Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Human Movement Science xxx (2007) xxx–xxx
HUMAN MOVEMENT SCIENCE
www.elsevier.com/locate/humov

The nature of the transition between novice and skilled coordination during learning to swing

Caroline Teulier [*], Didier Delignières

E.A. 2991 "Motor Efficiency and Deficiency", Faculty of Sport and Physical Education Sciences, University of Montpellier I, 700, avenue du Pic saint Loup, F-34090 Montpellier, France

---

Abstract

The purpose of this study was to analyze the nature of the coordination evolution during the process of learning a gross motor skill. Participants had to learn to oscillate as smoothly as possible on an experimental swing during 10 sessions of 10 trials. Using tools and methods of dynamical systems theory, two qualitatively different coordination modes were observed during learning. The change from the novice behavior (characterized by a single forcing) to the skilled behavior (characterized by a dual forcing) was characterized by a period during which the two behaviors were used in alternation. In accordance with Newell's [Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology*, *42*, 213–237] ideas, motor learning appears a non-linear process, and this non-linearity seems to have the form of a prolonged phase transition (like in a saddle-node bifurcation) which permits access to the skilled behavior.

PsycINFO classification: 2343; 3720

Keywords: Motor learning; Coordination; Phase transition

---

[*] Corresponding author. Tel.: +33 (0)4 67 41 57 54; fax: +33 (0)4 67 41 57 08.
E-mail address: caroteulier@yahoo.fr (C. Teulier).

0167-9457/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.humov.2007.01.013

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

1. Introduction

Since Bernstein's seminal work (1967), learning has been regarded by several authors as a discontinuous process, characterized by qualitative reorganizations of movement in the course of practice (Newell, 1991). For example, Zanone and Kelso (1992) required participants to learn a 90° of relative phase (RP) pattern between their hands. At the beginning of learning, participants produced a 0° RP pattern before adopting the required pattern (90° of RP) during practice. They considered learning as a phase transition, from the initial mode of coordination to the skilled behavior, and thus reinforced the concept of learning as a discontinuous process. In this case, learning is revealed by the appearance of a new attractor state in the dynamics of the system.

This basic idea was adapted in a more recent paper (Zanone & Kelso, 1997), which showed that when the to-be-learned pattern was close to a preexisting pattern, learning could become manifest as a simple shift of the initial attractor in the direction of the intended pattern. This result led the authors to distinguish between cooperative situations, where people could use preexisting coordination modes for reaching the assigned goal (generally with some parametric adaptations), and competitive situations, where the to-be-learned pattern, qualitatively distinct from the spontaneous coordination tendencies of the system, has to be constructed against this initial repertoire. In this competitive case, a qualitative modification occurs by way of a phase transition.

A number of studies provided evidence for qualitative differences between novice and expert coordination modes in gross motor skills. For example, this difference was observed in a volleyball serve (Temprado, Della-Grasta, Farrell, & Laurent, 1997), aiming at a target (Arutyunyan, Gurfinkel, & Mirskii, 1968), and swinging under parallel bars (Delignières et al., 1998). These studies suggested that the route from novice to expert behavior during learning is discontinuous, as novices need to qualitatively change their behavior to adopt the expert coordination. According to the Zanone and Kelso (1997) hypothesis, in such a competitive situation, the behavioral change could be considered as a phase transition. Nevertheless, this hypothesis appears rather counterintuitive: a phase transition is theoretically conceived as an abrupt change in behavior, while on the other hand learning is generally considered as a rather gradual process when only goal performance is considered (Newell & Rosenbloom, 1981; Schmidt & Lee, 1998). However, most of the studies on motor learning do not draw conclusions concerning the nature of the modification(s). In fact, many studies analyzed only few trials per practice session or calculated averages between participants (Hong & Newell, 2006; Vereijken, 1991; Zanone & Kelso, 1992). These methods could mask the learning process.

In order to observe the nature of changes during learning, Nourrit, Delignières, Caillou, Deschamps, and Lauriot (2003) looked at the individual evolution of behavior produced during each trial. Participants were asked to perform wide, lateral movements as frequently as possible on a modified version of the ski-simulator (converted to a mono-ski in order to increase the initial difficulty of the task). The authors applied the W-method proposed by Beek and Beek (1988) for modeling the dynamics of the simulator platform's motion. To use it, the authors considered the entire system as a self-sustained oscillator. Results showed that all participants adopted a Rayleigh damping behavior at the beginning of practice. At the end of the experiment, all participants adopted another forcing behavior, characterized by a Van der Pol damping. The authors explained the initial use of the Rayleigh behavior by the difficulties that beginners encounter in the management of the reversal points of the platform's motion: Rayleigh damping is characterized by a quite precocious velocity peak in the cycle, and as such provides the system with a kind of dwelling time in the second part of the trajectory (between the middle of the apparatus and the next reversal point). The Van der Pol behavior, on the other hand, allows participants to adopt the high frequencies preserving the large amplitudes that characterize skilled performance. In fact, in the Rayleigh damping behavior, an increase in frequency leads to a decrease in amplitude. To maintain high amplitudes, participants need to adopt a Van der Pol behavior, allowing independence between frequency and amplitude.

Results also showed that the transition from the initial Rayleigh behavior to the final Van der Pol damping was characterized by a quite prolonged bi-stable stage during which the two behaviors were adopted in alternation (Nourrit et al., 2003). The authors offered two possible interpretations for these results.

First, they could reflect a saddle-node bifurcation, characterized by a transition from an initial to a final mono-stable regime, through a bi-stable phase during which the two attractors are simultaneously present (Kelso, 1995, p. 208). This kind of bifurcation was already used, for example, to model the walking/running transition (Diedrich & Warren, 1995). According to Kelso and Jeka (1992; see also Jeka, Kelso, and Kiemel, 1993), saddle-node bifurcations are likely to occur when an asymmetry exists between oscillators, due to differences in eigenfrequencies or in (neuro-)anatomical structures (Kelso, 1995). In bimanual coordination, symmetry is preserved and bifurcations between patterns take a pitchfork-like form (Haken, Kelso, & Bunz, 1985). Conversely, in walk–run transition or in leg–arm coordination, asymmetry leads to the occurrence of saddle-node bifurcations. The same reasoning could be applied to the ski-simulator task, where body and platform have different eigenfrequencies and different structures.

The second hypothesis of Nourrit et al. (2003) was that the observed changes were an expression of the parametric evolution of a hybrid model, containing from the beginning of practice both Rayleigh and Van der Pol terms (see, for example, Kay, Saltzman, Kelso, & Schöner, 1987). This second hypothesis suggests a kind of continuity between successive behaviors, as the observed changes could only be due to the evolution of the relative importance of the two damping terms (Nourrit et al., 2003).

To determine the continuous or discontinuous nature of the process, the authors performed for some trials an analysis at the behavioral level calculating a discrete relative phase (RP) between the platform and the center of gravity. When participants adopted a Rayleigh behavior at the beginning of practice, they applied forces into the system twice per cycle, with mean RP values of 61° and 210°. At the end of practice the Van der Pol behavior was characterized by mean RP values of 95° and 239°. In this study, there were no findings at any level (like platform behavior or motor behavior) which could help to choose between the qualitative change hypothesis or the parametric evolution hypothesis. These results underscore the ambiguity of the chosen situation, which could correspond to a competitive or a cooperative situation (Zanone & Kelso, 1997), precluding any conclusions about the continuous or discontinuous nature of the evolution of the damping function. This ambiguity could be due to the specificity of the ski-simulator task, where two rubber belts fastened the platform to the rails, and ensured that it regained its resting position in the middle of the apparatus after a forced deviation. This active process strongly constrained the behavior, compelling the participants to apply forces into the system twice per cycle from the beginning of practice.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

The aim of the present experiment was to observe the evolution of the behavior during a competitive situation in order to examine Nourrit et al.'s qualitative change (i.e., saddle-node bifurcation). To introduce a discontinuity between novice and skilled behaviors, we used an experimental swing, especially designed for this study, where the motion of the platform is only due to the body's motion, allowing the participant to apply force into the system once or twice per cycle. For this type of task, which requires the exploitation of gravity through pendular oscillations, Delignières et al. (1998) showed a qualitative difference between novice and expert behaviors characteristic for a competitive situation. In this experiment, participants without significant experience in gymnastics were invited to swing in a hang-inverted position under parallel bars. This task was novel and uncomfortable, requiring beginners to support their weight with their arms and change their usual visual space. Delignières et al. also tested high level gymnasts to compare the adopted behaviors. Results indicated that novice behavior was characterized by a strict phase synchronization and frequency locking (0° of RP and 1:1 frequency ratio) between the pendular oscillations of the center of mass around the hands, and the vertical oscillations of the center of mass above the shoulders. According to the authors, the adoption by all participants of this quite simple coordination mode suggested that beginners opt for the most easily controllable coordination pattern. However, novice participants were unable to adopt another coordination pattern during practice sessions. In contrast, gymnast experts adopted a 2:1 frequency ratio with a 90°/270° relative phase. This rather complex behavior allows an optimal exploitation of the passive forces of the system, and as such an efficiency of the energetical cost (Bernstein, 1967; Sparrow, 1983).

In the aforementioned experiment (Delignières et al., 1998), novices were unable to overcome their first behavior, despite 80 trials of practice on the task. In fact, the experimental situation was particularly uncomfortable, and the trials were too short to allow participants to accumulate sufficient practice. In the present experiment, oscillations were therefore performed in a comfortable standing position, allowing cumulating sufficient practice to permit participants to reach a skilled behavior. Our experimental swing was made of a wooden board which allowed lateral oscillations, linked to a fixed ground support (Fig. 1). The board was connected to the support by four metal tubes of 50 cm, which

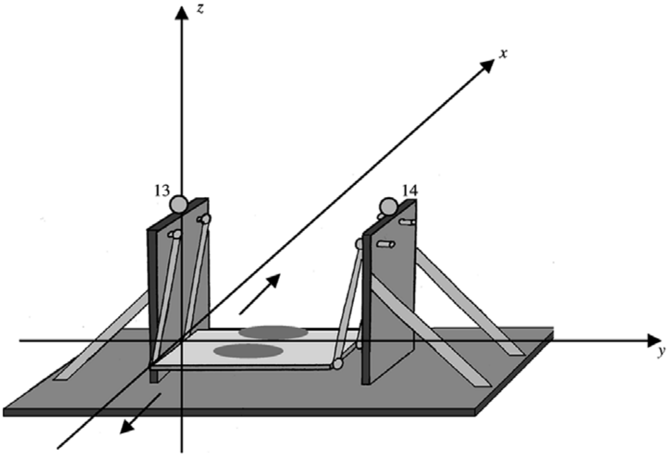

Fig. 1. The experimental swing (lateral view). Oscillations are performed along the x-axis.

enabled it to remain parallel to the ground throughout its oscillations. Participants stood on the board and were asked to amplify and maintain regular and fluid side-to-side oscillations in the medio-lateral plan.

This experimental swing is quite different from the traditional playground swing. Case (1996) identified two methods of energy insertion in a playground swing, called *driven oscillation* and *parametric pumping* (see also Kulkarni, 2003; Post, Peper, & Beek, 2003). These methods cannot be used on this experimental swing notably due to the difference of location of the center of gravity, which is *above* the point of rotation of the present experimental swing.

The only solution for sustaining and amplifying oscillations was to exert a force on the board by an extension of the body during the downward part of the swing (Fig. 2). This force can be decomposed into a radial component ($\vec{F}_{\mathrm{R}}$) and a tangential component ($\vec{F}_{\mathrm{T}}$). The tangential component represents the effective forcing applied on the board, for amplifying oscillations. This forcing should be initiated at the beginning of the swing, just after the reversal point, and should be pursued until passing through the rest position.

The application of this force can be revealed by the evolution of the distance (D) between the center of mass and the board. As such, for an optimal use of the swing, we expected to observe during the downward part of the swing, a progressive rising of the center of mass, relative to the board. As this forcing is repeated in the left swing and in the right swing, the resulting coordination should present a 2:1 frequency ratio between the evolution of D and the oscillations of the swing. A synchronization of the minima of D and the reversal points of the swing is also expected.

After practice, participants will most likely adopt this optimal behavior with a high consistency, consisting of a dual forcing located at the reversal points of the platform's cycle, corresponding to a 2:1 frequency ratio, with 0° and 180° of RP (at the left and right reversal point, respectively) between D and platform oscillations. In contrast, beginners should

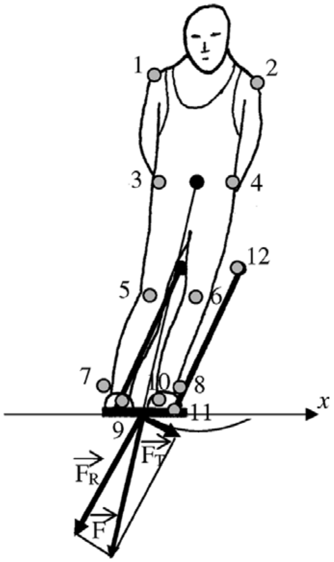

Fig. 2. Schematic representation of forcing during the right part of the swing, with the different marker positions.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

produce a unique forcing close to one of the reversal points. In accordance with frequency and phase locking principles a 1:1 frequency ratio is expected with a RP close to 0° or 180°. This is because this behavior should give some time to participants to reorganize their movement despite small amplitude of platform motion. Between these two behaviors, a bi-stable period reflecting a saddle-node bifurcation was expected, corresponding to an alternation between the novice behavior (single forcing with low consistency) and the skilled behavior (dual forcing with high consistency). Participants should enhance the amplitude of their swings and stabilize the oscillation frequency in order to produce stable behavior.

2. Method

2.1. Participants

Eight participants volunteered in this study (2 women and 6 men, mean age = 22.4 years, SD = 1.06; mean height = 170.1 cm, SD = 2.9; mean weight = 63.7 kg, SD = 4). None of them had any previous experience on the experimental task or particular expertise in related activities, such as skateboarding, skiing, gymnastics, or tightrope walking. They signed a consent form, and were not paid for their participation.

2.2. Apparatus

The experimental swing was made of a wooden board (supported by metal tubes) which oscillated in a medio-lateral plane defined by the x-axis (Fig. 1). Note that the board remained parallel to the ground throughout its oscillations.

2.3. Experimental protocol

The task was performed during ten sessions on five consecutive days, with two sessions per day. Each session comprised ten 20-s trials, with a 1-min resting period between two consecutive trials. Participants positioned themselves on the platform with feet apart and hands behind the back. They were asked to swing laterally “as smoothly as possible”. This instruction was repeated at the beginning of each session. No other verbal indication was given concerning the way to perform. Two weeks later, a post-test of one session was carried out.

2.4. Data collection

Participants were equipped with ten reflective markers as illustrated in Fig. 2, symmetrically placed on the humeral heads (marker 1 and 2), the great trochanters (marker 3 and 4), the knees (marker 5 and 6), the outer malleoli (marker 7 and 8), and the feet (marker 9 and 10). Each marker’s position was indicated on the skin (or clothes) with an indelible pen to ensure accurate repositioning over sessions. Two additional markers were placed at the extremities of one of the metal bars (11 and 12). These markers were used to assess the angular displacement of the platform relative to the vertical axis. Finally, two markers were symmetrically located at the top of the right and left bearings (marker 13 and 14, see Fig. 1). These last markers were used to define the transverse axis y of the apparatus.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

The markers' motions were recorded in three dimensions using a Vicon 370 motion analyzer (Biometrics) equipped with four cameras operating at a sampling frequency of 50 Hz. Cameras were positioned in a semicircle in front of participants. Recording started at the end of the first swing.

2.5. Data reduction

Data were obtained in the form of three-dimensional time series (x, y, z) for each marker. We first performed a rotation of the coordinates around the z-(vertical) axis in order to align the y-axis on the direction defined by the average positions of markers 13 and 14. We hypothesized that the essential information concerning swing motion and motor coordination would be concentrated in the transversal plane, so the new y-axis was ignored and the coordinates of the markers were analyzed in two dimensions (x and z). All these data were smoothed with a Butterworth filter, with a cut-off frequency of 10 Hz.

2.5.1. Outcome variables

We calculated a time series of the β angle between the marker 11/marker 12 axis and the vertical axis. This angle represented the instantaneous amplitude of the platform deviation from its resting position. A peak-finding algorithm was used to locate the reversal points of β angle's motion (i.e., the points of maximal deviation, to the right and to the left). β frequency (Hz) was defined as the inverse of the time between two successive right reversals. β amplitude (cm) was defined as the mean of the maximal deviations of the platform from the rest position at the right and left reversal points of the cycle. Mean and standard deviations of β amplitude and frequency, as well as the ratio between amplitude and frequency were calculated for each trial.

2.5.2. Coordination modes

2.5.2.1. Relative phase. The coordinates of the segmental centers of mass and the body center of mass were computed based on the data concerning segmental body weight/body weight ratios and position of center of mass/segment length ratios proposed by Winter (1990), (Table 3.1., pp. 56–57). Distance (D) between the barycenter of markers 9 and 10 (right and left feet) and the body center of mass was calculated. A peak-finding algorithm was used to locate the minima of D. The reversal points of swings corresponded to β extremes. In order to describe the local organization between these two components (β and D), a discontinuous relative phase (RP) was calculated according to the method of point estimate using the following formula:

$$RP = \frac{tD\min - t\beta_n \min}{t\beta_{(n+1)}\min - t\beta_n \min} * 360^\circ.$$

In this equation, $t\beta_n$ min and $t\beta_{(n+1)}$ min represent the times of the minima of β for cycles n and $n+1$, respectively, and tDmin represents the time of a minimum of D occurring during cycle n. For each swing or each period of $\beta(t\beta_{(n+1)}\min - t\beta_n\min)$, a peak-finding algorithm searched the number of Dminima (Dmin) and their times (tDmin). Single forcing was revealed by a unique Dmin during a β period whereas dual forcing corresponded to two Dmin in a same swing. An RP was calculated for each Dmin. RP_1 value corresponded to the first Dmin occurring in the cycle and RP_2 value corresponded to the second

Dmin occurring in the cycle. The RP_1 was always lower than the RP_2 value. This discrete relative phase corresponded to the phase angle of β at the initiation of platform forcing within each cycle and gave information about the time of forcing and the number of forcings exerted during each cycle.

2.5.2.2. Graphical representation. In order to represent these different behaviors on the same graph, a spherical representation of the RP values was created. For each cycle, one measure of RP or two measures in the case of dual forcing were obtained. For the purpose of the present analysis, a complete cycle of the platform was divided into a left swing, representing the trajectory of the platform in the left direction, starting and finishing in the resting position, and a right swing, in the opposite direction. When forcing occurred during the left swing, RP fell between 270° and 90° via 0°, and when forcing occurred during the right swing, RP fell between 90° and 270° via 180°.

Three main modes of coordination could be logically observed in this task: the first one involved a unique forcing performed during the left swing, the second a unique forcing performed during the right swing, and the third was characterized by a dual forcing. The first one occurred during the left swing and the second during the right swing (Fig. 3a). In order to obtain a convenient 3-dimensional representation of these three coordination modes, a projection of the right and left swings on two orthogonal phase planes was performed as illustrated in Fig. 3b, left and right, respectively.

Each single forcing was represented by a 'phase vector'. Depending of the nature of forcing, the direction of the 'phase vector' varied in this three-dimensional space. A forcing initiated during the left swing was represented by the corresponding phase vector in the horizontal plane. The end points of the set of possible vectors defined a semicircle of radius one in the plane. Similarly, a forcing initiated during the right swing was represented by a 'phase vector' in the vertical plane. Dual forcing was represented by the resultant vector of

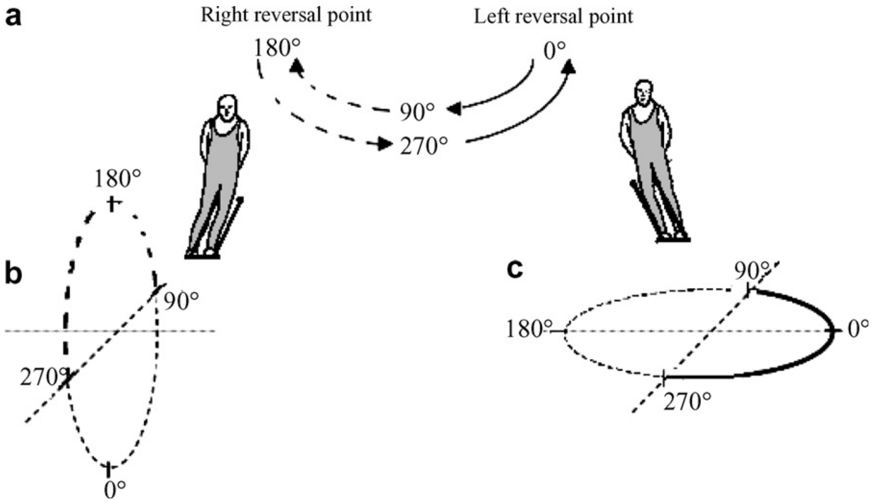

Fig. 3. (A) Representation of one cycle: (–––) right swing, (—) left swing. (B) Projections of right swing (left graph), and left swing (right graph) on orthogonal trigonometric circles.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

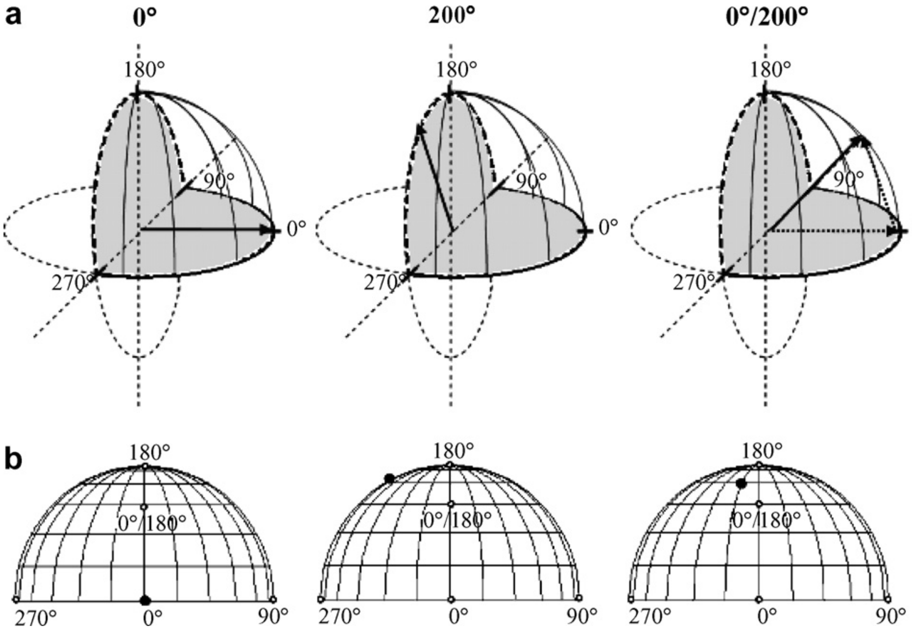

Fig. 4. (A) A merge of the circles was realized to create a sphere where all possible forcing patterns could be represented by vectors. Vectorial representation of a forcing initiated at 0° (left), at 200° (middle), and at 0° and 200° (right), vector obtained by adding 0° vector (step 1) with 200° vector (step 2) representing dual forcing (step 3). (B) Representation of the same forcing on the quarter sphere in front view.

the combination of the two constituent 'phase vectors'. This resultant vector was then divided by its norm in order to normalize its length to unity.

These two semicircles defined a quarter sphere (Fig. 4a) on which all possible coordination modes could be represented by the end points of the corresponding vectors. Fig. 4 represents three typical examples of the possible behaviors. The left spheres represent one of the possible left forcings, the 0° of RP. Each left forcing could be represented by a point on the equator line, like the 0° of RP (Fig. 4b).The middle spheres represent one of the possible right forcing (200° of RP), characterized by a point on the back meridian (Fig. 4b). And the right sphere represent one dual forcing (0°/200°) which appeared as a point in the central zone of the quarter sphere (Fig. 4b).

2.5.3. Consistency

2.5.3.1. Global consistency. Because RP values are bimodal in nature, normal descriptive statistics (mean and standard deviation) could not be applied in this study. Importantly, participants had not a specified pattern to produce and could explore all the possible behaviors (e.g., 0°, 150°, 340°, single or dual forcing). Calculating a mean does not give any information in this case. Moreover when participants adopt only a few dual forcings during the first session, the mean and the standard deviation would not provide meaningful results. However, the vectorial representation detailed above allowed for the derivation of a measure of 'forcing consistency' during the complete learning process. We computed the angle between the resultant vectors of each pairs of consecutive cycles, and then the mean angle was calculated for each trial, giving an indication of forcing consistency. A mean angle close to zero corresponded to a highly consistent forcing across cycles both in the type of forcing (1:1 or 2:1) and in the time of forcing (RP values). A high mean angle value (with a maximum of 180°) corresponds to a non-consistent behavior, with a total independency between consecutive forcing. A mean angle around 90° expressed a low consistency and could reveal an alternation between types of forcing or a high variability of time of forcing.

2.5.3.2. Type of forcing. For each session of practice, the percentage of single and dual forcing was calculated for each participant. The number of single and dual forcings for each trial was recorded. Then the percentage of cycles using each type of forcing was calculated for each session.

These percentages provided information on the consistency of the type of forcing. A session with all forcing located on the back meridian or on the equator line of the sphere corresponded to 100% of single forcing. A session with all forcing located in the central zone of the sphere corresponded to 100% of dual forcing.

2.6. Statistical analyses

Outcome variables (β amplitude, frequency, ratio between amplitude and frequency) and forcing consistencies (global and type of forcing) were analyzed by a one-way ANOVA (Session) with eleven levels of repeated measurements. Normality and variance homogeneity were tested before treatment. Statistical significance was set at $p < .05$. Taking into account a probable violation of the sphericity hypothesis, the probability was corrected according to the Greenhouse-Geisser procedure. The partial effect size (η^2) is reported and a Tukey post hoc test was used to follow up significant effects.

3. Results

3.1. Outcome variables

3.1.1. Amplitude

A significant effect of session was obtained, $F(10, 70) = 35.1$, $p < .05$, $\eta^2 = .83$. Mean amplitude increased from 69.1° (±17.5°) during the first session to 117.7° (±17.8°) during the last session (Fig. 5a). The Tukey test indicated that amplitude was significantly larger during session 2–10 than during session 1, larger during sessions 4–11 (post-test) than during session 2, and larger during sessions 8–10 than during session 3. There was no significant difference between the last session and the post-test.

3.1.2. Frequency

The effect of session on frequency was not significant, $F(10, 70) = 1.38$, $p = .2$, $\eta^2 = .16$. Fig. 5b shows that participants appeared to converge towards an average frequency of about 1.2 Hz across sessions. The atypical behavior of participant 7 should be noted. This participant only showed a frequency of around 1.2 Hz in the post-test after oscillating during the experiment at very high frequencies.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

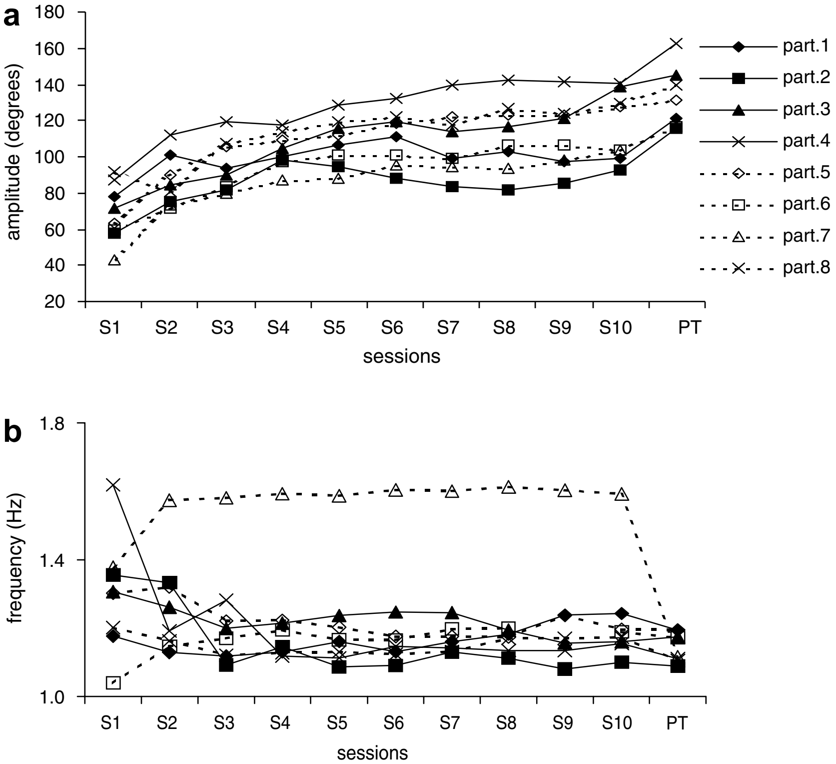

Fig. 5. Individual evolutions of amplitude (a) and β frequency (b) across sessions (S). PT is the post-test also corresponding to session 11.

3.1.3. *Amplitude/frequency ratio*

A significant effect of session on the amplitude/frequency ratio was found, $F(10,70) = 32.6$, $p < .05$, $\eta^2 = .77$. The Tukey test indicated that the ratio was significantly higher during sessions 2–11 than during session 1, higher during sessions 4–11 (post-test) than during session 2, and higher during sessions 6–10 than during session 3. There was no significant difference between the last session and the post-test.

3.1.4. *Consistency*

3.1.4.1. Global consistency. No significant effect of session on global consistence was obtained, $F(10,70) = 1.27$, $p = .26$, $\eta^2 = .15$, as can be appreciated from Fig. 6. The individual evolutions revealed that the mean angle decreased for participants 1, 3, 4, 6 and 8 (implying increased consistency) while it tended to increase and then stabilize for participants 2, 5 and 7 (implying a decrease in the consistency of forcing).

3.1.4.2. Type of forcing. A significant effect of session on type of forcing was found, $F(10,70) = 37.8$, $p < .05$, $\eta^2 = .85$. The average single forcing percentage decreased from 85% (±11.7%) during the first session to 17% (±4.3%) during the last session (Fig. 6). The Tukey test indicated that consistency of single forcing was significantly higher during

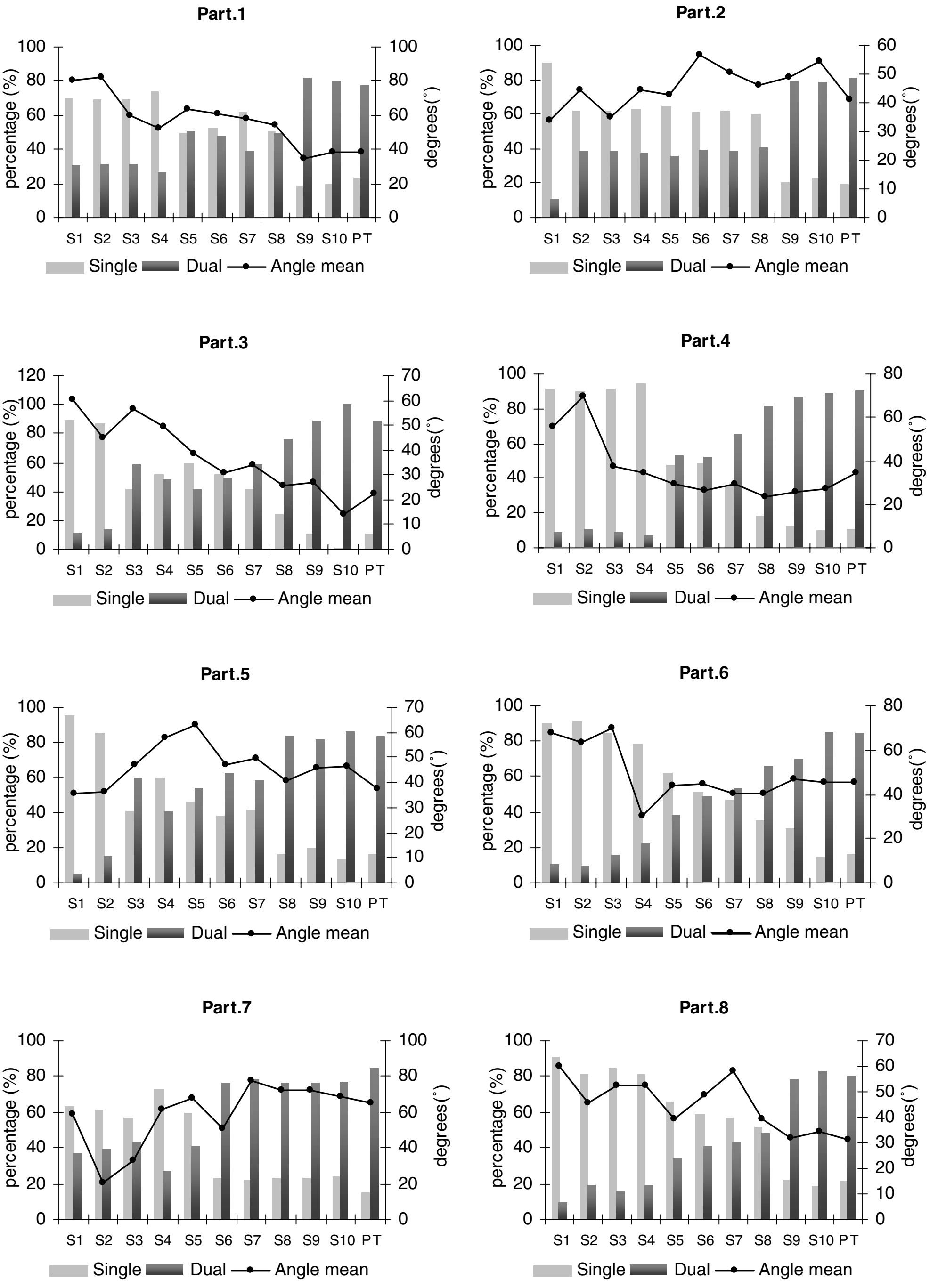

Fig. 6. Individual evolution of global consistency (mean angle) and the type of forcing (single vs. dual forcing) adopted during each session. The type of forcing corresponds to the percentage of cycles per session where single or dual forcings were adopted.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

sessions 1, 2, 3 and 4 than during session 6–11 (post-test), and during sessions 6 and 7 compared to sessions 9–11. There was no significant difference between the last session and the post-test. Type of forcing was significantly correlated with the ratio between amplitude and frequency $r(85) = -.47$, $p < .05$.

3.2. Coordination modes

3.2.1. Relative phase and graphical representation

The spherical representation allowed a qualitative assessment of the evolution of forcing strategies with learning (representation of RP values and frequency ratios). Fig. 7 shows the spheres obtained for four participants, representing trial 5 in sessions 1, 5, and 10. These evolutions of four behaviors are representative of other participants in the sample. Participants 4 and 6 exhibited the same evolution as participants 3 and 8, with only a difference on the trial in the fifth session: the upper graph represents an alternation period, during which participant 4 used only the right reversal point during single forcing, while participant 6 produced single forcing around the right and left reversal points. Participant 5 exhibited a similar evolution to participant 2, who had a stable behavior during the first session, before adopting the same evolution as participants 3, 4, 6, and 8. Finally, the bottom spheres represents the evolution of participant 1 (similar to the evolution of participant 7), who employed dual forcing since the first session.

In general, the first trials were characterized by an unstable coordination as illustrated in Fig. 6, dominated by single forcing strategies (see Figs. 6 and 7). These behaviors could

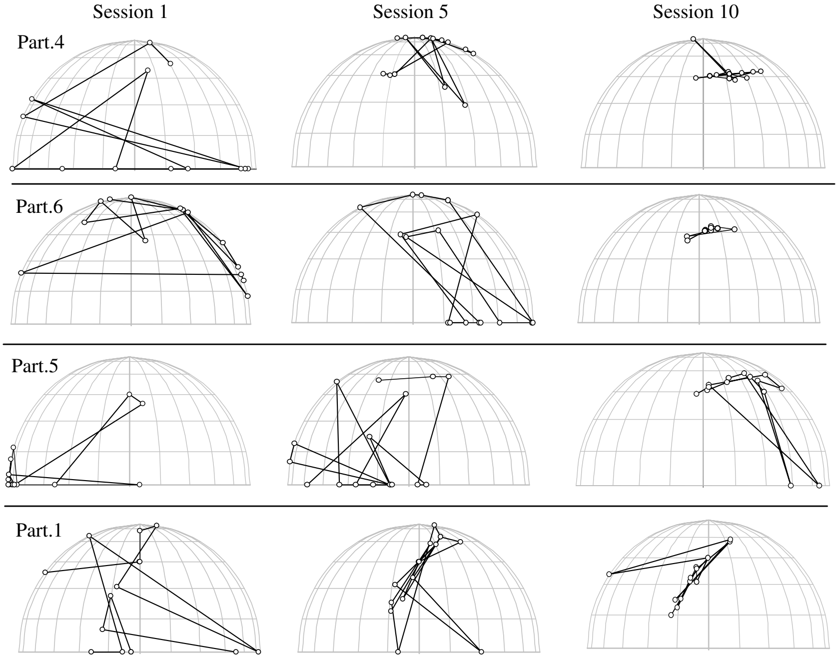

Fig. 7. Spherical representations of the evolution of forcing for four participants (4,6,5 and 1) during session 1 trial 5 (left), session 5 trial 5 (middle), and session 10 trial 5 (right).

reflect an erratic exploration of possible coordination modes. In the middle course of learning, single forcing appeared more centered around the reversal points of the platform's motion (i.e., in Fig. 7, around the pole and the central part of the equator). Single forcing was adopted in alternation with dual forcing, with frequent switches, from one cycle to the next, from one kind of coordination mode to the other. The final trials appeared dominated by dual forcing strategies. This coordination mode was adopted in a more consistent way than early in practice, with some rare excursions toward a single forcing coordination, in an isolated cycle (Figs. 6 and 7, session 10).

4. Discussion

This study focused on the evolution of coordination modes during a competitive situation (Zanone & Kelso, 1997). An alternation period was expected during which participants oscillated between novice and skilled behaviors, represented by single and dual forcing, respectively.

In the course of the experiment, all participants enhanced their amplitude of swinging (during the three first sessions) and converged toward a frequency of about 1.2 Hz, which could correspond to the optimal oscillation frequency of the system (Durand, Geoffroi, Varray, & Préfaut, 1994). The ratio between amplitude and frequency increased significantly during the first three sessions, and the type of forcing evolved significantly during the first four sessions. Stabilizing a certain value of this amplitude/frequency ratio seemed necessary to adopt a dual forcing, as evidenced by the correlation between these two variables (i.e., ratio of amplitude and frequency and type of forcing). Nevertheless, the rather low value of this correlation ($-.47$) suggested that the amplitude/frequency ratio is not the only factor that was implicated in the adoption of dual forcing.

At the behavioral level, inter-individual differences in the strategies of forcing appeared during the first trials of the task. Actually two kinds of behavior could be described: some participants adopted a strategy based predominantly on single forcing (participants 2, 3, 4, 5, 6 and 8), while others (participants 1 and 7) alternated from the beginning of practice between single and dual forcing. These behaviors could correspond to an exploration of the perceptual-motor workspace, that is, an exploration of all available behavioral possibilities (Newell, Kugler, Van Emmerick, & Mc Donald, 1989). In these two cases, the consistency of forcing was rather poor as forcing occurred anywhere in the swing.

Later in practice, single forcing converged toward the reversal points of the swing's motion, which were also used in dual forcing. With practice, dual forcing was used more frequently, and this forcing prevailed in all participants during the last sessions. Behavioral consistency appeared stronger at the end of practice in all participants, except for participant 7. This participant oscillated following a very high frequency during the whole experiment (except during the post-test, see Fig. 5). One could suppose that this high frequency did not allow for the adoption of a consistent behavior, which could explain the low consistency of this participant's forcing behavior at the end of practice compared to the other participants.

It seems evident that in the present study participants did not possess the same skill level as at the beginning of practice. Participants who adopted single forcing strategies could be considered as true beginners, but those who produced alternation between single and dual forcing from the first trial appeared more skilled, as this behavior corresponded to the strategy adopted by the former participants after 3 or 4 practice sessions. In terms of

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013

Newell (1986) constraint taxonomy, these differences could arise from individual-specific organismic constraints. Organismic constraints are composed of structural constraints (weight, height) and the participant's history (knowledge, motor skills). In the present experiment, participants had quite similar structural constraints as evidenced by low SDs for height and weight variables. Thus, differences in the evolution of behavior could be due to differences in the initial skill level of participants due to previous motor experiences (e.g., experience in skiing, in gymnastic or in other sports). Despite these early differences, the route of learning varied little across participants, with 6/8 participants using a single forcing strategy before entering into an alternation period and then progressing to a stable period characterized by dual forcing.

During the first trials, the adoption of single forcing for some participants corresponded to the expected novice behavior (see Delignières et al., 1998). These participants exhibited inconsistent relative phase as indexed by high global consistency values, when participants produced only single forcing (see Fig. 6). This kind of erratic behavior was observed earlier by Vereijken (1991) on the ski-simulator, who interpreted this instability in relative phase as phase correction or 'phase slippage', whereby one of the oscillators gains a period with respect to the other (Kelso, DeGuzman, & Holroyd, 1991). This correction could be used when the divergence between the phases of the platform and that of the center of gravity became too large for sustaining performance. Novices seemed to use phase slippage, introducing for example an extra cycle (corresponding here to a dual forcing) in one of the oscillators (i.e., the distance between the center of gravity and the feet) in order to recover a manageable relation with the other oscillator (i.e., the platform). This kind of strategy appears when each oscillator tends to follow its eigenfrequency, a phenomenon termed 'relative coordination' by Von Holst (1973). This strategy perturbs the time series of both platform (by reducing the amplitude) and center of gravity (by creating supplementary cycles) and could occur everywhere in the cycle, resulting in a somewhat erratic forcing behavior (Vereijken, 1991).

After some practice participants generally applied force at the reversal points of the platform's motion (Fig. 7, sessions 5 and 10). This stabilization around reversal point (RP of 0° or 180°) occurred by a drift of forcing in the course of learning. After one or two sessions of relative phase exploration, participants stabilized their behavior around 0° or 180° RP. For example, participant 4 adopted very different single forcing during the first session (Fig. 7) with a low consistency (Fig. 6). During sessions 2–4, the person continued to adopt single forcing in a more consistent way (see the decrease of mean angle between sessions 2 and 4, with more than 80% of single forcing in Fig. 6), expressing a stabilization of the time of forcing. This centering of coordination for participant 4 can be seen in Fig. 7 during session 5, where single forcing is produced only around the pole (i.e., RP of 180°), and dual forcing in the central zone of the sphere (i.e., 0° and 180° of RP).

This stabilization of forcing was revealed by consistent behaviors for participants 2, 3, 4, 5, and 6 during the sessions preceding the alternation period, whereby an alternation period is defined by a period during which participants adopt less than 75% of a same type of forcing behavior. During this period, the frequency ratios between the platform and the distance between the center of gravity and the platform oscillated between two integers, representing by single or dual forcing. According to Kelso and Jeka (1992) this kind of behavior could correspond to an intermittency period. In their study, participants had to produce different relative phases between right or left arms, legs, or both, and the authors showed that this period during which participants oscillated between behaviors could correspond to an intermittency period, a generic characteristic of dynamical systems close to a saddle-node bifurcation (Kelso et al., 1991). Such a system contains simultaneously an unstable attractor point and a stable one, which drifts in the direction of the new state before the transition. The saddle-node bifurcation corresponds to the coexistence of these stable and unstable points which collapse to give a unique attractor point after the transition (Kelso, 1995, p. 208). The results of the present study suggest a drift of the initial single forcing in direction of the reversal points, followed by the coexistence of single and dual forcing. Finally, participants adopted dual forcing. These results could correspond to a saddle-node bifurcation with an intermittency period, corroborating the hypothesis of Nourrit et al. (2003) and reinforcing the idea of Zanone and Kelso (1992, 1997) on the assimilation of learning process as a phase transition in competitive situations.

In conclusion, this study shows that gross motor skill learning in a competitive situation may involve qualitative changes taking the form of a saddle-node bifurcation, with a stable state corresponding to novice behavior, followed by a bi-stable stage during which participants alternate between novice and skilled behaviors, and thirdly, a new stable state corresponding to the skilled behavior. In this kind of bifurcation, the transition occurs due to a drift of the first stable state, raising the question of the role of novice behavior in the learning process in competitive situation, which could constitute an anchor point permitting the emergence of the skilled behavior.

References

Arutyunyan, G. H., Gurfinkel, V. S., & Mirskii, M. L. (1968). Investigation of aiming at a target. *Biophysics, 13*, 536–538.

Beek, P. J., & Beek, W. J. (1988). Tools for constructing dynamical models of rhythmic movement. *Human Movement Science, 7*, 301–342.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Case, W. (1996). The pumping of a swing from the standing position. *American Journal of Physics, 64*, 215–220.

Delignières, D., Nourrit, D., Sioud, R., Leroyer, P., Zattara, M., & Micaleff, J.-P. (1998). Preferred coordination modes in the first steps of the learning of a complex gymnastics skill. *Human Movement Science, 17*, 221–241.

Diedrich, F. J., & Warren, W. H. Jr., (1995). Why change gaits? Dynamics of the walk–run transition. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 183–202.

Durand, M., Geoffroi, V., Varray, A., & Préfaut, C. (1994). Study of the energy correlates in the learning of a complex self-paced cyclical skill. *Human Movement Science, 13*, 785–799.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51*, 347–356.

Hong, S. L., & Newell, K. M. (2006). Practice effects on local and global dynamics of the ski-simulator task. *Experimental Brain Research, 169*, 350–360.

Jeka, J. J., Kelso, J. A. S., & Kiemel, T. (1993). Spontaneous transitions and symmetry: Pattern dynamics in human four-limb coordination. *Human Movement Science, 12*, 627–651.

Kay, B. A., Saltzman, E. L., Kelso, J. A. S., & Schöner, G. (1987). Space-time behavior of single and bimanual rhythmical movements: Data and limit cycle model. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 172–192.

Kelso, J. A. S. (1995). *Dynamic patterns. The self-organization of brain and behavior*. Cambridge, Mass: MIT Press.

Kelso, J. A. S., DeGuzman, G. C., & Holroyd, T. (1991). The self-organized phase attractive dynamics of coordination. In A. Babloyantz (Ed.), *Self-organisation, emerging properties, and learning* (pp. 41–62). New York: Plenum.

Kelso, J. A. S., & Jeka, J. J. (1992). Symmetry breaking dynamics of human multilimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 645–668.

Kulkarni, J. E. (2003). Time-optimal control of a swing. Paper presented at the 42nd IEEE conference on decision and control, Hawaï, USA.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition*. Hillsdale: Erlbaum.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341–360). Dordrecht: Nijhoff.

Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42*, 213–237.

Newell, K. M., Kugler, P. N., Van Emmerick, R. E. A., & Mc Donald, P. V. (1989). Search strategies and the acquisition of coordination. In S. A. Wallace (Ed.), *Perspectives on the coordination of movement* (pp. 85–122). Amsterdam: North-Holland.

Nourrit, D., Delignières, D., Caillou, N., Deschamps, T., & Lauriot, B. (2003). On discontinuities in motor learning: A longitudinal study of complex skill acquisition on a ski-simulator. *Journal of Motor Behavior, 35*, 151–170.

Post, A. A., Peper, C. E., & Beek, P. J. (2003). Effects of visual information and task constraints on intersegmental coordination in playground swinging. *Journal of Motor Behavior, 35*, 64–78.

Schmidt, R. A., & Lee, T. (1998). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.

Sparrow, W. A. (1983). The efficiency of skilled performance. *Journal of Motor Behavior, 15*, 237–261.

Temprado, J., Della-Grasta, M., Farrell, M., & Laurent, M. (1997). A novice-expert comparison of (intra-limb) coordination subserving the volleyball serve. *Human Movement Science, 16*, 653–676.

Vereijken, B. (1991). *The dynamics of skill acquisition*. Amsterdam: Free University of Amsterdam.

Von Holst, E. (1973). Relative coordination as a phenomenon and a method of analysis of central nervous function. In R. Martin (Ed.), *The collected papers of Erich Von Holst* (pp. 33–135). Coral Gables, FL: University of Miami.

Winter, D. A. (1990). *Biomechanics and motor control of human movement* (2nd ed.). New York: Wiley.

Zanone, P. G., & Kelso, J. A. S. (1992). Evolution of behavioral attractors with learning: Nonequilibrium phase transitions. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 403–421.

Zanone, P. G., & Kelso, J. A. S. (1997). Coordination dynamics of learning and transfer: Collective and component levels. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1454–1480.

Please cite this article in press as: Teulier, C., & Delignières, D., The nature of the transition between novice ..., *Human Movement Science* (2007), doi:10.1016/j.humov.2007.01.013