Overcoming Spontaneous Patterns of Coordination During the Acquisition of a Complex Balancing task

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Abstract Learning in complex tasks is usually conceived as the problem of mastering the multiple and redundant degrees of freedom of the system. To reduce control requirements, two different strategies are conceivable. The first one consists of a "freezing-freeing" process for most articular joints to reduce the number of *active* biomechanical degrees of freedom to be managed. The second strategy consists of introducing rigid couplings between the oscillators building the system. In this case, learning implies the dissolution of initial couplings and the emergence of new, more task-specific couplings.

The goal of our study was to analyze the spontaneous coordination of beginners and its development in a complex balancing task on a stabilometer, and to examine the emergence of these two strategies. Our results showed that beginners were characterized by strong couplings between the joints of the lower limbs. During learning, new and more task-specific couplings emerged that reflected a new organization of the trunk and a decoupling of some joints of the lower limbs that were initially coupled during the first few trials.

Bernstein (1967) claimed that the main concern for a beginner in a motor task is to master the multiple and redundant degrees of freedom potentially involved. According to Vereijken and Bongaardt (1999), the control of this initial complexity can be achieved by following two alternative and/or complementary strategies. The first one consists of "freezing" a number of joints, thus reducing the number of *active* degrees of freedom. In accordance with this view, Newell and van Emmerik (1989) showed that the shoulder was the unique joint involved in the realization of signatures with the nondominant arm (see also Arutyunyan, Gurfinkel, & Mirskii, 1968; Vereijken, 1991).

Improvements of skill are then characterized by a progressive freeing of articular degrees of freedom. This occurs systematically: Degrees of freedom are progressively integrated in so-called *coordinative structures*, conceived as temporary assemblies of muscular synergies, with the intention of reducing the controlled degrees of freedom (Whiting, Vogt, & Vereijken, 1992).

Learning should be characterized by an increase in the number of active degrees of freedom and an increase of the amplitude of articular movements. Accordingly, Newell and van Emmerik (1989) showed that when subjects signed with their dominant hand, every joint of the upper limb was involved. Similarly, in a ski simulator experiment, the amplitude of articular movements grew during learning (Vereijken, 1991), testifying to this progressive release of the degrees of freedom. In both of these two cases, the first steps of learning were characterized by low amplitude movements of the various joints. This means that control requirements were concentrated on the main and the most powerful joints: the shoulder for the writing task with the nondominant hand and the hips for the skiing task. With practice, participants progressively freed their joints. This freeing was characterized by an increase in the movement amplitude of the joints of the knees and the ankles in Vereijken's experiment and an increased use of the joints of the elbow and wrist when participants signed with their dominant hand.

The second strategy described by Vereijken and Bongaardt (1999) consists of introducing rigid couplings between the various articular degrees of freedom, which are thus constrained to function as one. This hypothesis finds its origins in von Holst's analyses (1939/1973) that suggest that biological movements are characterized by the synchronization of the various oscillators comprising the system. Especially when these oscillators have similar eigenfrequencies (i.e., the spontaneous oscillation frequency in the absence of external constraint), an absolute synchronization of phases and frequencies emerges spontaneously. (When eigenfrequencies are dissimilar, other coordination modes can appear, generally characterized by shifts in the relative phase.) This appears to be applicable to collections of human body parts that can be modeled

as assemblies of different oscillators; an example, at a macroscopic level, would be the legs or the arms. Von Holst's analyses predict that these oscillators, with close eigen frequencies, would tend to become synchronized. These spontaneous coordination modes would tend to be stable and to reflect the attractors of the intrinsic dynamics of the system. For example, in the bimanual coordination task used by Kelso, Holt, Rubin, and Kugler (1981), these spontaneous modes correspond to two intrinsic attractors: the in-phase and anti-phase coordination modes. In both cases the frequency ratio is 1:1, and the reversal points are synchronized.

Spontaneous behaviour of beginners facing a new task could be interpreted following these principles (Delignières, Nourrit, Sioud, Leroyer, Zattara, & Micaleff, 1998; Swinnen, Dounskaia, Walter, & Serrien, 1997; Walter & Swinnen, 1994). Identification of the spontaneous coordination modes would clarify the background against which learning would have to be carried out. Indeed, if the pattern to be learned corresponds to these spontaneous coordination tendencies, learning will be enhanced. On the other hand, if the pattern to be learned is qualitatively distinct from the preferred pattern, the subject will have to overcome the spontaneous coordination tendencies.

In both the experiment of Delignières et al. (1998) and that of Swinnen et al. (1997), participants faced a novel situation, and the required pattern was not present in the initial repertoire of the system. The tasks in these two studies were different: Subjects were asked to swing under parallel bars in Delignières et al.'s experiment and to perform a bimanual coordination task with a 2:1 frequency ratio in Swinnen et al.'s experiment. However, the theoretical background was the same: In both cases, the spontaneous coordination modes constituted a major obstacle for learning. Within this framework, learning entails overcoming spontaneous coordination modes and developing new coordinative structures that exploit in the mechanical properties of the task. Thus, we expect the initial rigid couplings to disappear over time, and new coordination modes more specific to the constraints of the task to emerge. These new modes would reflect the development of a new attractor basin in the coordination dynamics. This kind of evolution of coordination patterns was in fact observed by Vereijken (1991) and Delignières et al. (1998).

The two aforementioned strategies have been studied and evidenced in quite distinct tasks. Indeed, authors aiming at highlighting the *freezing/freeing* process have generally used tasks that involve handling objects or instruments and, in addition, that require precise postural adjustments (Arutyunyan et al., 1968; Newell & van Emmerik, 1989; Steenbergen, Marteniuk,

TABLE 1
Anthropometrical Characteristics of the Experimental Participants

Participants	Gender	Age	Size (cm)	Weight (kg)
HER	M	25	179	80
THI	M	27	180	70
MAX	M	21	187	82
ARM	M	23	180	65
DAV	M	25	182	75
ERI	M	26	180	77
DEB	F	27	180	64
KAR	F	25	168	58
HEL	F	25	165	60
Average		24.89	177.89	70.11
Standard deviation		+ /- 1.90	+/- 6.92	+/- 8.82

& Kalbfleisch, 1995). Researches focused on the coupling phenomena have obviously used tasks with oscillatory characteristics (Delignières et al., 1998; Kelso et al., 1981; Swinnen et al., 1997). Therefore, the use of a given strategy of learning may be task-dependent. However, previous studies did not establish a clear relation between learning strategies and such task constraints. The present research was intended to address this issue.

With this aim, we chose to study spontaneous coordination modes and their change during learning, using the task of balancing on a stabilometer. This task potentially allows the use of both learning strategies. On one hand, the task requires precise postural adjustments like the majority of tasks in which the freezing/freeing strategy is observed. On the other hand, these adjustments are carried out on a mobile platform as in Vereijken's experiments (1991, 1997). Thus, it might be possible that learning involves the dissolution of initial couplings and the emergence of new coordination modes more specific to the task. As noted previously, our current knowledge does not allow us to predict what kind of learning strategy would be observed in this task. Will novices initially freeze their different articular joints or will they synchronize them? Nevertheless, we can predict that if the freezing/freeing strategy is used, we should observe a progressive increase in the movement amplitude of the different joints of the body. If the coupling strategy is used, we should observe strong couplings during the first few trials that weaken as a function of practice and, at the same time, the development of new, more task-specific couplings.

Method

Nine participants (average = 24.89 +/- 1.90 years) took

Figure 1. Locations of the passive markers on the subject and the stabilometer .

part in our experiment. Their anthropometrical characteristics are given in Table 1. For each of them, the task was novel. Moreover, they did not have any expertise in an activity that might facilitate learning (i.e., gymnastics, dancing, skiing, etc.).

A commercially available stabilometer (Lafayette, see Figure 1) was used. Subjects were instructed to maintain the board of the stabilometer as still and as horizontal as possible. They started with the board resting on the right side, and were asked to look straight in front of them and to maintain their arms behind their backs throughout the experiment. These instructions were given at the beginning of each session.

For technical reasons concerning the video recording system, the distance between the feet was fixed at 53 cm. Despite variations in height, all participants found this stance comfortable. Participants undertook five sessions of 10 trials on five consecutive days. The duration of each trial was one minute and thirty seconds, with one minute and thirty seconds of rest between two trials. Participants practiced each day at the same time. No feedback was given.

As in Vereijken's experiments (1991, 1997), subjects were equipped with 10 circular reflective markers (Figure 1). The markers were located on both shoulders (on the frontal aspect of the caput humeri), on both hips (on the anterior superior spina illiaca), on both knees (on the patella), on both ankles (on the frontal side between the lateral and the medial malleoli), and on the tips of both feet. Finally, one additional marker was fixed on the right end of the stabilometer board (see Figure 1).

The position of the markers was recorded at 50Hz by two video cameras interfaced to a VICON 140 (BIO-METRICS) image analysis system. The system was calibrated to each participant at the beginning of each session.

A 15-second acquisition period was carried out during the first three and the last three trials of each session. Data acquisition started one minute after the beginning of the trial. This delay was motivated by the observation, during pilot investigations, that behaviour at the onset of each trial was often chaotic, especially early in practice. The articular angles of hips, knees, and ankles were derived, as time series, from the three-dimensional coordinates of the markers. Then the following dependent variables were derived:

(a) The variability (standard deviation) of the vertical coordinate of the marker located on the stabilometer board was used as a performance index.

(b) The variability (standard deviation) of the angles of the hips, knees, and ankles was computed to evaluate a possible freezing/freeing process during the course of practice (Vereijken, 1991). We decided to complement this absolute measurement of angular variability with a relative index, calculated by dividing the standard deviation of each articular angle by the standard deviation of the vertical coordinate of the marker fixed on the board. The introduction of this new variable, the *relative variability*, was motivated by the fact that in our task, joint variability could be related to practice (by means of the freezing/freeing process), but also to the variability of the movements of the board. Note that these influences would presumably act in opposite directions, and would make it difficult to interpret the results. Relative variability is likely to be more specifically related to the effect of practice on joint variability since it controls for the variability of the board. This form of relative index could be useful in other experiments in which joint variability appears to be constrained by the amplitude of the oscillations of the platform (e.g., on a ski simulator; see Vereijken, 1991).

(c) The cross-correlations between the angular time series for knee and ankle, hip and knee, and hip and ankle, were calculated in order to evaluate the presence of coupling between the joints of the lower limbs. Zero time-lag cross-correlations were used, as we never observed, in the visual examination of our data, any systematic shift between two angular time series. Such a shift would have been revealed, for example, by an elliptical trajectory in a Lissajous (angle vs. angle) graph.

(d) The cross-correlation between the angular time series of the axis of the shoulders and the axis of the hips was calculated to assess coupling in the upper part of the body. The axis of the shoulders was defined as the slope of the line through the two shoulder mark-
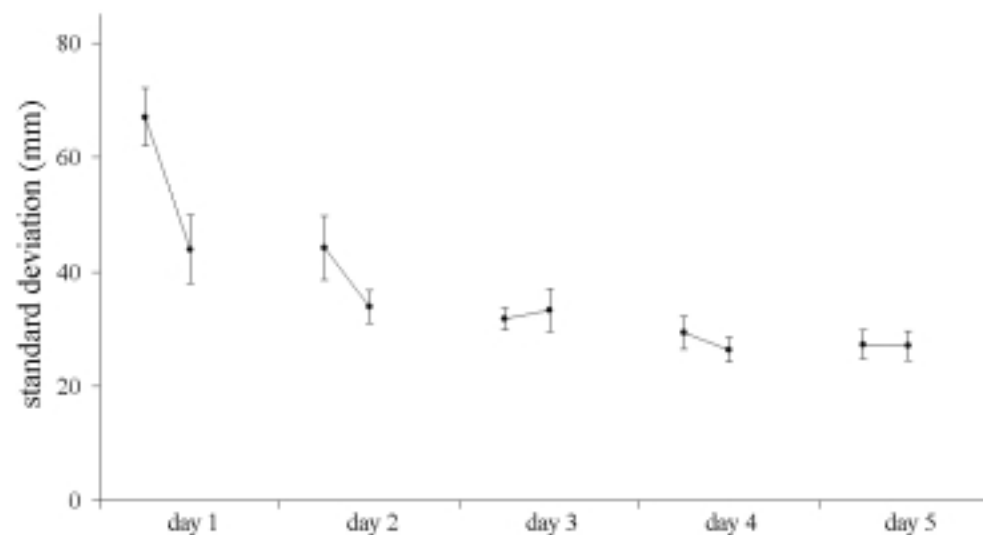
Figure 2. Variability of the position of the stabilometer board (standard deviation in millimetres) as a function of practice and standard error. Data were averaged across subjects.

ers, and the axis of the hips as the slope of the line through the two hip markers. These slopes were calculated in the frontal plane because the oscillations of the stabilometer board were leaded in this plane.

(e) Finally, to assess other possible kinds of coupling between the body and the apparatus, cross-correlations were calculated between the vertical coordinate of the marker of the board and the articular angles of the lower limbs (hips, knees, and ankles), the axis of the shoulders, and the axis of the hips.

For similar reasons as those described in (c), the cross-correlations defined in (d) and (e) were computed without time-lag. Before statistical analysis, the correlation coefficients were transformed using Fisher's Z transform in order to normalize the sample distribution. All of the dependent variables were averaged over the first three trials and over the last three trials for each session. Then they were analyzed in a 5 (Session) x 2 (intra-session) ANOVA, with repeated measurements for each factor. The significance of p values was adjusted according to the so-called Huynh-Feldt procedure in order to control for possible violations of the assumption of compound symmetry (Huynh & Feldt, 1970).

Results

VARIABILITY OF THE BOARD
The analysis revealed a main effect of the Session factor, $F(4,32) = 35.74$, $p < 0.01$, indicating that the vertical variability of the marker located on the board decreased during the experiment (see Figure 2). The Intra-session factor was significant, $F(1,8) = 18.61$, $p < 0.01$, as well as the Session by Intra-session interaction, $F(4,32) = 8.31$, $p < 0.01$. These results suggested that

TABLE 2
Statistical Results for the Absolute Variability of Articular Angles

Dependent variables	Session	Intra-session	Session intra-session
Right hip	$p < 0.01$	$p < 0.01$	ns
Right knee	$p < 0.01$	$p < 0.01$	ns
Right ankle	$p < 0.01$	ns	ns
Left hip	$p < 0.01$	$p < 0.05$	$p < 0.01$
Left knee	$p < 0.01$	$p < 0.05$	$p < 0.01$
Left ankle	$p < 0.01$	ns	$p < 0.01$

the enhancement of performance was greater during early sessions than during later ones.

ABSOLUTE VARIABILITY OF ARTICULAR ANGLES
For each angle, a main effect of the Session factor was obtained (statistical results are resumed in Table 2). There was also an Intra-session effect for the right hip, the left hip, the right knee, the left knee, but not for the ankles. Finally, a significant Session by Intra-session interaction was obtained for the left hip, the left knee, and for the left ankle.

All of these results suggest a general decrease, with practice, of the absolute variability of the articular angles of the lower limbs (see Figure 3). This decrease was particularly pronounced within and between the first two sessions.
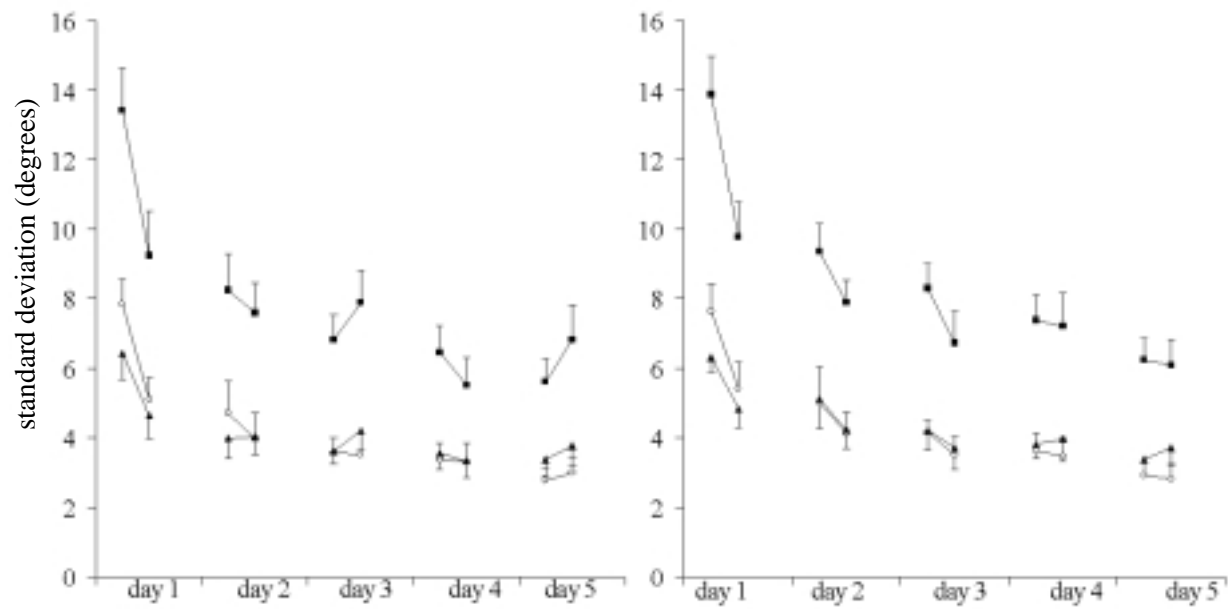
Figure 3. Absolute variability (in degrees) for the left side (left panel) and the right side (right panel) articular angles of the hip (circle points), the knee (square points), and the ankle (triangular points) as a function of practice and standard error. Data were averaged across subjects.
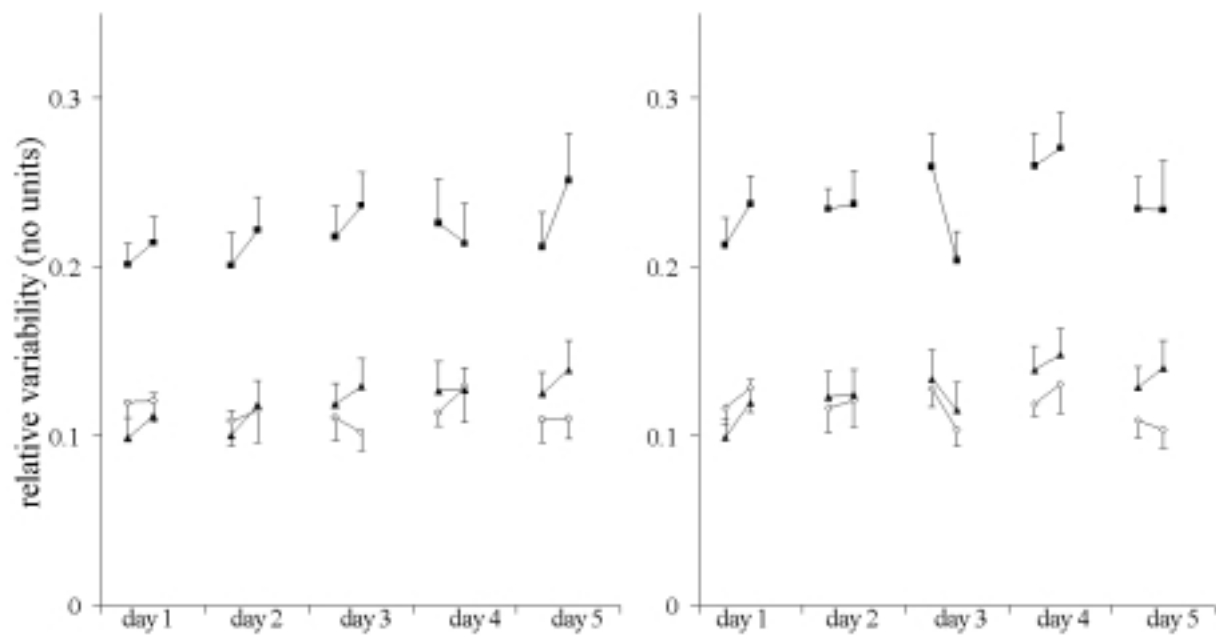

Figure 4. Relative variability for the lower limbs articular angles for the left (left panel) and the right (right panel) body sides (hips: circle points; knees: square points; ankles: triangular points) as a function of practice and standard error. Data were averaged across subjects.
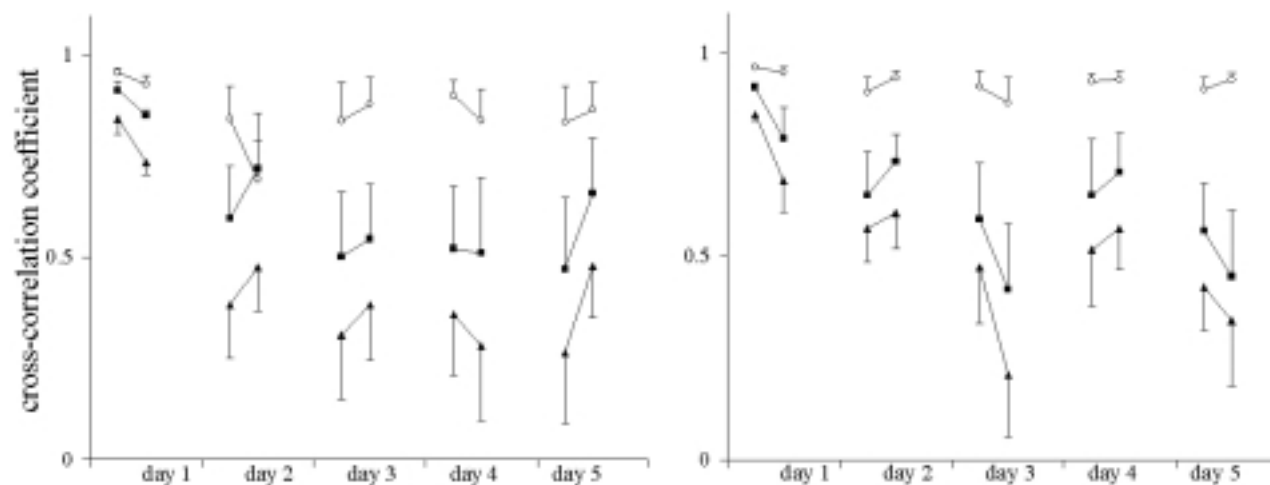
Figure 5. Articular angle cross-correlation, for the left (left panel) and the right (right panel) body sides (hip/knee: square points; hip/ankle: triangular points; knee/ankle: circle points) as a function of practice and standard error. Data are averaged across subjects.

RELATIVE VARIABILITY OF THE ARTICULAR ANGLES

No effect was found for relative variability for either hips or knees angles (Figure 4). An effect of Session was found only for the ankles' angles (right ankle: $F_{(4,32)} = 3.07$, $p < 0.05$; left ankle: $F_{(4,32)} = 9.57$, $p < 0.01$). Additionally, a significant Session by Intra-session interaction was shown for the left ankle, $F_{(4,32)} = 5.33$, $p < 0.01$). These effects revealed a progressive increase of the ankles' relative variability with practice.

CROSS-CORRELATIONS BETWEEN THE ARTICULAR ANGLES OF THE LOWER LIMBS

The change in cross-correlation coefficients varied depending on which angles are considered. As can be seen in Figure 5, the knee-ankle cross-correlations were high (around 0.9) and remained quite stable over the five sessions. A main effect of the Session factor was nevertheless obtained for the left side (all the statistical results were reported in Table 3). This effect was primarily due to the low mean value obtained for the last trials of the second session (see Figure 5).

For the hip/knee and hip/ankle cross-correlations, a main effect of the Session factor was consistently obtained (see Figure 5). Generally, these results showed that the cross-correlations between hip and knee and between hip and ankle tended to decrease with practice, from values of around 0.9 during the very first trials, to values of around 0.4 from the third session onward.

There was no evidence for a consistent Intra-session

TABLE 3
Statistical Results for the Cross-Correlation Coefficients of the Lower Limbs

Dependent variables	Session	Intra-session	Session intra-session
Right hip/knee	$p < 0.01$	ns	ns
Right hip/ankle	$p < 0.01$	$p < 0.01$	$p < 0.05$
Right knee/ankle	ns	ns	ns
Left hip/knee	$p < 0.05$	ns	$p < 0.05$
Left hip/ankle	$p < 0.01$	ns	$p < 0.05$
Left knee/ankle	$p < 0.05$	ns	ns

effect. On the other hand, three Session x Intra-session interactions were obtained: for the right hip/ankle cross-correlation, the left hip/knee cross-correlation, and the left hip/ankle cross-correlation. Most of these interactions were due to the lack of consistency in changes in the cross-correlation from one session to another.

CROSS-CORRELATIONS BETWEEN THE ARTICULAR ANGLES OF THE LOWER LIMBS AND THE BOARD

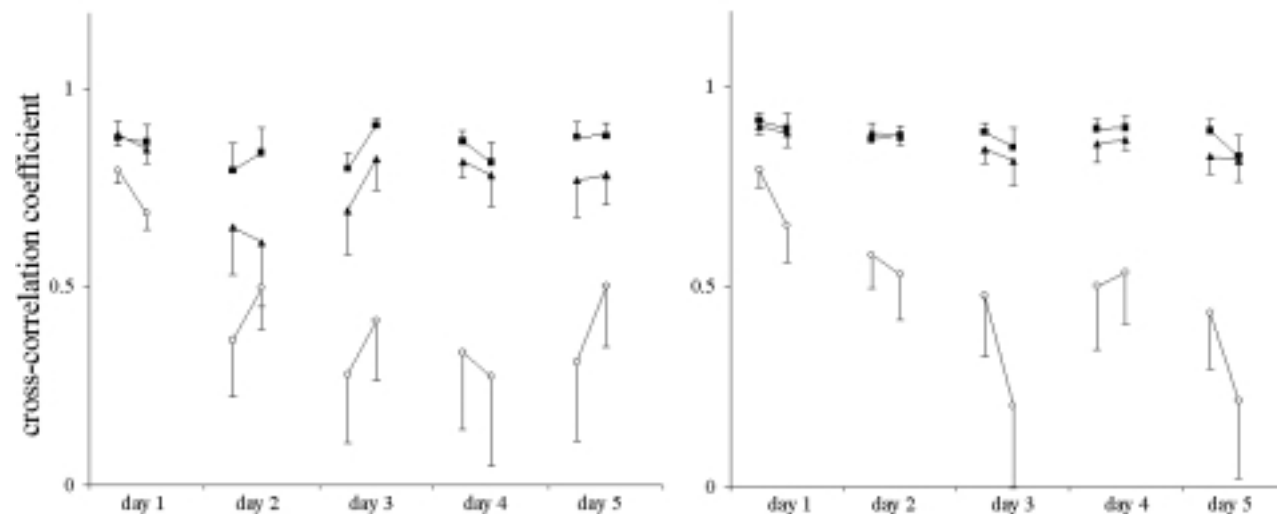As can be seen in Figure 6, the development of the

Figure 6. Cross-correlations between the articular angles of the lower limbs and the board of the stabilometer as a function of practice and standard error. The left panel represents the cross-correlations for the left side and the right panel the cross-correlations for the right side (hip/board: circle points; knee/board: square points; ankle/board: triangular points). Data were averaged and in absolute values for the right side.

cross-correlations between the articular angles of the lower limbs and the board varied depending on which joint was considered. For the ankles and knees, the cross-correlations were large initially and remained stable over practice, suggesting a strong coupling between the board and the lower joints. In contrast, the correlations between the hips and the board also started out high but decreased progressively with practice. However, because of subject variability for the hip correlations, this tendency was significant only for the right side of the body (right hip, Session factor: $F(4,32)$ = 4.50, $p < 0.05$; Intra-session factor: $F(1,8)$ = 6.01, $p < 0.05$.

CROSS-CORRELATIONS BETWEEN THE BOARD, THE AXIS OF THE HIPS AND THE AXIS OF THE SHOULDERS

The development of the cross-correlations between the board, the axis of the hips, and the axis of the shoulders is depicted in Figure 7. The hip axis/board cross-correlation remained very high (around 0.92) during the five sessions of practice, and there was little effect of practice. However, because of the very low subject variability for this variable, the Intra-session effect was significant, $F(1,8)$ = 11.15, $p < 0.05$, indicating a slight decrease of this cross-correlation within each session.

The analyses of the shoulder axis/hip axis and the shoulder axis/board cross-correlations showed a Session main effect (shoulders/hips: $F(4,32)$ = 11.55, $p < 0.01$; shoulders/board: $F(4,32)$ = 9.17, $p < 0.01$. These results demonstrate the specific development of trunk coordination during practice. More precisely, practice led to an increase in the coupling between the

shoulder and hip axes and between the shoulder axis and the board.

Discussion

The results of the present experiment show, first of all, that behavioural adaptation on the stabilometer appeared very early in practice. This accords with the results of Wulf et al. (1998). In terms of both performance and articular variability or coupling, the most significant changes occurred during the two first sessions. This trend is similar to the results of Vereijken (1991) in which the greatest changes were observed in the very first sessions of practice on the ski simulator. Note, nevertheless, that such a fast adaptation is clearly task-specific. For example, Delignières et al. (1998), in their experiment with parallel bars, did not find any change in the initial coordination patterns, even after eight sessions of practice. Similarly, Delignières, Nourrit, and Deschamps (2000), using a modified version of the ski simulator, did not observe any change in behaviour before the 10th session of practice.

Secondly, the results did not support the hypothesis of an initial freezing of the articular degrees of freedom. The absolute angular variability of the joints of the lower limbs decreased with practice, and the results for relative variability suggested that the variability of the joints was related to the stability of the board. This strong coupling between the movements of the board and the coordination of the lower limbs was confirmed by the high cross-correlations, observed from the first trials, between the hip axis and the board (see Figure 7).
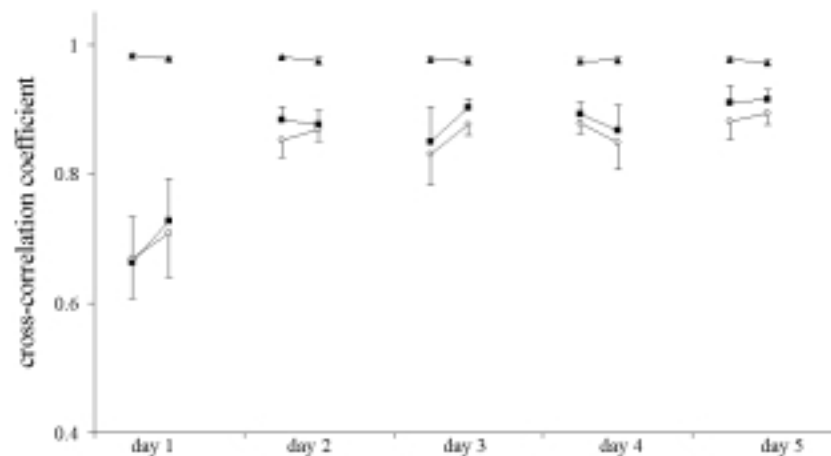
Figure 7. Cross-correlations between the shoulder axis and the hip axis (square points), between the shoulder axis and the board (circle points), and between the hip axis and the board (triangular points) as a function of practice and standard error. Data were averaged across subjects.

Finally, the results demonstrate a lateral bias related to absolute variability (see Figure 3). The variability of the joints for the left side tended to increase near the end of the experiment, suggesting that this body side is central to the control requirements of the task. This interpretation is surprising given that all of the subjects were right-handed. Perhaps for right-handed subjects, the right side of the body is useful for the stabilization of the behaviour while the left side is used as a postural regulator. However, a longer experiment would be needed to confirm this hypothesis.

All these results suggest that the hypotheses of Bernstein (1967) concerning the management of the degrees of freedom during the process of learning is not relevant for this kind of task. More generally, the behavioural adaptation of participants to a novel task seems highly specific. Joint freezing appears to be a useful strategy when tasks allow complete postural control (as in Newell & van Emmerik's 1989 experiment) and/or a limitation of the amplitude of the oscillations (as in Vereijken's 1991 experiment). Our results suggest that such a control or limitation is impossible on the stabilometer, at least during the first few trials. The stabilometer tends to amplify postural imbalances, and as a result, the movements of the board during the first trials of our experiment appeared particularly chaotic, with frequent abrupt transitions from an extreme position to its opposite. In the ski simulator used in Vereijken's 1991 experiments, participants were not faced with such uncontrollable instability.

However, we did obtain a slight, but significant, increase in the relative variability of the ankle joints,

which could be interpreted as a freeing process. Our experiment was too short to allow this interpretation to be confirmed. Nonetheless, it is interesting to note that such freeing at a distal joint would constitute a violation of the principles of directional trends (cephalo-caudal and proximo-distal) as suggested by Gesell (1929) for development and by Newell and van Emmerick (1990) for learning. As pointed out by Newell and van Emmerick (1990, see also Newell & McDonald, 1995), the directional trends of the freeing process could be highly task-specific. In the present case, the freeing of the ankles could play a major role in the postural adaptability. In fact, the task constraints seem to be as relevant as the biomechanical constraints, and it appears important to take such task constraints into account in motor learning. Newell and van Emmerick (1990) emphasized that when organism and task constraints act in the same way, one can observe directional trends as defined by Gesell. But when these constraints are at odds with each other, as in the present experiment, the directional trends are task-specific and are determined by the relationships among the organism, the task, and the environment. In line with these arguments, we hypothesize that in a longer experiment freeing should be observed in the knees in order to gain more precise postural control.

Another important result was the progressive weakening of the initial couplings among the joints of the lower limbs. This decoupling tendency was clearly illustrated by the change in the hip/knee and the hip/ankle cross-correlations (see Figure 6). During the very first few trials, the movements of the joints of the

lower limbs were strictly synchronized, indicating that the limb was constrained to act (and in this case to react to the movements of the board) as a single unit. These cross-correlations were around 0.9 initially, but declined to approximately 0.5 by the third session. Nevertheless, the knee/ankle cross-correlations remained high over the entire experiment, indicating that the decoupling in the lower limbs was mainly related to a development of the behaviour of the pelvis. Similar results were described by Vereijken (1991) on the ski simulator. In her experiment, the ankle/knee cross-correlations remained high after more than 50 cumulated tests, even though a progressive reduction of the knee/hip and ankle/hip cross-correlations was observed over the same period. These results suggest that in this kind of task, critical elements of the behavioural adaptation pertain to the upper part of the body.

The first few trials were characterized by strong cross-correlations between the board and the joints of the lower limbs. However, with practice and the decrease in the magnitude of the oscillations, the cross-correlations of the upper joints of the lower limbs progressively decreased. This was the case for the hips, whose cross-correlations with the board declined from values near 0.9 to values near 0.4 for the left side, and from values near -0.9 to values near -0.4 for the right side. At the same time, cross-correlations between the board and the joints of the knees and the ankles remained high. This result is not so surprising given that the ankle joint is fixed on one side by the board; consequently, its variability is mainly determined by knee movements, resulting in high cross-correlations. These results confirm the preceding suggestion that the strength of couplings, and their adaptations, were not strongly determined by the characteristics of the task during the first stages of learning. Moreover, this result shows that the decrease in the correlations involving the upper joints of the lower limbs was not trivial. For example, one might suggest that the decrease of the cross-correlation coefficients could be simply related to a restriction of the displacement range as the performance became more stable. However, the previous result shows that the cross-correlation coefficients of the joints could in principle remain high despite more stable performance.

The appearance of new couplings in the frontal plan between the shoulder axis and the hip axis can be seen in Figure 7. A strong synchronization between the two axes was established by the third session, and our results show that the whole trunk was then strictly coupled with the oscillations of the board. These results indicate that the trunk was progressively incorporated in a coordinative structure. This development would seem to be essential given that the trunk represents a large part of the body mass and constitutes an important element in the control of posture and centre of gravity. Consistent with this interpretation, we also observed an increase in the correlation between the hip axis and the board accompanied by a decrease in the correlation between the hip joints and the board.

As can be seen from the error bars in Figures 5, 6, and 7, interindividual variability increased with practice. This suggests that beyond a common set of behavioural trends, individuals could adopt different coordination modes and/or follow different learning strategies. A precise analysis of such individual strategies is clearly beyond the scope of the present paper. Nevertheless, some explanation of the origin of this intersubject variability seems necessary.

For three participants, there was no noticeable change in the initial coordination mode, despite a clear improvement in board stabilization performance. Such a result is in line with the high stability of the spontaneous coordination mode reported by Delignières et al. (1998), despite a significant increase in oscillation amplitude.

The other participants exhibited a clear development of their coordination modes, but with large interindividual differences. For example, we observed on average a decrease in the cross-correlations between the hip angles and the board (see Figure 7). Hips tended to be synchronized with the movements of the board during the first few trials, but seemed to act more independently latter in practice. For participant HEL, this trend led to the emergence of an inverse synchronization, revealed by significant negative cross-correlation coefficients. This suggests that the coordination modes for this task are highly individualistic and that different behaviours could lead to equivalent levels of performance.

These differences in the development of coordination with practice could be related to the characteristics of the initial coordination modes. For example, during the first session the three "stable" participants had a higher cross-correlation coefficient between the axes of the shoulders and the hips than the others participants.

Further experiments involving a greater number of participants would be needed to investigate the origins of this interindividual variability in depth. Morphological characteristics, prior experiences, inherent aptitudes, and specific intentions could underlie such interindividual differences. The experimental control of such variables could determine their relationships to the resulting behaviour. However, such an approach is clearly beyond the scope of the present experiment, which was focused on the common trends in the adaptation of beginners to a novel task.

To sum up, our experiment showed that learning on a stabilometer was characterized by an important development of the coordination of the system. During the very first trials, the joints of the lower limbs appeared strictly coupled and tied to the movements of the board. In contrast, the upper part of the body moved more independently, leading to poor control of general balance. Quite early during practice, the trunk became progressively involved in the coordinative structure that allowed the control of the oscillations of the board. This development led to a partial dissolution of the couplings within the lower limbs, suggesting a more subtle adaptability of the system and a finer control of the apparatus. This new coordination mode allowed a significant improvement in the stability of the board. However, all of these adaptations did not characterize every participant, suggesting that the adaptation to a complex task is to some extent idiosyncratic.

Conclusion

The aim of this experiment was to study the coordination modes spontaneously adopted by beginners on a stabilometer and their potential change with practice. The results did not reveal any obvious phenomenon of freezing/freeing degrees of freedom, leading us to question the general relevance of the assumptions of Bernstein (1967). Vereijken and Bongaardt (1999) suggested that the freezing of the degrees of freedom and the initial coupling of various joints constitute two "strategies" available to the subject to solve the fundamental problem of Bernstein. The term strategy remains awkward because it suggests that subjects could have the choice between one or the other mode of resolution. We think on the contrary that these two types of adaptation are strongly constrained by the characteristics of the task.

This research confirmed a number of previous results and showed that learning could be conceived as the replacement of spontaneous coordination modes with new coordinative structures more adapted to the constraints of the task. It shows, moreover, that the temporal scale of these transformations can vary from one situation to another and from one subject to another. While the essential changes occurred during the two first sessions in the present experiment, other work has shown that spontaneous coordination modes may be resistant to change over a similar time period. These differences in temporal scale could be related to the degree of convergence between the initial spontaneous coordination mode and the coordinative structures finally adopted (Zanone & Kelso, 1992).

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Sommaire

Le but de cette expérimentation était de tester la pertinence de deux modèles de l'apprentissage issus du courant dynamique lors de l'apprentissage d'une tâche complexe. L'apprentissage pour ce type de tâche est généralement appréhendé au travers du problème de contrôle des différents degrés de liberté du système. Dès lors, la gestion des degrés de liberté peut se faire sur la base d'un processus de « gel/dégel » des degrés de liberté. La première étape de l'apprentissage se définit dans ce cas comme un gel des degrés de liberté pour n'en solliciter qu'un faible nombre. Ensuite, apparaîtrait un dégel progressif des degrés de liberté augmentant ainsi leur nombre actif. La seconde stratégie consiste en l'introduction de couplages rigides entre les différents oscillateurs composant le système caractérisant les coordinations spontanées. Cette stratégie trouve son origine dans les travaux de von Holst. Dans ce deuxième cas, l'apprentissage passe par un dépassement de ces coordinations spontanées et par l'apparition de nouveaux couplages plus efficients et spécifiques à la tâche. L'émergence de l'une ou l'autre de ces deux stratégies dépend du type de tâche. Ainsi dans des tâches impliquant des ajustements posturaux, la stratégie « gel/dégel » a été mise en évidence. Par contre, la stratégie de couplage des degrés de liberté caractérise l'évolution des coordinations motrices lors de tâches requérant des ajustements sur un support mobile. Ainsi, la tâche demandée, tenir en équilibre sur un stabilomètre, présentait la particularité de permettre l'émergence des deux stratégies.

Neuf sujets ont pris part à cette expérimentation durant quatre jours. Les résultats montrent que les sujets débutants sont caractérisés par de forts couplages entre les articulations des membres inférieurs. Certains de ces couplages tendent à s'atténuer au cours de l'apprentissage, en particulier les couplages entre les articulations des hanches et des genoux. Au cours de la pratique, nous avons noté l'apparition d'une nouvelle organisation au niveau du tronc mettant en évidence des couplages plus spécifiques à la tâche. En revanche, nous n'avons pas observé de réel phénomène de gel/dégel des degrés de liberté falsifiant ainsi, pour notre tâche, la validité de ce type d'adaptation.

Enfin, cette expérimentation met en avant le caractère hautement individuel des adaptations lors de l'exécution de tâche d'équilibration sur un support mobile. Ainsi pour une performance donnée, différents patrons de coordination semblent être efficaces mettant en évidence la grande complexité de l'espace de travail perceptivo-moteur.