Acquiring Bimanual Skills: Contrasting Forms of Information Feedback for Interlimb Decoupling

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The present experiments addressed the learner’s capability to perform different upper-limb actions simultaneously with the help of various sources of information feedback. An elbow flexion movement was made in the left limb together with a flexion-extension-flexion movement in the right limb. Interlimb interactions were assessed at the structural as well as the metrical level of movement specification during acquisition and retention. Despite a strong initial tendency for the limbs to be synchronized, findings revealed that Ss became gradually more successful in interlimb decoupling as a result of practice with augmented feedback. However, detailed knowledge of movement kinematics was no more effective than global outcome information for interlimb decoupling, indicating that knowledge of results may have more potential for acquiring multiple degree-of-freedom tasks than previously believed. Finally, the data support the general notion that learning new coordination tasks involves the suppression of preexisting preferred coordination tendencies, which is often a prerequisite for building new coordination modes.

We are often faced with severe performance limitations when trying to do more than one thing at a time, and this becomes evident through various patterns of interference. Think, for example, about patting the head while rubbing the stomach, a task that most of us have attempted at one time. A natural tendency emerges to perform the same movements with both limbs. This simple example points rather dramatically to limitations or constraints\(^1\) that are inherent in the motor control system as a result of various interactions. In the past decade, these interactions have received considerable attention in the motor behavior literature, and they have been described under a variety of experimental conditions, in particular those circumstances in which subjects are instructed to perform different limb movements simultaneously (Franz. Zelaznik, & McCabe, 1991; Kelso, Southard, & Goodman, 1979; Marteniuk, MacKenzie, & Baba, 1984; Sherwood, 1990; Swinnen, Walter, Beirinckx, & Meugens, 1991; Swinnen, Walter, & Shapiro, 1988). Limitations in doing more than one thing at a time have been a central focus of study in experimental psychology and related disciplines that have predominantly sought explanations in terms of limitations in the division of attention. Some authors have suggested a neurobehavioral account for the observed patterns of interlimb interference. Neural accounts underscore the high degree of interconnectedness that characterizes the central nervous system. Activity set up in one cerebral locus is therefore likely to spread to other control centers, also referred to as neural crosstalk (Kinsbourne & Hicks, 1978; Marteniuk et al., 1984; Swinnen, Young, Walter, & Serrien, 1991). There is ample evidence that patterns of activity performed in one limb flow over into similar patterns in the contralateral limb (Cernacek, 1961; Hopf, Schlegel, & Lowitzsch, 1974; Swinnen, Young, Walter, & Serrien, 1991). The crosstalk hypothesis is congruent with other perspectives that have underscored the importance of “outcome conflict” as a basic source of interference in dual tasks (Navon & Miller, 1987). It therefore has the potential to account for multiple-task interference across a variety of task dimensions and sensory modalities.

Even though preferred modes of movement coordination exist to which the performer is naturally drawn when trying to do different things at the same time, the human motor system is endowed with plasticity and flexibility to overcome these intrinsic coordination tendencies. This basic observation was the major source of inspiration for the present series of experiments. In particular, the goals were to gain information (a) about the way learners cope with preexisting coordination tendencies that give rise to persistent errors in...

\(^1\) The concept of constraints is used in a generic sense here and refers to limitations inherent in the motor control system that bias attempts to produce new coordination patterns, often in a predictable manner.
performance; (b) about the extent to which these tendencies can be overcome with practice; and (c) about the way the learning environment needs to be organized to accomplish these goals, in particular the role of various sources of augmented information feedback in acquiring new patterns of interlimb coordination.

In the present experiments, subjects learned to perform a horizontal elbow flexion movement in the nondominant limb together with an elbow flexion-extension-flexion movement in the dominant limb. We have investigated this particular task combination intensively in the past several years to address various motor learning and control issues (Swinnen & Walter, 1988; Swinnen, Walter, Pauwels, Meugens, & Beirinckx, 1990; Swinnen et al., 1988; Walter & Swinnen, 1990a, 1990b). Whereas each of the tasks is easy to perform unimanually, they are difficult to perform concurrently.

Because there exists a natural tendency to couple or synchronize the upper limbs during simultaneous movements, we denote the overcoming or abandoning of this initial tendency as decoupling or dissociation. For the present purposes, interlimb decoupling implies that each limb produces the required but divergent spatiotemporal trajectories simultaneously, thereby overcoming the synchronization tendency. Decoupling does not necessarily imply lack of coordination or fully independent control of the two arms. It is conceivable that the central nervous system solves this particular problem by generating an overall control structure in which both movement patterns are embedded.

In these experiments, a successful bimanual trial required the production of two distinct spatiotemporal trajectories (structural decoupling) as well as a differentiation of each limb’s intensity specifications (metrical decoupling). Indeed, producing the flexion-extension-flexion movement required much more force than did the flexion movement. The distinction between metrical and structural decoupling or dissociation (Swinnen, Walter, Beirinckx, & Meugens, 1991) builds on the distinction between two levels of movement specification (Kelso & Tuller, 1984; Schmidt, 1988; Turvey, Shaw, & Mace, 1978). Structural or invariant features relate to the qualitative or form aspects of movement, whereas metrical features refer to quantitative changes that can be imposed on movement while leaving its underlying structure basically intact. These concepts can be illustrated by using the example presented in the introduction. When subjects are not able to perform the separate actions of patting the head and rubbing the stomach simultaneously, we contend that subjects fail to dissociate the basic movement structures or patterns of action. When patting harder or faster would result in more intensive rubbing, a failure to dissociate the metrical specifications of both limb actions is evident. In other words, metrical decoupling points to the capability to assign different intensity specifications to each limb and therefore it is distinct from structural decoupling.

Experiment 1

Experiment 1 focused on the role of kinematic (displacement) information feedback in structural decoupling. To aid subjects in accomplishing the task goal, they were shown the left and right arm displacement patterns as a function of time.

Method

Subjects

Subjects were 24 right-handed, 18-year-old female students from the Catholic University of Louvain.

Apparatus and Task

The apparatus consisted of two horizontal metal levers (43 cm long) attached to virtually frictionless vertical axes. An adjustable handle and a 350-g weight were located at the distal end of each lever. Shaft encoders (4,096 bits per revolution) were mounted at the base of the axes to determine elbow displacement, sampled at 500 Hz. The subject was seated behind the apparatus such that the front of the body was aligned between the lever axes. When the arms rested upon the levers, they were nearly extended in the starting position. The end position was located in front of the subjects (85° from the start position). The elbow was positioned just above the axis of rotation of the lever.

Subjects were instructed to make a horizontal elbow flexion in the nondominant arm (hereinafter referred to as the unidirectional movement) and an elbow flexion-extension-flexion movement in the dominant arm (hereinafter referred to as the reversal movement) (Figure 1). The unidirectional movement covered a distance of 85° whereas the reversal movement consisted of three segments: Subjects flexed the elbow across an angular distance of 57°, then reversed direction and extended the elbow 33°, and finally flexed the elbow again across a distance of 61° (total = 151°). Both reversals were made at indicated targets (width = 5°). Subjects were instructed to initiate the movement shortly after the “go” signal, but reaction times were neither stressed nor measured.

As both movements were to be made in 600 ms, the reversal movement constituted a more forceful and spatially more complex action, requiring a quick alternation of biceps and triceps muscle bursts (Swinnen, Young, Walter, & Serrien, 1991). A reversal was also made at both movements’ endpoints to determine the end of movement unambiguously (see arrows in Figure 1), after which subjects returned to the start position. They were informed that the movement back to the starting position was not part of the overall task goal. The final peak displacement defined the end of movement.

Procedure

Two acquisition phases were administered on consecutive days, each consisting of 50 trials. Movement time (MT = 600 ms) and endpoint amplitude (AMP) were the same for both limbs (85°). Subjects were instructed to “perform both movements simultaneously, that is, initiate and terminate them at the same time.” In addition, they were told that a smooth elbow flexion was to be made in the nondominant limb together with the double reversal movement in the dominant limb. This was exemplified through a slow demonstration of the component movements by the experimenter. The information given to the subjects after completion of the task provided both overall movement timing and kinematic information (depending on the experimental condition). All subjects were informed about the deviations of each limb from the target MT of 600 ms after every fourth trial. Timing of the movement was initiated as soon as the subject left the starting position and stopped when
peak displacement was reached at the end position for each limb (Figure 1).

The kinematic information was provided to only half of the subjects, resulting in two experimental conditions: The displacement feedback (displacement FB) group was informed about the degree of coupling between the limbs through displacement information feedback. Following every fourth trial, the computer terminal was turned to the subject and the angular displacement patterns of both limbs were superimposed against the same time scale. The left limb movement pattern was shown in yellow and the right limb pattern in blue. The experimenter explained the patterns of interference, predominantly observed in the left limb, which usually became evident as an actual reversal, a short hesitation, or a small wavy section in the left displacement pattern. The no-FB group was not provided this augmented information feedback.

Upon entering the testing room, the subject read preliminary information concerning the goal of the experiment and the details of the experimental manipulations. It was stressed that independent limb movements were to be performed, both in the target time of 600 ms. Both instructions were repeated after the 10th and 30th trial of each day of acquisition. A picture of an ideal bimanual trial was displayed in front of the subjects at all times, with both patterns presented against the same time scale but in their respective colors.

\footnote{As subjects of both groups received movement time knowledge of results, the term no-FB only refers to the absence of kinematic information feedback or information about the degree of coupling between the limbs.}
Retention tests, consisting of 10 trials each, were administered 10 min and 5 months after acquisition. Subjects performed both limb movements together in the absence of any timing or kinematic information feedback. They performed 3 warm-up trials prior to the retention trials.

Data Analysis

The only dependent variable used referred to structural decoupling of the limbs. Acceleration was computed through double differentiation of the displacement data. Subsequently, on each trial, data points were taken from both acceleration traces every 10 ms as long as both limbs were being moved simultaneously (i.e., from the time of the last initiated movement until the time that the first movement was completed). These data points were then correlated to determine the degree of functional coupling between the limbs (Swinnen, Walter, Beirinckx, & Meugens, 1991). Correlations were calculated per trial, transformed into Fisher's $Z'$ scores, and then averaged across 10-trial blocks. These correlation scores approach zero when the movements are made independently of each other (Swinnen, Walter, Serrien, & Vandendriessche, 1992). No onset synchronization and normalization was applied because it was intended to determine interactions between the limbs during actual motion. It was decided to correlate the angular acceleration traces because it is at the higher time derivatives that interlimb interactions become most clearly evident. Furthermore, acceleration is proportional to torque in the present task setup, which we consider to be an important variable under direct or indirect control of the central nervous system. Cross-correlations were used as a measure of interlimb coupling and decoupling, and not coordination perse. Moreover, although the appropriateness of cross-correlations has been established for the present task in previous studies (Swinnen, Walter, Beirinckx, & Meugens, 1991; Swinnen et al., 1992), we do not claim that this technique is suitable for any task combination.

The acquisition data were analyzed by means of a $2 \times 2 \times 5$ (Group $\times$ Acquisition Phase $\times$ Block) analysis of variance (ANOVA) following transformation into Fisher's $Z'$ scores. For the retention data, a $2 \times 2$ (Group $\times$ Retention Level) ANOVA was conducted. Retention levels consisted of the immediate (10 min) and delayed (5 months) retention test.

Results

Acquisition

Figure 2 shows the cross-correlations of both groups across acquisition and retention. It is apparent that cross-correlations diverged between the groups as practice continued. In the no-FB group, cross-correlations remained at a high level during both days of acquisition, although they

3 Some limitations are inherent in the use of the cross-correlation technique. However, previous research has indicated that high cross-correlations are indeed indicative of interlimb coupling whereas low correlations stand for the correct decoupled pattern. Furthermore, the majority of subjects generally comply with the imposed requirement to initiate and terminate the limb movements simultaneously. Of those subjects who do not, the left limb movement is often found to be fully synchronized with the first right elbow flexion movement after which it is terminated too early. This results in a high cross-correlation that correctly points to full interlimb synchronization. Normalization of such acceleration traces would result in a low cross-correlation, leading to wrong interpretations. Therefore, normalization is argued not to be justified under the present circumstances. The generalizability of this technique to other tasks that involve simultaneous limb actions remains to be determined for each particular application.
were slightly lower during the 2nd day. Correlations of the kinematic-FB group were generally lower than those of the no-FB group, resulting in a significant group effect, $F(1, 22) = 7.49, p < .05, M_{SE} = 1.53$. The differences between groups increased as practice continued. Correlations were generally lower during the 2nd day of practice than the 1st and this effect was also significant, $F(1, 22) = 8.53, p < .01, M_{SE} = 0.34$. The block effect was not significant ($F < 1$), but the Group × Block interaction was, $F(4, 88) = 2.94, p < .05$. This resulted from the differential changes in cross-correlations between the two groups across trial blocks. The remaining interactions were not significant ($ps > .05$).

**Retention**

In comparison to the end of acquisition, cross-correlations were slightly higher for both groups at immediate retention. However, the differences in cross-correlations between groups remained significant, $F(1, 22) = 5.21, p < .05, M_{SE} = 0.50$. The effect for retention level did not reach significance ($F < 1$), nor did the Group × Retention Level interaction, $F(1, 22) = 1.97, p > .05$.

**Discussion**

Experiment 1 showed that the coupling between the limbs was fairly strong at the start of practice, even though the spatiotemporal characteristics of the movements were clearly different. This can be inferred from the high initial cross-correlations between the angular acceleration patterns of both limb movements for both groups. The group not receiving displacement information feedback showed fairly high correlations throughout practice. In contrast, the provision of displacement feedback information led to significantly lower degrees of interlimb coupling. The differences between groups became more apparent as practice continued and persisted across 5 months of no practice. This finding suggests that the acquired coordination pattern was relatively resistant to forgetting. In sum, a specific type of information feedback resulted in a specific type of learning, namely structural decoupling. The question remains whether other sources of information feedback can be used to enhance structural decoupling, metrical decoupling, or both. To examine the unique contribution of displacement feedback, it was compared with general outcome information about the degree of success in accomplishing the goal. The former differs from the latter in that it provides more detail about the errors made in performance and, for that reason, holds more direct suggestions for improvement.

**Experiment 2**

The primary objective of the present experiment was to replicate and extend the findings of Experiment 1. Here, the effect of kinematic information feedback was compared with general outcome information about success in goal achievement. The former type of feedback refers to information about the pattern of movement itself, also termed knowledge of performance (KP; Gentile, 1972). The latter type of feedback is termed knowledge of results (KR), defined as verbal terminal extrinsic feedback (Schmidt, 1988). Numerous authors have underscored the crucial importance of KR in skill acquisition (Adams, 1971; Salmoni, Schmidt, & Walter, 1984; Schmidt, 1988). However, the generalizability of this statement across a variety of task conditions has received some criticism (Fowler & Turvey, 1978; Newell, 1981, 1985; Newell & Walter, 1981). For example, Fowler and Turvey (1978) raised concerns about the efficacy of KR in tasks involving the control of more than one degree of freedom. Whereas quantitative KR conforms with one degree of constraint that would match the one degree of freedom to be controlled in many simple tasks, such information was deemed inadequate for tasks involving more degrees of freedom (such as the task used in the present experiment).

In view of these criticisms about KR, the effects of general outcome and kinematic information feedback on learning the present bimanual skill were investigated. Similar to the previous experiment, kinematic information was operationalized as displacement information feedback about both limb movements. KR was provided as a score reflecting the overall degree of success in accomplishing interlimb decoupling. Performance of both these feedback groups was compared with that of a third group not informed about interlimb coupling. A fourth group was added in which a combination of kinematic and general outcome information was presented. This choice was inspired by the idea that it makes sense to first provide learners with an overall appreciation of goal achievement after which more detailed information about the kinematics of movement is presented.

The present study also differs from Experiment 1 in that a more complete investigation of interlimb interactions was pursued at the metrical as well as the structural level. Metrical decoupling was deemed invaluable for a general test of Basmajan's (1977) hypothesis that learning involves the elimination of the superfluous and even disturbing surplus of muscular activity that is usually evident at the start of practice. Even though structural and metrical decoupling quantify the degree of interference, the information they generate is to a large extent distinct. For example, high degrees of structural decoupling do not necessarily imply high degrees of metrical coupling or vice versa. In previous studies, it has been observed that subjects with high degrees of structural coupling can largely differ from each other with respect to the nature of the intensity differentiation they accomplish (Swinnen, Walter, Beirincx, & Meugens, 1991). Whereas in some subjects very similar intensity specifications may be generated in both limbs to the extent that a double reversal becomes apparent in the left limb, other subjects are highly successful in intensity differentiation.

**Method**

**Subjects**

Subjects were 64 right-handed, 18- and 19-year-old female students from the Catholic University of Leuven. None had had previous experience with the task.
Apparatus and Task

The experimental setup was the same as that used in the previous experiment.

Procedure

Similar to Experiment 1, there were two acquisition phases, consisting of 50 trials each. Retention tests were held 10 min and 4 months later, consisting of 10 trials each. The same bimanual task was used (MT = 600 ms).

There were four experimental groups: (a) the displacement-FB group and (b) no-FB group were similar to those of Experiment 1, (c) the goal-FB group received a score ranging from 0 to 100 about the degree of structural interlimb decoupling, and (d) the displacement and goal-FB group received a combination of displacement feedback and the overall score. Augmented information about the degree of interlimb decoupling was presented after every fourth trial. The goal-directed feedback information was computed as follows: Upon completion of every fourth trial, the angular acceleration-time traces of both limb movements were generated through double-differentiation of the displacement data and subsequently cross-correlated for the time that both limbs had moved simultaneously. The resulting cross-correlation score was multiplied by 100 and reported verbally to the subject. Subjects in the goal-FB group were informed that a high score referred to strong coupling and a low score to decoupling, and they were instructed to reduce their score as close to zero as possible.

Similar to Experiment 1, all subjects were informed about the major goals of the task: to make the movement patterns independently but simultaneously and to make both movements in the target time of 600 ms. These instructions were repeated after the 10th and 30th trial on both days. All subjects received movement timing information.

Data Analysis

Structural dissociation. This was assessed by cross-correlating the acceleration patterns of the right and left limb movement, similar to Experiment 1.

Metrical dissociation. To be successful, activity in the right biceps and triceps muscles for generation of the reversal movement was much higher than the level of activity required in the corresponding muscles of the contralateral limb (Swinnen, Young, Walter, & Serrien, 1991). In view of the natural tendency to assign the same intensity specifications to both limbs when being moved simultaneously (Swinnen et al., 1992; Walter, Swinnen, & Franz, 1993), the degree of success in accomplishing these differential levels of work was determined. In searching for a variable that fulfilled the goal of assessing intensity differentiation while carrying some biophysical meaning, it was decided to determine and compare the amount of net mechanical work produced in each limb (see Swinnen, Walter, Beirinckx, & Meugens, 1991, for a rationale of this technique). Work was calculated from the time integral of the power curve. Power, defined as the rate of doing work, was generated by multiplying acceleration by velocity for each data sample (Enoka, 1988). As a consequence, the variable so obtained is proportional to work, and therefore is denoted as relative work. Subsequently, the degree of differentiation of relative work output between the limbs (metrical dissociation or decoupling) was determined through division of the total amount of work generated in the right limb by that of the left limb. The resulting ratio is to be interpreted as follows: The higher the score, the higher the degree of intensity differentiation between the limbs. Conversely, the closer the score to one, the more similar the intensity specifications are to each other. Previous research with a similar movement task revealed that optimal dissociation (i.e., when both limb movements are performed in complete isolation of each other) resulted in a score of approximately eight units (Swinnen & Walter, 1991), but this upper limit is dependent on the features of the subtasks.

When first practicing a task, beginners often produce an excessive amount of work (Fitts, 1962/1990). Skill acquisition then involves the progressive elimination of this superfluous muscle activity (Basmajian, 1977). Even though economy of effort is at the heart of many definitions of skillful performance, attempts to assess it during motor learning are rare. For that reason, the metrical decoupling ratio was considered an important addition to the measurement of structural decoupling.

Results

Structural Dissociation

Acquisition. Cross-correlations for the four groups across both days of practice are shown in Figure 3. All groups showed fairly high correlations at the start of practice, indicative of interlimb coupling. The no-FB group (who did not receive information about interlimb coupling) displayed high correlations throughout acquisition. Correlations in the remaining groups decreased across trial blocks during the 1st day of practice and stabilized during the 2nd day. The group effect was significant, \( F(3, 60) = 3.26, p < .05, M_S = 1.41 \). Tukey's posterior tests only revealed significant differences between the displacement-FB group and the no-FB group across practice (\( p < .05 \)). No significant differences were found among the three feedback groups (\( p > .05 \)).

The main effect for acquisition phase was also significant, indicative of lower cross-correlations during the 2nd day of practice in comparison to the 1st, \( F(1, 60) = 30.61, p < .01, M_S = 0.23 \). The block effect was significant as well, \( F(4, 240) = 6.52, p < .01, M_S = 0.04 \). Of the interaction effects, only the Acquisition Phase × Block interaction was significant, suggesting that the pattern of the cross-correlations across trial blocks was different between the 1st and 2nd days, \( F(4, 240) = 9.22, p < .01, M_S = 0.04 \). None of the remaining interactions were significant (\( p > .05 \)).

Retention. Cross-correlations at retention were similar to those reached at the end of acquisition for the four groups (see Figure 3, right portion). The three feedback groups performed similarly. Moreover, no apparent changes occurred from the 10-min to the 4-month retention test. The group

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4 Because of the reciprocity of positive and negative work for this task, only the total amount of positive work (when the muscle moment acts in the same direction as the angular velocity) was computed for each of the limb movements.

5 Power is the product of the net muscle moment and angular velocity. Because of the proportionality between acceleration and force under the present task conditions, the power–time profile associated with the movement was obtained by multiplication of angular velocity and acceleration, expressed in degrees per second and degrees per second squared, respectively. Accordingly, the variable so obtained in the present study is proportional to power and its time integral is proportional to work.
effect was significant, $F(3, 60) = 4.64, p < .01, MS_e = 0.28$. The effect for retention levels was not significant, $F(1, 60) = 1.42, p > .05, MS_e = 0.05$, nor was the Group $\times$ Retention Level interaction ($F < 1$). Tukey's a posteriori tests revealed that cross-correlations of the no-FB group were significantly higher than those of the remaining three feedback groups ($p < .05$), which were not different among each other ($p > .05$).

Figure 3. Cross-correlations between the angular acceleration patterns of the right and left limb movements across acquisition and retention for the four groups of Experiment 2. (FB = feedback.)

Figure 4. Metrical dissociation across acquisition and retention for the four groups of Experiment 2. (Mts = months, FB = feedback.)
Metrical Dissociation

Acquisition. As shown in Figure 4, the work dissociation ratio differed among groups. To simplify interpretation, the higher the ratio, the higher the degree of success in intensity differentiation. The highest ratio was found for the displacement and goal-FB group, followed by the displacement-FB group, the goal-FB group, and the no-FB group. The scores of both latter groups were very similar to each other. The group effect was significant, \( F(3, 60) = 3.62, p < .05, MS_\nu = 25.76 \). Tukey’s a posteriori tests indicated significant differences between the displacement and goal-FB group and the no-FB group only \( (p < .05) \). All groups showed an increase in the decoupling ratio across practice, resulting in a significant effect for acquisition phase, \( F(1, 60) = 21.60, p < .01, MS_\nu = 4.60 \). There were also significant increases in the decoupling ratio across practice blocks, \( F(4, 240) = 8.41, p < .01, MS_\nu = 0.78 \). None of the interaction effects reached significance \( (p > .05) \).

Retention. The pattern of the group differences was maintained at retention and the group effect remained significant, \( F(3, 60) = 3.82, p < .05, MS_\nu = 5.80 \). A posteriori tests indicated that the no-FB and goal-FB groups’ ratios were significantly lower than those of the displacement and goal-FB group. Differences between the goal- and displacement-FB groups and between the displacement-FB and displacement and goal-FB groups were not significant \( (p > .05) \). All groups showed a decrease in the decoupling ratio from the 10-min to the 4-month retention test, except for the goal-FB group (see Figure 4). The retention interval effect was significant, \( F(1, 60) = 5.16, p < .05, MS_\nu = 0.70 \). The Group × Retention Interval interaction was not significant, \( F(3, 60) = 1.16, p > .05 \).

Discussion

The findings of the present experiment support those of Experiment 1, showing more successful structural interlimb decoupling in the group that received kinematic information feedback compared with a group that was not informed about the degree of coupling. However, this detailed information feedback was not found more effective than general outcome information about interlimb coupling in the form of an overall score. When structural and metrical decoupling are taken together, it appears that the group receiving a combination of kinematic and goal feedback produced the best results.

The findings suggest that an overall outcome score is nearly as effective as more detailed displacement information feedback for inducing a fundamental change in the coordination pattern, suggesting that KR plays a role in acquiring multiarticular movements. Even though the detail carried by kinematic and goal feedback is clearly distinct, they produce qualitatively similar effects on motor performance. Two additional points are worth making. First, a plateau in performance may have masked any differential effects of both feedback forms even though there was room left for improvement. Second, it may be the case that displacement information feedback is not sensitive enough to convey subtle interlimb interactions to subjects and that higher time derivatives are therefore needed. Indeed, a stagnation in dissociation was evident, and it remained unclear whether this was due to lack of detail in the information feedback or to fundamental limitations in the subjects’ capability to decouple movements.

The latter issue was addressed in a third experiment in which the effect of velocity and displacement information feedback on interlimb coupling were compared. This selection of feedback variables was based on the notion that higher time derivatives better reflect emergent interactions between the limbs (Swinnen et al., 1990; Swinnen et al., 1988).

Experiment 3

To aid subjects in further dissociating the upper limbs, the present experiment focused on a manipulation of different kinematic information feedback sources. We decided to use velocity information feedback, based on the concern (a) that displacement information might not be sufficiently informative about the more subtle aspects of interlimb coupling, and (b) that acceleration information would be difficult to interpret and use for modifying action. A velocity-time trace has the advantage that it displays the instantaneous rate of change of displacement of both limb movements, clearly showing any patterns of interference that may be evident between the movement forms. Furthermore, a comparison of the heights of both limbs’ velocity peaks provides direct visual information about the degree of metrical decoupling. Performance of the displacement and velocity feedback groups was compared with that of a group that did not receive kinematic information feedback. Moreover, to assess the extent to which the kinematic information feedback groups were still removed from perfect decoupling, a fourth group was added that always performed each limb movement separately (baseline condition).

A final question addressed in the present experiment pertained to the possible emergence across practice of an overall control structure in which both limb movements would be embedded. This issue was studied through correlating the temporal occurrence of major landmarks in both limbs’ acceleration profiles.

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A separate analysis of amount of work in each limb revealed that the groups differed from each other with respect to work produced for the unidirectional movement \( (p < .05) \). Work in the no-FB group was almost twice as high as that in the other groups. Amount of work was significantly decreased across practice \( (p < .01) \), pointing to a reduction of excess of work. During retention, the group effect failed to reach significance \( (p > .05) \). The general increase in amount of work, found between the 10-min and 4-month retention test, was almost significant \( (p = .07) \). With respect to the reversal movement, no significant main or interaction effects were found during acquisition or retention \( (p > .05) \).
Method

Subjects

Subjects were 72, right-handed, 18- and 19-year-old female students from the Catholic University of Leuven. They did not have previous experience with the task.

Apparatus and Task

The experimental setup was the same as that used in the previous experiment. However, the unidirectional movement covered an amplitude of 90°. In the reversal movement, subjects flexed the elbow across an angular distance of 60°, then reversed direction and extended the elbow 35°, and finally flexed the elbow again across a distance of 65°. The amplitude from start to movement endpoint was also 90° in the reversal movement.

Procedure

The practice schedule was the same as in the previous experiments, except that no long-term retention test was administered. There were four experimental groups: (a) the displacement-FB group and (b) no-FB group were similar to those in the previous experiments; (c) the velocity-FB group received information of the velocity profiles of both limb movements as a function of time, following a short graphical presentation of the displacement patterns; and (d) the unimanual group performed both limb movements in isolation at all times and served as the baseline condition to assess the effects of interlimb interactions under each of the other feedback conditions.

Augmented information about interlimb coupling was provided after every fourth trial. The velocity-FB group received the velocity-time profiles of both limb movements in different colors and superimposed upon each other. The experimenter aided subjects in interpreting this information, mostly by drawing their attention to the shape of the velocity profile of the unidirectional movement. The latter movement’s typically bell-shaped profile was often moderately to severely disrupted and this was commonly revealed as a skewed profile with irregularities in the trace and additional zero crossings, depending on the degree of interference that was caused by the right limb movement. Subjects of the unimanual group first performed 50 trials of the flexion movement followed by 50 reversal trials during each day of acquisition. They never performed the movements simultaneously.

Subjects were informed of the major goals of the task, similar to those of the previous studies. In addition, they were encouraged more vigorously to comply with the temporal (speed) requirements of movement. An ideal displacement-time and velocity-time representation of a perfectly decoupled trial was displayed in front of all subjects at all times. A retention test was held on the 2nd day, 10 min following the last trial of acquisition, in which subjects performed 10 trials in the absence of any augmented information feedback.

Results

Structural Dissociation

The changes in the displacement-time and acceleration-time traces across practice are shown in Figure 5 for a successful subject. The initial (left column) and final (right column) 10 trials are displayed in a three-dimensional plot, with time on the x-axis, angular displacement or acceleration on the y-axis, and Trials 1 to 10 on the z-axis (pointing away from the reader). As the figure shows, structural decoupling is accomplished across practice. The unidirectional displacement pattern shows some disruption (top row, left trace) at the start of practice but it disappears as practice progresses (top row, right trace). The evolution from interlimb coupling to decoupling is even more clearly revealed in the acceleration-time traces: The additional peaks that were evident at the start of practice (second row, left trace) have essentially disappeared at retention (second row, right trace). The pattern is now clearly distinct from that of the reversal movement (fourth row, left and right traces), and this is indicative of structural decoupling. The changes in the reversal pattern are less dramatic (third and fourth rows). As far as metrical decoupling is concerned, it is evident that peak acceleration values in the unidirectional movement (second row, right trace) for this successful subject are only a fraction of those observed in the reversal movement (fourth row, right trace).

Acquisition. Cross-correlations for the four groups across both days of practice are shown in Figure 6. All three bimanual groups showed high correlations at the start of practice, indicative of strong interlimb coupling. As expected, the cross-correlations in the unimanual group (computed following onset synchronization and normalization for time) were low (<.10). The no-FB group displayed high correlations throughout acquisition. Correlations in the displacement- and velocity-FB groups decreased across trial blocks during the 1st day of practice and stabilized during the 2nd day. The group effect was significant, F(3, 68) = 31.72, p < .01, MS_e = 1.38. Tukey’s a posteriori tests revealed significant differences between the unimanual and all bimanual groups (p < .05). The no-FB group showed higher correlations than the displacement- and velocity-FB groups (p < .05), which did not differ from each other (p > .05). The main effect for acquisition phase was also significant, indicative of lower cross-correlations during the 2nd day of practice in comparison with the 1st, F(1, 68) = 11.03, p < .01, MS_e = 0.21. The block effect was significant as well, F(4, 272) = 4.93, p < .01, MS_e = 0.04. Of the interaction effects, the Group × Block interaction was significant, F(4, 272) = 4.93, p < .01, MS_e = 0.04, as well as the Group × Acquisition Phase × Block interaction, F(12, 272) = 2.38, p < .01, MS_e = 0.04. None of the remaining interaction effects were significant (p > .05). The significant two-way interaction suggests that the performance pattern across blocks differed among the groups and this pattern also differed across both days of practice.

Retention. Cross-correlations were similar to those obtained at the end of acquisition and were higher in all bimanual groups than in the unimanual group. Among the bimanual groups, the no-FB group demonstrated higher correlations than both FB groups (see Figure 6, right side). The group effect was significant, F(3, 68) = 16.75, p < .01, MS_e = 0.25. A posteriori tests revealed that the unimanual group differed from all bimanual groups (p < .05). Among the bimanual groups, both the displacement- and velocity-FB
Figure 5. Evolution of displacement-time and acceleration-time traces across practice of a successful subject from the velocity-feedback condition of Experiment 3.
groups differed from the no-FB group ($p < .05$), but they did not differ from each other ($p > .05$).

**Metrical Dissociation**

*Acquisition.* As shown in Figure 7, the work decoupling ratio differences among groups became larger as practice continued. The highest ratios were found for the unimanual group (approaching 7.5), serving as the optimal baseline for assessing perfect decoupling. The lowest ratio was found in the no-FB group. The displacement- and velocity-FB groups were intermediate. The group effect was significant, $F(3, 68) = 22.26$, $p < .01$, $MSc = 22.76$. Tukey’s a posteriori tests
indicated that the decoupling score was significantly lower in the bimanual groups than in the unimanual group ($p < .05$). The no-FB group’s ratios differed from those of the velocity-FB group ($p < .05$) but not from those of the displacement-FB group ($p > .05$); both feedback groups did not differ from each other ($p > .05$). There was a significant increase in the decoupling ratio across both days of practice, $F(1, 68) = 21.51, p < .01, M_S = 2.26$. The block effect was significant, indicative of increases in the ratios across practice blocks, $F(4, 272) = 41.8, p < .01, M_S = 0.82$. Three interaction effects were significant: the Group × Block interaction, $F(12, 272) = 19.95, p < .01$; the Acquisition Phase × Block interaction, $F(4, 12) = 3.17, p < .05$; and the Group × Acquisition Phase × Block interaction, $F(12, 272) = 3.00, p < .01$. These interactions point to differential changes across practice blocks among groups that also differed between Day 1 and 2. Specifically, the unimanual group showed large increases in the ratio across both practice days in contrast to the bimanual groups. The initial decreases in metrical decoupling found for the unimanual group at the start of the 2nd day of practice are a consequence of the order in which the unidirectional and reversal movements were practiced. During the 1st day, the unidirectional movement was practiced first, followed by the more forceful reversal movement, and this increased level of muscle activity carried over to practice of the unidirectional movement during the 2nd day.

**Retention.** The pattern of group differences observed during acquisition was also evident at retention, and the group effect remained significant, $F(3, 68) = 18.39, p < .01, M_S = 5.46$ (see Figure 7). A posteriori tests revealed significant differences only between the unimanual group and the three bimanual groups ($p < .05$).\(^7\)

**Within-Subject Correlations of the Time of Occurrence of Major Landmarks in the Right and Left Limbs’ Acceleration Profiles**

The cross correlations, described previously with respect to structural decoupling, are indicative of the degree of interlimb synchronization during movement production. They do not necessarily speak to the existence of a common control or command structure in which both limb patterns are possibly integrated. Therefore, the time of occurrence of various landmarks, extracted from both limbs’ acceleration profiles, were correlated with each other. All landmarks were computed in reference to the onset of the right limb movement. Seven landmarks, all representing objectively recognizable and distinctive features of the kinematic traces, were extracted from the right limb’s acceleration profile: the time of occurrence of two peak accelerations, two peak decelerations, and three zero crossings. These landmarks are labeled from 1 to 7 in Table 1, according to their temporal order of occurrence. A correct acceleration profile for the left limb movement was characterized by one peak acceleration and one peak deceleration. However, some subjects demonstrated additional landmarks that were due to synchronization tendencies with the right limb movement. Therefore, the largest peak acceleration and peak deceleration landmarks were selected and it was subsequently verified whether these occurred at the same relative position within a subject and across the trials investigated. Correlations were computed for each subject of the velocity-FB condition across retention trials and were transformed to Fisher’s $Z$ coefficients. Because the velocity-FB group was overall the most successful in decoupling, we decided to perform the additional analysis on this group. Correlations were conducted on the retention trials because here performance was most consistent in the absence of information feedback. Because some interlimb correlations were negative, the values were squared before averages for the total group of 18 subjects were computed.

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\(^7\) A separate analysis of the amount of work produced for generation of the unidirectional movement demonstrated that the group effect was significant during acquisition ($p < .01$). The values of the displacement- and velocity-FB groups were almost twice as high as those of the unimanual group, and those of the no-FB group were even four times as high. Amount of work decreased significantly across practice ($p < .01$), indicative of a reduction of excess work being produced. During retention, the group effect was again significant ($p < .01$). No significant effects were observed with respect to the reversal movement ($p > .05$). In sum, the amount of work generated by the kinematic feedback groups was not significantly different from that of the unimanual baseline group at retention.
The rationale underlying the interpretation of the correlations is as follows: High correlations between the limbs' landmarks may be indicative of an overall control structure common to both limbs, whereas low values suggest independent control of both limb actions. As can be observed from Table 1, the squared correlations (using Z' transform) among the right limb's landmarks were moderate to very high. This finding suggests that the temporal locations of these landmarks showed a high degree of common variance. On the contrary, correlations between the right and left limbs' landmarks were substantially lower. Inspection of the individual correlations showed a great diversity among subjects: The interlimb correlations ranged from very high to near zero across subjects; some even demonstrated negative correlations. In other subjects, high correlations were evident only between the left landmarks and the first or final landmarks of the right limb movement. Overall, these marked individual differences suggest that no uniform control strategy was evident among the 18 subjects studied.

Discussion

The major focus of the present experiment was to compare the effects of augmented displacement and velocity information feedback. The results showed a very similar performance pattern for both groups: Neither metrical nor structural decoupling was different between both kinematic feedback groups, although metrical decoupling was slightly better in the velocity-FB group, as expected. Apparently, it was difficult to further dissociate the action patterns despite the fact that complete decoupling (as implied by the unimanual group) was not yet evident. Metrical decoupling was also significantly less successful in the bimanual groups compared with the unimanual group: Both the displacement- and velocity-FB groups still produced an excess of work (although not significant) in the left arm toward the end of practice whereas work in the right arm was slightly lower than that in the unimanual group. This finding is indicative of a mutual interaction effect in which the intensity specifications for both limbs tend to converge. Nevertheless, both kinematic feedback groups were more successful in reducing excessive work in the left limb than was the group not informed about interlimb coupling.

General Discussion

Interlimb Synchronization and Dissociation

The findings of all three experiments suggest that mutual interactions were evident between the limbs, despite the detailed information feedback that was provided to the subjects. Whereas our task differed from the bimanual tasks used in previous work (Kelso et al., 1979; Marteniuk et al., 1984), there is convergent evidence for a moderate to strong tendency toward interlimb coupling. Coupling was demonstrated at both the structural and metrical level of movement specification in the present series of experiments. Structural interactions were determined by cross-correlating the acceleration patterns of the unidirectional and reversal movements, thus providing an indication of the degree of linear association between the limbs. The correlations were found to be high for all groups at the start of practice and remained high throughout practice for the groups who were not informed about interlimb coupling (no-FB group): Correlations remained at around .70 or higher during the 1st day of practice and were only slightly lower during the 2nd day for the no-FB group.

Despite the strong interlimb synchronization, practice with augmented information feedback enabled learners to defy these intrinsic coordination tendencies. All augmented feedback groups showed lower cross-correlations than the no-FB group as a function of practice. Nevertheless, the obtained values remained higher at the end of practice than would have occurred if the movements were performed separately (i.e., if they had not been completely decoupled). This was inferred from the higher correlation scores for the bimanual groups in comparison to the unimanual group (Experiment 3), which served to simulate completely independent actions (i.e., r < .10). It is also noteworthy that the pattern of coordination acquired through practice was largely resistant to forgetting across retention intervals that ranged from a few minutes to 4 or 5 months (Experiments 1 and 2). Thus, the findings suggest that the preferred interlimb coordination tendencies to which performers are initially biased or attracted are certainly not obligatory and can be overcome with practice. A major goal in learning new coordination patterns involves the suppression of these preferred coordination tendencies.

A comparison of the coefficients of determination across groups revealed that the common variance in structural specifications was up to 40% lower in the augmented feedback groups than in the no-FB groups by the end of practice. This finding reflects considerable progress in interlimb decoupling, given the additional observation that subjects gradually sped up the movement across practice. Indeed, it is important to note here that increases in movement speed or torque would normally result in stronger degrees of interlimb coupling (Swinnen et al., 1992; Walter & Swinnen, 1990a, 1990b). That the correlations did not increase but decreased across practice is therefore even more noteworthy.

Besides determining qualitative (structural) interactions, quantitative or intensity interactions were also investigated through the use of a metrical decoupling coefficient, that is, the ratio between the amount of net work produced for generation of the reversal and unidirectional movements. On the basis of the idea that conceptualizations of skillful performance often imply the reduction or elimination of excessive work (Basmajian, 1977; Fitts, 1962/1990), it was decided to

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8 Previous experiments have demonstrated that correlating the acceleration-time traces of the left and right limb movements, performed separately, approach zero (Swinnen, Walter, Beirinckx, & Meugens, 1991; Swinnen et al., 1992). In addition, it has also been demonstrated that high correlations between the right and left limb acceleration patterns during bimanual performance are associated with low correlations between the acceleration pattern of the unidirectional movement, performed singly versus together with the reversal movement. That effect is not as clearly evident for the reversal movement.
carefully investigate this matter in the present study. To perform the movements successfully, a differentiation of the intensity specifications for both limb movements was required. The decoupling ratio was found to improve across practice, and this effect was more prevalent for the groups receiving augmented information feedback about interlimb coupling. This finding suggests that practice led to a more successful differentiation of the limbs' intensity specifications. However, a significant decrease in the decoupling ratio was found after the 4-month retention interval (Experiment 2), suggesting that the differentiation of intensity specifications between limbs deteriorated in the absence of practice.

The improved decoupling ratio during acquisition was due mainly to a decrease in the excess of work generated in the left limb for production of the unidirectional movement. This excess was a direct result of the obstructive nature of preferred movement tendencies. In a general way, the current findings lend support to Basmajian's (1977) hypothesis that skill acquisition involves the inhibition or suppression of superfluous and unnecessary muscle activity.

Crosstalk has been proposed as a likely source of limitations in dual-task performance in general (Navon, 1984; Navon & Miller, 1987) and interlimb coordination in particular (Marteniuk et al., 1984; Swinnen, 1992; Swinnen & Walter, 1991). In contrast to models of structural and capacity interference (Kahneman, 1973), which have respectively underscored the importance of task similarity and task difficulty in explaining dual-task interference, the crosstalk model accounts for both. When two tasks are highly similar to each other, they often can be produced together as easily as separately, and it requires no special effort to synchronize them. The more dissimilar the tasks are, the greater the risk for (mutual) interference because the tasks tend to assimilate each other's spatiotemporal features. Previous work in which the electromyographic patterns of the left and right elbow flexors and extensors during the performance of a similar bimanual task were studied demonstrated that the phasic right biceps-triceps-biceps sequence of activity for the reversal action showed up in the electrical activity of the left limb muscles (Swinnen, Young, Walter, & Serrien, 1991). Furthermore, the higher the speed or force requirements of the task (i.e., a manipulation of task difficulty), the larger the dual-task interference becomes (Swinnen et al., 1992; Walter & Swinnen, 1990a, 1990b). A principal requirement in learning to decouple movements then is the progressive insulation of neural crosstalk with practice (Swinnen, Young, Walter, & Serrien, 1991).

Augmented Information Feedback for Interlimb Decoupling

Optimal learning is dependent on two general sources of information: (a) prescriptive information, necessary to convey to learners the movement standard or reference of correctness (what should be done), and (b) feedback, providing information about the actually produced movements, either by means of intrinsic information feedback sources or through augmented information feedback (what was actually done). The present experiments revealed that augmented information feedback was necessary to learn to decouple the limbs. Apparently, the intrinsic information sources failed to convey performance errors resulting from interlimb synchronization.

Some researchers in motor behavior (Fowler & Turvey, 1978; Newell & Walter, 1981) have tempered the enthusiasm surrounding the widely accepted idea that KR is a very powerful variable in motor learning. The arguments are built mainly on the assumption that KR does not match the task constraints when task complexity increases and that KR is often redundant information. Indeed, past research has shown the powerful effects of KR predominantly with rather simple tasks, like blind lever positioning and ballistic timing. Because KR provides information only about the overall outcome of the action and not about the necessary movement patterns or force-time histories that give rise to that outcome, it would appear desirable to draw the learners' attention to the pattern itself, especially when pattern modification is central to learning the new task. The present experiments failed to demonstrate a clear superiority for detailed kinematic information feedback in comparison to general outcome information, even though the former was more prescriptive for improving performance than the latter. Indeed, change in the goal-FB group was left to the subjects' introspection and problem-solving operations. Thus, KR, in the form of an overall outcome score, induced profound changes in movement kinematics and interlimb coordination, extending previous evidence by Young and Schmidt (1990) with a coincident anticipation timing task. KR may thus have more potential for the acquisition of multiple degree-of-freedom tasks than previously believed. Although KR was a rather vague code of success in achieving the outcome in Experiment 2, it may have made subjects aware of erroneous performance, subsequently increasing their sensitivity to response-produced information. Because the goal to be achieved was made available to the subjects, it is conceivable that they were largely capable of comparing what was done with what should be done, using the limited amount of extra KR feedback. This comparison process is at the heart of error detection and correction.

A major objective of the present experiments was to investigate the subjects' capability to decouple the limb movements. In our exploration of various information feedback sources from very general to very detailed, we failed to demonstrate full decoupling. Even the velocity feedback condition, which provided detailed information about the degree of structural and metrical coupling, failed to establish perfect decoupling. Inspection of the individual subjects' data revealed that some were largely successful by the end of practice whereas others had not made substantial improvements. This finding points to fundamental individual differences in the capability to overcome preferred coordination tendencies. However, it can also be taken to imply that limitations are inherent in the use of feedback manipulations as instructional techniques. Alternative critical manipulations of the instructional environment should be sought, and Walter and Swinnen (1992) have suggested one such possibility. Using
a similar bimanual task, they showed that progressively tuning the speed of movement execution resulted in more successful decoupling of the bimanual actions than did imposition of the target speed from the start of practice. Apparently, careful scaling of movement speed reduced the pull of attraction toward interlimb synchronization, enabling a more correct execution of the movement forms.

**Long-Term Retention of Movement Topologies and Metrics**

The investigation of subjects' long-term retention performance in Experiments 1 and 2 demonstrated good retention with respect to structural decoupling. The cross-correlations did not undergo large changes from immediate to delayed retention performance, and the group differences persisted as well. On the other hand, shifts did occur in the work measures (metrical decoupling). The metrical decoupling ratio deteriorated significantly across the 4-month interval (Experiment 2). Several reasons may underlie the differential trends in the structural and metrical variables across retention, some of which may be akin to their intrinsic nature. However, an equally viable reason is that structural aspects of movement are much more resistant to forgetting than are metrical specifications (Swinnen et al., 1990). This reason raises questions regarding the nature of the memory structure underlying these movement features or the way they are represented in the central nervous system.

**Reconsiderations for Motor Learning**

In addition to the traditional notion of skill acquisition as the formation of new action patterns, the present study underscores the viewpoint that motor learning requires overcoming the limitations imposed by preexisting (preferred) patterns. In other words, abandoning preferred coordination modes is often a prerequisite for acquiring new coordination patterns (Swinnen, 1991; Swinnen & Walter, 1988). Indeed, the inability to dissolve naturally emergent coordination patterns may play a significant role in the appearance of bad habits during the acquisition of complex skills (Walter & Swinnen, 1993). Preferred movement tendencies refer to or are brought about by inborn synergies, reflexes, central pattern generators, particular interlimb interactions, and so forth. This has consequences for the design of the learning environment. Feedback information should be provided to learners about the way that these preferred (often intrusive) movement patterns enter into attempts to perform a new task. Improvement in learning is not only dependent on getting to know the features of the new task but also on becoming aware of the interfering effects caused by preexisting patterns.

In general terms, a similar perspective was expressed by Bruner (1974), although it has largely been neglected by scientists in motor behavior. He stated, "There is one element in skill acquisition that is best called inhibition, suppressing old reaction patterns that continue to intrude" (p. 267). Fitts and Posner (1967) also hinted at the effects of old habits on new skills, but they mainly interpreted this in terms of generating new responses to similar stimulus situations, causing negative transfer effects.

Although the present perspective emerged from experimental work on discrete actions, it is consistent with a recent account of learning that was developed within the dynamical systems perspective (Schmidt, Trefner, Shaw, & Turvey, 1992; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992). This perspective starts with the observation that there exist intrinsic tendencies of coordination. For the specific case of bimanual cyclical hand or finger movements, studies have demonstrated a general preference to move either in-phase (simultaneous contraction of homologous muscles) or antiphase (simultaneous contraction of nonhomologous muscles) (Kelso, 1984). However, it is possible to acquire coordination patterns that deviate from these intrinsic modes through practice and with the aid of behavioral information. The nature of change that is due to learning arises from the competitive and cooperative interplay between the newly required and preexisting preferred coordination patterns. There is cooperation when the required coordination pattern joins with preexisting patterns and competition when it deviates substantially from them (Zanone & Kelso, 1992).

Previous theories of motor learning have failed to recognize the role of preexisting movement repertoires in learning new motor skills (Adams, 1971; Schmidt, 1975). The present work demonstrates that consideration should be given to the background of initial movement constraints within which new movements are acquired. Uncovering and describing the nature of intrinsic coordination modes inherent in the motor control system is an important research objective. In general, we conjecture that it is as important for a theory of motor behavior to identify the restricted range of interlimb interactions as it is to obtain insights into the way patterns of activity can be differentiated (Swinnen, 1991).

Whereas much attention has so far been paid in this article to the description of the potential (limiting) role of intrinsic or preferred coordination tendencies that form the backdrop against which new patterns have to be acquired, not much has been said about the mechanism or structure that governs the new coordination pattern when it becomes established. Preliminary insights into this problem can possibly be obtained from related research on polyrhythmic performance. Polyrhythms refer to the simultaneous production of two conflicting but isochronous movement sequences with the hands or fingers (e.g., a 3:2 or 5:2 pattern of finger tapping). Aside from a few fundamental differences, these actions bear similarities to the bimanual task used in the present study in that the subtasks' temporal structures are incompatible in both cases. It has been suggested that successful production of polyrhythms depends on the development of an integrated pattern representation (Deutsch, 1983; Jagaciński, Marshburn, Klapp, & Jones, 1988; Klapp et al., 1985; Peters & Schwarz, 1989; Summers, 1990; Summers & Kennedy, 1992). Despite this viewpoint, correlation analyses of the temporal occurrence of major landmarks in the right and left limbs' acceleration profiles in Experiment 3 did not provide strong support for the integration of both tasks into a superordinate control structure. Whereas the landmarks within the right limb movement were moderately to strongly correlated, relations between limbs were much lower and individual differences were clearly apparent. In some subjects,
the correlations were very high (> 90); in others they were low. Sometimes, relations were evident between certain fractions of both limb movements. A few subjects even displayed negative correlations. These individual differences are suggestive of a variety of control strategies in producing the bimanual pattern, with task integration appearing to be only one of them. The issue of integration of control structures merits further investigation in the future whereby various task combinations should be explored in relation to differing degrees of skill level. In particular, special attention should be devoted to the potential differ-ences between the control structure underlying discrete and cyclical tasks.

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P&C Board Appoints Editor for New Journal:
Journal of Experimental Psychology: Applied

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