turn abstract learning goals into meaningful 'graspable' coordination patterns for the learner.

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