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The Evolution of Oscillatory Behavior During Learning on a Ski Simulator

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Recent experiments on the ski simulator produced ambiguous results and raised unanswered questions concerning the true nature of "novice" behavior and the occurrence of behavioral changes during learning. The aim of the present experiment was to analyze the evolving behavior of three beginners during six practice sessions on a ski simulator. The position of the apparatus platform was recorded as time series and used for constructing dynamical models, including stiffness and damping functions. The results showed that novices tended to exploit a Rayleigh damping behavior during the first trials and then transition toward a van der Pol damping. These results replicate previous observations by Nourrit, Delignières, Caillou, Deschamps, and Lauriot (2003) and suggest the transition to the expert behavior could arise early in practice, when the task is of moderate difficulty. The discussion focuses on the properties of the observed learning dynamics and proposes a global conceptualization for acquiring complex motor skills.

Key words: complex skill acquisition, dynamical modeling, learning transition, spontaneous behavior

From a dynamical systems point of view, the initial behavior of beginners facing a novel task is conceived as the expression of the system's intrinsic dynamics (Delignières, Nourrit, Sioud, Leroyer, Zattara & Micaleff, 1998). The system's spontaneous coordination tendencies determine attractive states, which strongly constrain the emergence of new behavior. The intrinsic dynamics of bimanual coordination have been extensively studied, and in-phase and antiphase coordination have been identified as the primary intrinsic coordination tendencies of the bimanual system during oscillatory tasks (e.g. Kelso, 1984; 1995). The in-phase bimanual pattern involves symmetric hand motion in opposite directions, with simultaneous homologous muscle activity, and the antiphase pattern involves motion in the same direction, with simultaneous nonhomologous muscle activity. Due to the strong attraction of systems intrinsic patterns, naive participants encounter difficulties in performing other phase relationships between the hands (Zanone & Kelso, 1992). As such, learning frequently necessitates the performer to overcome the spontaneous tendencies to stabilize a new, qualitatively distinct pattern. Learning is then characterized by qualitative shifts in the coordination mode and could be conceived as a bifurcation process, from initial to skilled behavior (Zanone & Kelso, 1992).

Vereijken (1991) observed such qualitative reorganizations of behavior during learning on a ski simulator and described skill acquisition as the succession of three distinct stages, characterized by different mechanical models. More precisely, she described the learners' behavior as an inverted balancing pendulum during the first practice trials, a simple hanging pendulum (resembling the pendulum of a clock) during an advanced stage, and finally as a buckling compound pendulum (incorporating additional degrees of freedom and especially hip and knee motions) during the expert stage. The author interpreted this evolution based on Bernstein's assumptions about learning, with an initial freezing of articular joints and then a progressive release of degrees of freedom and their incorporation

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into a coordinative structure, allowing efficient exploitation of the mechanical properties of the apparatus.

This first approach, nevertheless, was qualitative and didn't allow for analysis of the transition from one coordination mode to the other during learning. In a series of experiments, Delignières, Nourrit, and colleagues tried to develop a new method to assess the dynamical properties of learners' behavior and especially the way they forced the simulator to sustain oscillations (Delignières, Nourrit, Deschamps, Lauriot & Caillou, 1999; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). They applied the W-method proposed by Beek and Beek (1988), which is a series of graphical and statistical tools aimed at deriving dynamical models from kinematic data. In this framework, rhythmic movements are modeled as oscillators obeying second order ordinary differential equations of the kind:

$$m\ddot{x} + g(x) + f(x, \dot{x})\dot{x} = 0, \qquad (1)$$

where x represents position. The dot notation indicates differentiation with respect to time. The first term expresses the inertia of the system, the second the system's stiffness (or elasticity; i.e., the intensity of the restoring force when the system is moved away from its resting position) and the third, the system's damping (negative and positive; i.e., injection and dissipation of energy). The major concern of this approach is to identify the nonlinear stiffness and damping functions that characterize the dynamics of the movement.

In a first experiment (Delignières et al., 1999), three groups of participants practiced on the simulator for four sessions. Each group had to reach and maintain a given oscillation amplitude—15, 22.5, or 30 cm, respectively. Analyses focused on the oscillations of the simulator platform, considered an end-effector. In a first step, data were averaged and normalized at the group level, according to the procedure proposed by Mottet and Bootsma (1999). Then the W-method was applied to the resulting normalized cycles. The results showed the platform oscillations were adequately captured by the following model:

$$\ddot{x} + c_{10}x + c_{30}x^3 + c_{50}x^5 + c_{01}\dot{x} + c_{21}x^2\dot{x} = 0 \qquad (2)$$

which contained a nonlinear stiffness function $g(x) = c_{10}x + c_{30}x^3 + c_{50}x^5$ (c_{30} was negative and c_{50} positive, denoting a complex process of softening/hardening of the stiffness during the oscillation), and a van der Pol damping function $f(x, \dot{x})\dot{x} = c_{01} \quad + c_{21}x^2\dot{x}$ (note that in these equations, the coefficients are indexed using the W-method notation proposed by Beek and Beek (1988), where cij denotes the coefficient of $x^i\dot{x}^j$).

These analyses revealed the presence of high nonlinearities in the stiffness function. The inclusion of negative cubic and positive quintic Duffing terms was necessary to account for the deviations from a harmonic motion. Further analyses showed that these nonlinear stiffness terms increased with required amplitude and decreased with practice. Conversely, the damping function was statistically identical among groups and remained stable with practice.

This first experiment failed to evidence any qualitative evolution of the dynamical model with practice. In other words, and at least within the window explored in this experiment, practice resulted in continuous changes in coordination rather than in qualitative transitions. Two divergent explanations could be evoked following this result. The first refers to a possible difference between the Vereijken (1991) and Delignières et al. (1999) experiments in the prior capabilities of the respective participants. In the second work, the participants were able from the first experimental trials to reach the required amplitudes, even in the 30-cm and 22.5-cm groups, when the average initial amplitudes reported in Vereijken's experiments were around 10 cm (Vereijken, 1991). It is important to note that in the Delignières et al. (1999) study participants were students of sport science, and, while naive on use of the ski simulator, all had previous ski experiences. In addition, they performed two warm-up trials prior to the experiment, which could have allowed them to quickly solve the initial task problems. This suggests that, from the beginning of the experiment, they could have been beyond the first stage identified by Vereijken (the "balancing pendulum").

A second explanation could be the narrowness of the temporal window considered in this experiment. Motor skill acquisition requires a large amount of practice (Schmidt & Lee, 2005), and in such complex tasks transitions could need more time to occur. From this point of view, a longer observation period would be necessary to obtain clear bifurcations in learners' behavior.

To test these two hypotheses, a second experiment was performed with a better control of the (relative) initial task difficulty and a longitudinal design (Nourrit et al., 2003). For this experiment, 5 participants practiced on the ski simulator for 13 weeks, with three sessions of ten 1-min trials per week (i.e., a total amount of 390 trials). A modified monoski version of the simulator was used—a single board, moving around a saggital axis, replaced the two independent foot supports of the original apparatus. This new task was clearly more difficult than the classical simulator and was believed to ensure the observation of novice behavior, at least during the first trials.

The preceding modeling procedure was applied on individual data. The results showed that from the first trials all participants exploited a Rayleigh behavior. The model was of the following form:

$$\ddot{x} + c_{10}x + c_{30}x^3 + c_{50}x^5 + c01\,\dot{x} + c_{03}\dot{x}^3 = 0 \qquad (3),$$

including a Rayleigh damping function $f(x, \dot{x})\,\dot{x} = c_{01}\dot{x} + c_{03}\dot{x}^3$.

Later in the experiment, all participants transitioned from the Rayleigh to a van der Pol behavior (see Equation 2). This transition was not abrupt but characterized by a quite long bistable transition period, during which the two damping behaviors were alternatively exploited within each trial. The authors interpreted this transient bistable regime as the signature of the so-called *saddle-node* bifurcation. In such bifurcation, the transition from the initial pattern to the final one is achieved through a stage during which the two solutions are simultaneously available. During this transition stage, the two attractors present a lower stability than during the initial and the final monostable regimes. Diedrich and Warren (1995) notably used this bifurcation was for modeling the walk-run transition.

In the Nourrit et al. (2003) experiment, this period of transition appeared approximately during the second week of practice (i.e., after 50 or 60 trials), but its duration was different among participants. Some definitely adopted the van der Pol behavior during the third week, but one was not stabilized on the new behavior before the 10th week.

These results strongly suggested that exploiting a Rayleigh damping function should characterize beginners' "true" behavior during their first trials. The consequence of the task modification was to delay emergence of the transition. But one could hypothesize that with the "traditional" ski simulator, this transition could occur early in practice during the first trials or sessions. From this point of view, it could be hypothesized that participants of the Delignières et al. (1999) work, who exhibited a clear van der Pol behavior, were beyond this transition from the beginning of the experiment.

The aim of the present experiment was to confirm (a) beginners' exploitation of a Rayleigh damping function during the first trials and (b) the precocious appearance of a bifurcation from Rayleigh to van der Pol behavior during the first practice sessions on the traditional simulator. Additionally, we assessed oxygen intake throughout the experiment to check whether the transition from a damping behavior to the other led to discernable evolution of movement efficiency.

Method

Participants

Three participants (*M* age = 22.8 years, *SD* = 2.1; *M* weight = 71.8 kg, *SD* = 3.5; *M* height: 177.6 cm, *SD* = 5.2) volunteered for this experiment. All were occasional skiers, but none had previous experience on the ski simulator. They signed a consent form and were not paid for their participation.

Experimental Task

Participants performed the task on a slalom ski simulator (Skier's Edge, Park City, UT; see Figure 1), which consists of a wheeled platform that moves back and forth on two bowed, parallel metal rails. The participant's feet were strapped to the platform, which was fastened to the rails by two adjustable rubber belts. The belt tension was controlled with a dynamometer at the beginning of each session and adjusted to a displacement of 4 cm of the platform from the central position, with a tangential force of 100 N. To test the intrinsic dynamics of the apparatus, we analyzed the relationship between displacement (x) and restoring force (F); within the range of amplitudes used in the present experiment, this relation appeared perfectly linear ($F = 1{,}715.9x$, $r^2 = .99$), suggesting that the rubber belts acted as perfect linear springs.

Procedure

Participants were to perform oscillations as large as possible. Note that the maximal deviation from the resting position on the simulator is about 50 cm. They were instructed to keep their hands behind their back at all times and fix their eyes on a point on the floor, 3 m in front of the apparatus. Participants performed six practice sessions over 6 consecutive days. Each session was composed of four 4-min trials with a 4-min break in between. Participants practiced individually.

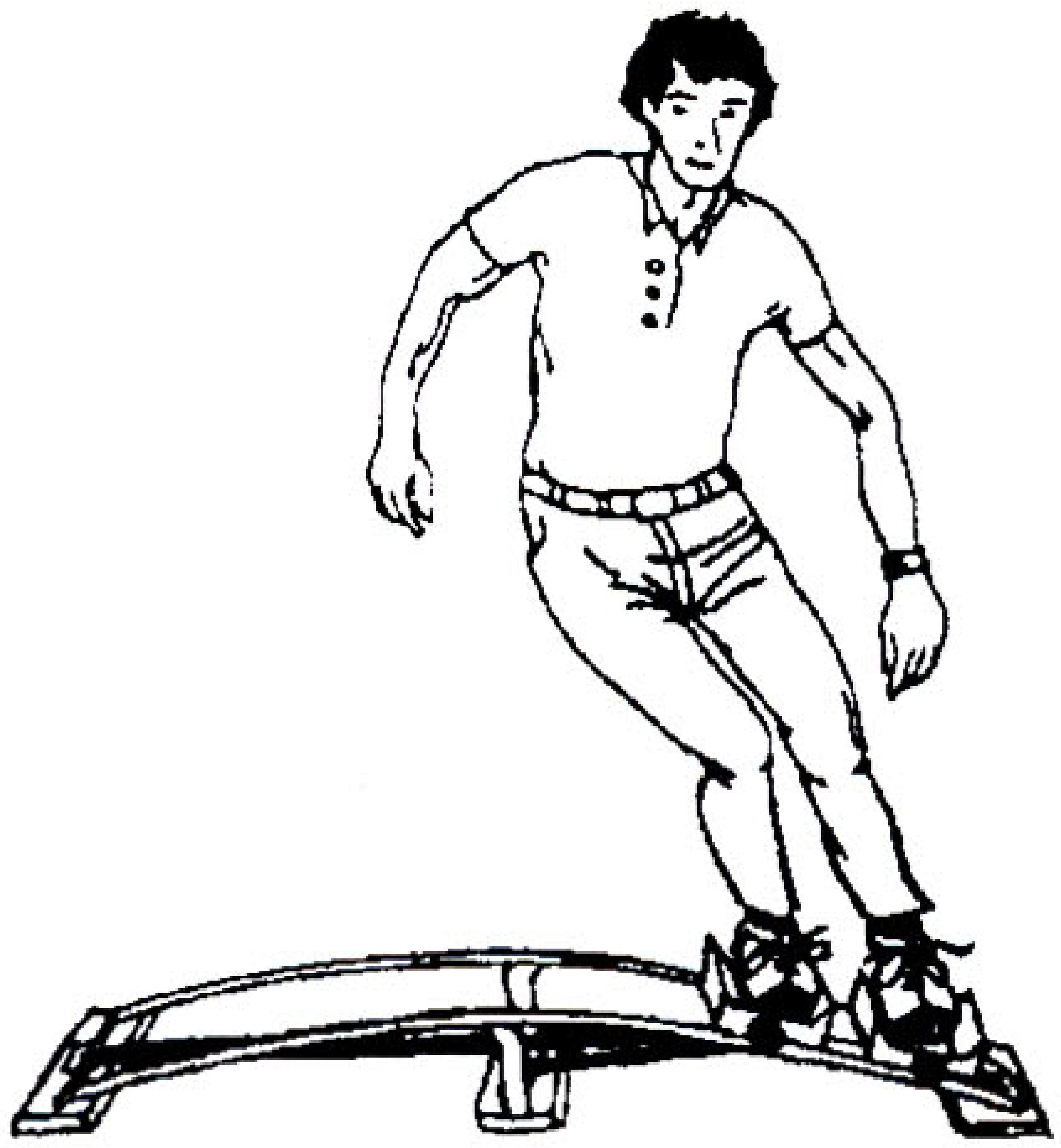

Figure 1. The ski simulator.

The middle point of the platform was measured by a potentiometer (Radiospares, Beauvais, France; resistance 20 K, linearity .25%) and sampled at a frequency of 100 Hz. A complete revolution of the potentiometer corresponded to a 12.5-cm displacement of the platform. Data were stored on a personal computer for further analyses. Within each trial, four samples of 2,000 data points were extracted, beginning from 30, 90, 150, and 210 s, respectively. Each series comprised 14–20 complete cycles, according to oscillation frequency. Ninety-six time series were then considered for each participant.

The time series were first filtered using a second order dual-pass Butterworth filter, with a cutoff frequency of 10 Hz. This cutoff frequency was chosen following an analysis of the series' spectral composition and was considered appropriate to preserve the signal's essential characteristics. A peak-finding algorithm was used to localize the movement's reversal points. Cycle frequency (in Hz) was defined as the inverse of the time between two successive ipsilateral reversals. Cycle amplitude (in cm) was defined as the mean of the platform's maximal deviations from the rest position at the right and left reversal points of the cycle. Means and standard deviations of amplitude and frequency were computed for each sample, which was then summarized in a normalized average cycle. Each cycle was normalized in time using 84 equidistant points by linear interpolation (Nourrit et al., 2003; Mottet & Bootsma, 1999). These points were then rescaled within the interval [-1,+1] and the normalized cycles were averaged point by point, leading to a unique normalized average cycle of 84 points. The first and second derivatives were computed from the normalized average cycle and rescaled within the interval [-1, +1]. This average cycle represented the dynamical organization that emerged in response to the task demand, the stochastic noise from the microscaled fluctuation being cancelled through the averaging process.

Modeling Strategy

Our modeling strategy was based on the analysis of these average normalized cycles. Our method, according to the principles developed by Beek and Beek (1988), combined qualitative graphical analyses—to identify the nonlinear components underlying platform movements—and quantitative statistical procedures—to estimate the magnitude of each component's contribution and its change with practice.

In a first step, we used Hooke's plane representations (position vs. acceleration; see Figure 2) for a direct assessment of the stiffness function (Delignières et al.,1999; Guiard, 1993; Mottet & Bootsma, 1999). Hooke's portraits give a straight line for a perfect harmonic oscillator, and all tendencies to deviate from this line provide valuable information on the nonlinear stiffness terms to include in the model. For example, obtaining an N-shape in the Hooke's plane suggests a local softening spring behavior, which could be accounted for by the inclusion of a negative cubic Duffing term ($-x^3$) in the model (Mottet & Bootsma, 1999). Previous analyses on ski simulator data showed the necessity to add a positive quintic term (x^5) in the stiffness function to account for a restoration of stiffness near the movement's reversal points (see Figure 2, and Delignières et al., 1999, Fig .1, p. 775).

The determination of relevant nonlinear damping terms was also based on graphical analyses. To isolate the contribution of nonlinear damping, we first performed a regression of -   against all previously identified linear and nonlinear stiffness terms and linear damping ($\dot{x}$). The residual (RES) of this regression was assumed to reflect the contribution of nonlinear damping terms on behavior. Then we applied the principles proposed by Beek and Beek (1988). We searched for van der Pol behavior by plotting the value of RES/$\dot{x}$ as a function of x (in this case a parabola is expected, revealing the presence of a $x^2\dot{x}$ term in the residuals) and for Rayleigh behavior by plotting the value of RES as a function of $\dot{x}$ (expecting an N shape, revealing the presence of a $\dot{x}^3$ term in the residuals; for graphical examples, see Nourrit et al., Figure 6, p. 159).

The aim of these graphical analyses was to determine a minimal dynamical model, containing a limited set of relevant terms. Then the relative importance of each coefficient was assessed using a stepwise multiple regression procedure of all relevant terms onto $-\ddot{x}$, as suggested by the original W-method (Beek & Beek, 1988).

Physiological Data

Oxygen intake was measured continuously using a portable telemetric system (K2, Cosmed, Roma, Italy) that measures the volume of expired air (VE) in liters per min and the volume of oxygen consumed (VO_2) in liters per min. Participants were equipped with a face mask connected to an analysis/transmitter unit (weighting 400 g) attached in front of the participant. Data were sent telemetrically to a receiver unit and stored for further analyses. Data were averaged by the system for each 30-s interval. Physiological efficiency was assessed by computing the movement cost, defined by the product amplitude by frequency by VO_2, expressed in $ml.kg.s^{-1}$ (Durand, Geoffroi, Varray, & Préfaut, 1994). Because of the latency of aerobic processes, VO_2 data were not considered as valid during the first 2 min of each trial. Movement cost was then calculated for the last 30-s intervals of the last 2 min of each trial.

Results

Amplitude

A similar evolution of amplitude was evidenced for the 3 participants (see Figure 3). Participant 1 reached maximal amplitude during the third trial of the first session, and Participants 2 and 3 reached that level in the second session. From the beginning of the experiment, participants seemed able to perform at amplitudes between 15 and 20 cm. Nevertheless, maximal amplitudes remained relatively low: 30 cm for Participant 1, just above 40 cm for Participant 2, after which amplitude tended to decrease, and 35 cm for Participant 3.

Frequency

The evolving frequency patterns were different among participants despite a general increasing trend during the experiment (see Figure 4). Participant 1 presented a progressive and moderated frequency increase. Participant 2 had a more abrupt increase just after the first trial, with a subsequent stabilization around 1.0 Hz. Finally, Participant 3 presented an abrupt but late frequency increase at the beginning of the fifth session.

Stiffness Coefficients

The coefficients of the stiffness function (c_{10}, c_{30}, and c_{50}) presented parallel evolutions during the experiment. As an example, Figure 5 shows the evolution of the c_{30} coefficient. As c_{10} and c_{50} are both of opposite signs, their evolutions mirrored that of c_{30}. As in the Nourrit et al. experiment, with the monoski, the coefficients presented high absolute values at the beginning of practice (c_{10} and c_{50} being positive, and c_{30}

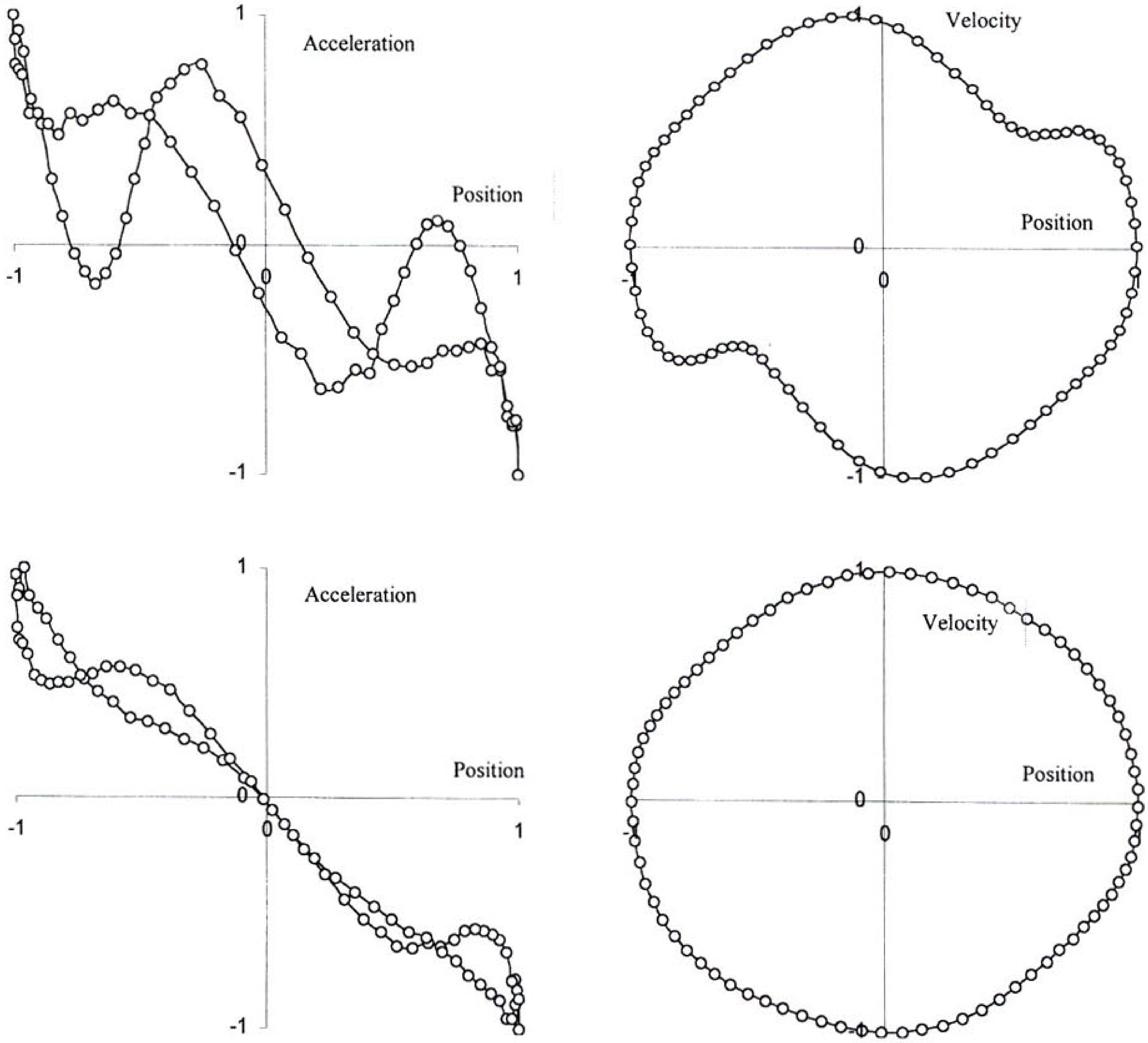

Figure 2. Representative examples of Hooke portraits (acceleration vs. position, left column) and phase portraits (velocity vs. position, right column). The two upper portraits correspond to the behavior observed at the beginning of practice (Participant 2, Session 1, Trial 1, Sample 3), and the lower to the behavior of the same participant, latter in practice (Session 5, Trial 1, Sample 3). The Hooke portraits clearly illustrate the initial nonlinearities of the stiffness function, and its linearization with practice. The evolution of the phase portraits reflects the transition from a Rayleigh to a van der Pol damping behavior.

negative). With practice, c_{10} stabilized around 1.0, and c_{30} and c_{50} reached values near 0. Practice seemed to induce, as in the previous experiment, a linearization of the stiffness function (see also Figure 2). This linearization appeared progressively for Participants 1 and 3 but more abruptly for Participant 2, with a sudden decrease of the absolute coefficient value during the second trial of the first session.

Damping Function

The evolution of the model was similar among participants. As in the Nourrit et al. (2003) experiment, participants exploited a Rayleigh-type damping function in the first trials and tended to switch toward a van der Pol behavior with practice. To visualize this transition through the evolution of a single metric, we applied the method proposed by Nourrit et al. (2003), which consists of forcing assessment of a Duffing + Rayleigh model for all the measured trials. This method provides a negative value for the linear damping term (c_{01}), when the underlying model is of Rayleigh type, and a positive value for a van der Pol type. Nourrit et al. (2003) called $c_{01(\text{Rayleigh})}$ this "forced" linear damping coefficient. This coefficient allows a continuous description of the damping behavior, despite a qualitative evolution of the underlying models. Moreover, the absolute value of $c_{01(\text{Rayleigh})}$ indicates the stability of the corresponding behavior, with values near zero (positive or negative) suggesting unstable limit cycles. The individual evolution of $c_{01(\text{Rayleigh})}$ is presented in Figure 6.

Participant 1 presented a relatively unstable behavior during the two first sessions, frequently alternating between Rayleigh and van der Pol damping. The third session revealed a kind of regression, considering the overall shape of the evolution, with the participant clearly adopting a stable Rayleigh behavior, especially during Trials 2 and 3. The three last sessions appeared conversely dominated by a van der Pol damping behavior. Nevertheless, the coefficient came back frequently to values near 0, suggesting the persisting instability of the system.

Participant 2 exhibited a typical Rayleigh behavior during the first trial. Then he seemed to initiate a particularly unstable stage, during which the coefficient

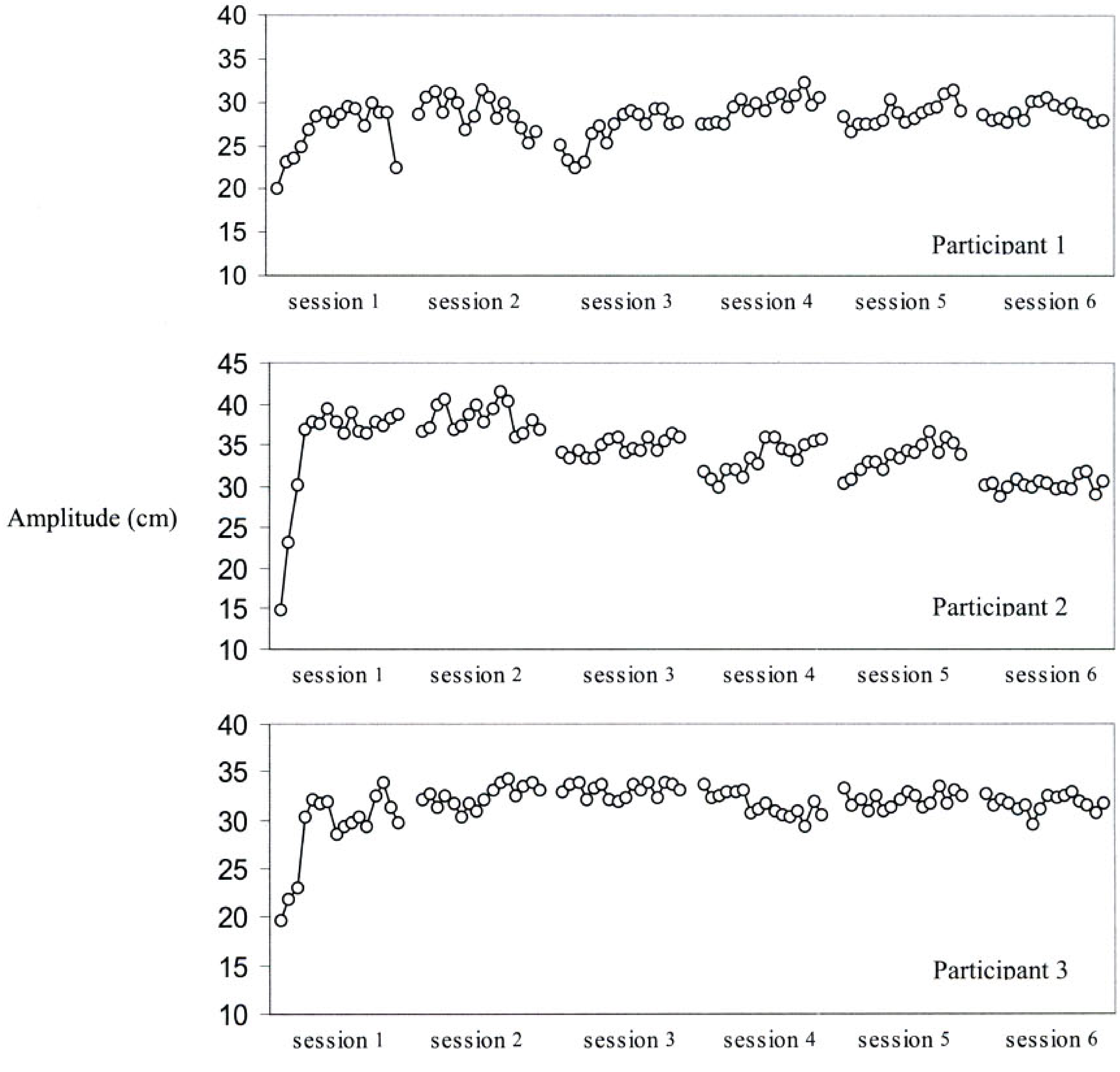

Figure 3. Individual evolution of oscillation amplitude (cm) with practice.

$c_{01\,(\mathrm{Rayleigh})}$ oscillated continuously between positive and negative values, until the end of the third session. From the beginning of the fourth session, this participant exploited a van der Pol damping behavior more systematically, even if his behavior during the last session appeared less stable.

Finally, the third participant presented a progressive evolution. The three first sessions were characterized by a quite consistent Rayleigh behavior, except for the third trial of the second session, during which a van der Pol damping seemed to be exploited. Then this participant reached an unstable phase, during which damping alternated between the two kinds of behavior. This instability remained until the end of the experiment, and this participant never seemed to exploit the van der Pol behavior definitely.

Movement Cost

Generally, our results described a decrease of movement cost with practice (see Figure 7). Here, also, the evolution seemed highly individualized. For participant 1, the cost remained stable during the three first sessions and decreased from the fourth session on. Participant 2 presented an exponential decreasing trend, with a particularly important decrease during the first session. Participant 3 exhibited a similar shape with, nevertheless, a transient increase of movement cost during the fourth session.

Discussion

The results concerning the evolution of amplitude revealed that participants adapted rather quickly to the task requirements. All participants reached maximal performance in the first session and, more precisely, from the second trial of the first session. Similar results were previously observed in other experiments on the ski simulator (e.g., Hong & Newell, 2006; Vereijken, 1991). Note, nevertheless, that performance enhancement is not necessarily a good index of learning, as shown in most recent experiments on complex skill

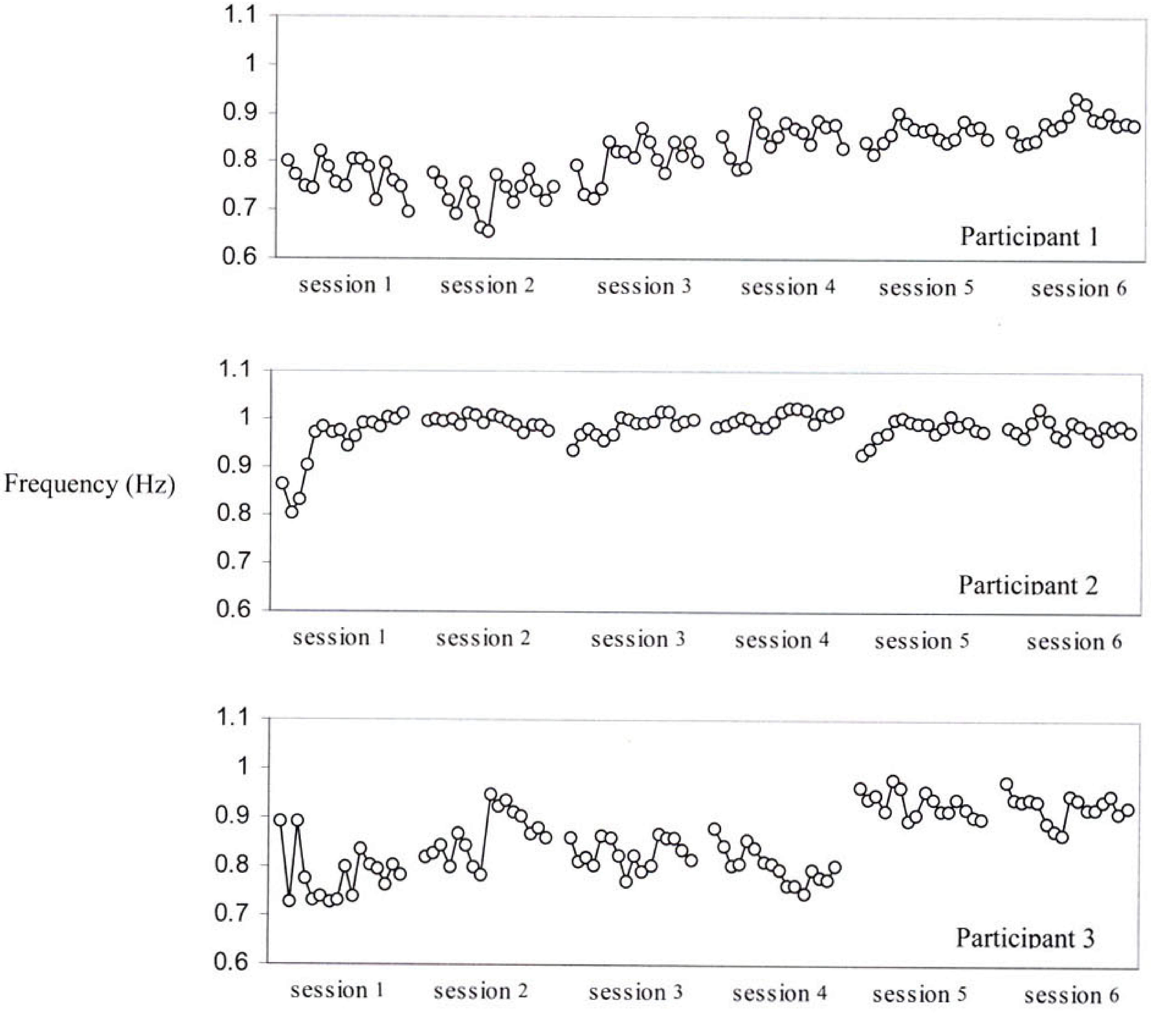

Figure 4. Individual evolution of oscillation frequency (Hz) with practice.

acquisition (Delignières et al., 1998; Nourrit et al., 2003): Novices seemed to exploit their initial behavior to reach acceptable performance levels before engaging a true behavioral change. Delignières et al. (1998), for example, showed in an experiment on parallel bars that participants were able to reach amplitudes similar to those of experts while continuing to exploit a typical novice behavior. As well, Nourrit et al. (2003) reported that significant changes in coordination generally occurred some sessions after participants reached maximal performance. In other words, it seems necessary to distinguish between adaptation (a rather short-term process that allows performers to roughly overcome the basic task requirements and reach an acceptable performance level) and learning (characterized by the adoption and the stabilization of a new coordination pattern). This distinction seems particularly important for such complex skills, which require a complete reorganization of coordination modes, even if the explicit goal is "only" to reach a given performance level.

Despite interindividual differences, the other variables revealed a common shape in the evolution of behavior. The most important result was the increase, during practice, of the coefficient $c_{01(\mathrm{Rayleigh})}$, revealing a transition from a Rayleigh damping behavior at the beginning of the experiment to a van der Pol behavior. This result was consistent with the observations of Nourrit et al. (2003) and confirmed that the Rayleigh damping behavior represented the typical solution exploited by beginners on the ski simulator.

The model observed during the first trials, involving a highly nonlinear stiffness function and a Rayleigh damping behavior, provided the novice with a kind of dwelling time in the second part of the half-cycle, allowing a comfortable management of the reversal of the oscillation. This dwelling time is provided in part in the first part of the half-cycle by the negative cubic term of the Duffing function (c_{30}), which induces a local slowing down beyond a critical amplitude, and by the Rayleigh damping function, which is characterized by a precocious peak velocity.

Note that Participants 1 and 2 clearly adopted the van der Pol behavior from the third session, as revealed by the positive coefficient values, but this remained

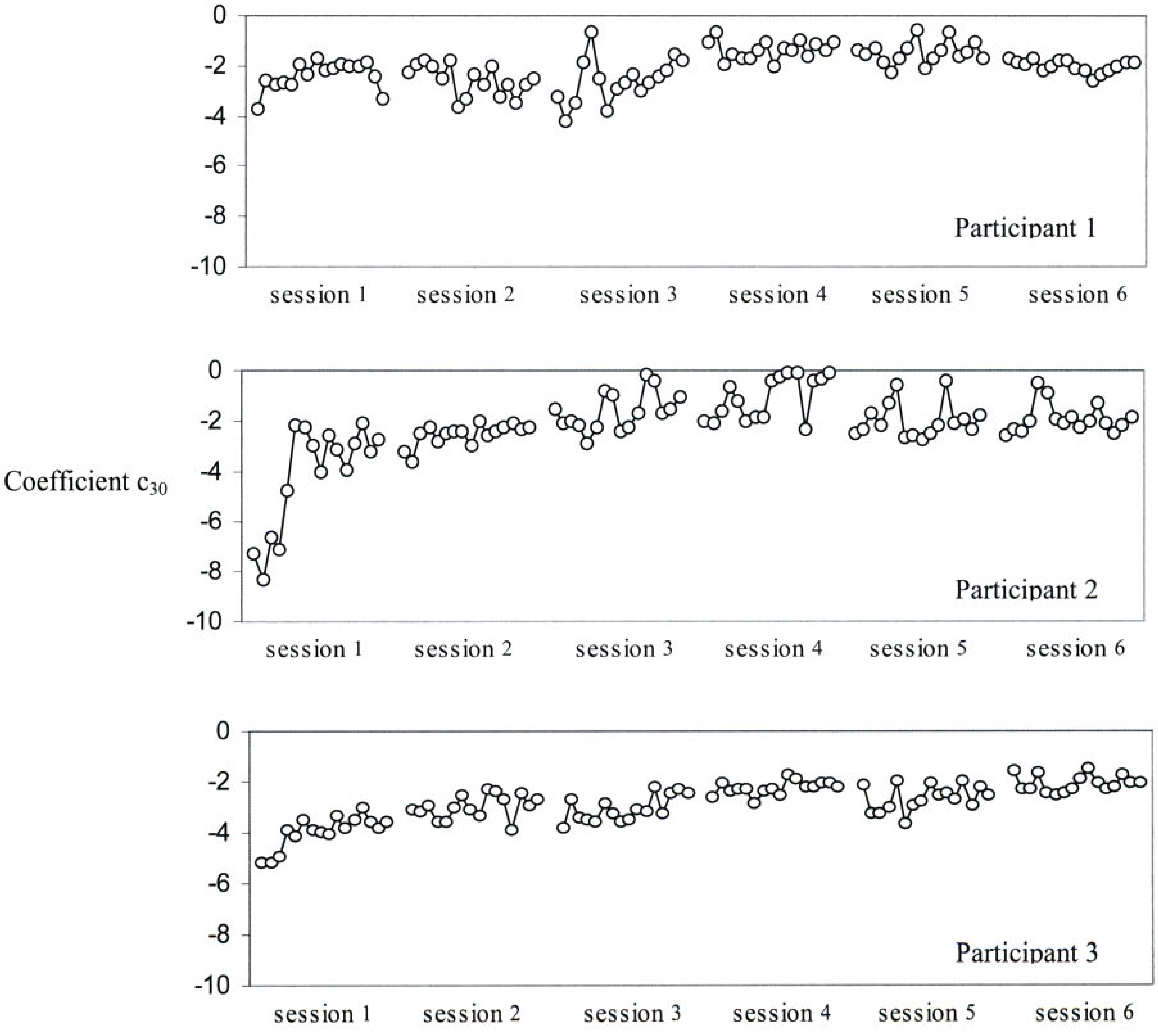

Figure 5. Individual evolution of the stiffness coefficient c_{30} with practice.

uncertain for Participant 3, who exhibited a prolonged alternation between positive and negative value throughout the experiment. Additionally, the positive values observed for Participants 1 and 2 remained rather low, as compared to those obtained by Nourrit et al. (2003), suggesting that the practice duration was not sufficient to allow the complete installation of the new behavior.

Nourrit et al. (2003) showed that an increase of oscillation frequency (from 1.0 to 1.4 Hz, approximately, in their experiment) characterized the beginning of the transition from the Rayleigh to van der Pol behavior. Two well known properties of these damping functions, which induce different relations between amplitude and frequency, explain this link between damping and frequency. In the case of van der Pol damping, amplitude is independent of frequency. On the contrary, in a Rayleigh oscillator an increase of frequency leads to a decrease in amplitude.

According to Nourrit et al. (2003), these properties constitute a determinant point for the transition from the Rayleigh to the van der Pol model. As participants become able to satisfactorily master the reversal points of the movement, the local slowing down (controlled by the x^3 term) is no longer necessary. Then the c_{30} coefficient decreases, determining an increase of frequency. Nevertheless, at this point in the experiment participants have already reached large amplitudes. The typical amplitude-frequency relationship of the Rayleigh oscillator does not allow the maintenance of such large amplitudes with an increase of frequency. As a consequence, adopting a damping behavior preserving amplitude under high frequencies appeared to be necessary.

This link between frequency and damping is apparent in the present results, with similar shapes observed for the frequency and $c_{01\,(\mathrm{Rayleigh})}$ evolutions (see Figures 4 and 6). A more detailed observation, neverthe-

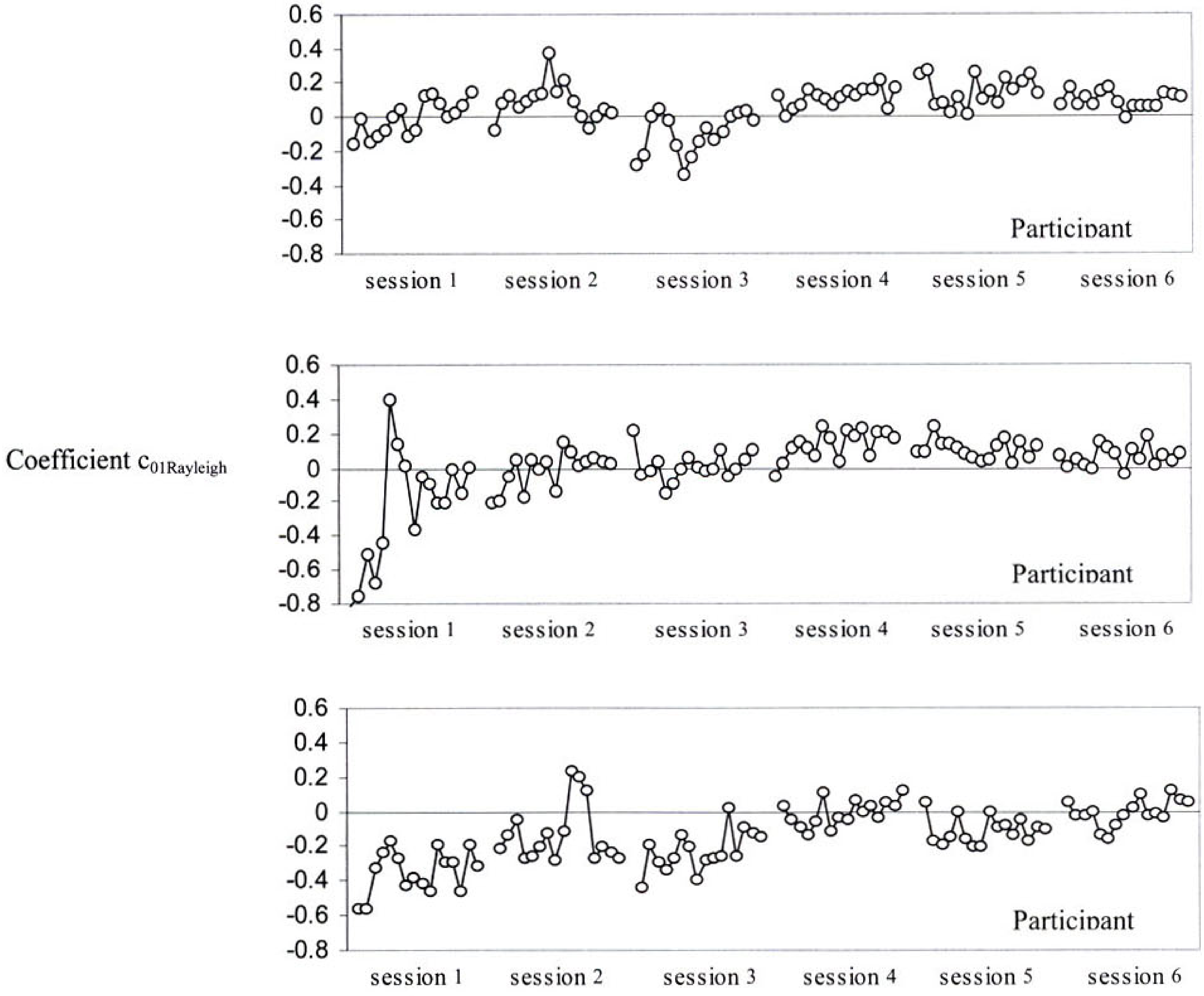

Figure 6. Individual evolution of the coefficient $c_{01(\mathrm{Rayleigh})}$ with practice. This coefficient was obtained by forcing the Duffing + Rayleigh model ($\ddot{x}$ + c10x + c30x3 + c50x5 + c01$\dot{x}$ + c03$\dot{x}^3$ = 0) on each averaged normalized cycle, using multiple regression analysis. $c_{01(\mathrm{Rayleigh})}$ is negative when the limit cycle is sustained by a Rayleigh behavior, and positive for a van der Pol behavior. Zero-crossings indicate a transition between behaviors.

less, suggests that this link is not so direct: for example, the sudden frequency increase for Participant 3 during Sessions 5 and 6 was not accompanied by a damping coefficient increase. As suggested by Nourrit et al. (2003), the increase of frequency offers the possibility to switch more easily to the van der Pol behavior, but this transition could be delayed in some cases. One can also note that the final frequency, around 1.0 Hz, was lower than that observed by Nourrit et al. (2003). This discrepancy could be related to a difference in the tension of the rubber belts used in the two experiments.

The evolution of damping behavior also seems to be closely related to movement cost. Rayleigh behavior appears to be particularly inefficient (see, for example, Participants 2 and 3, Session 1, and Participant 1, Session 3), and conversely the van der Pol behavior seems to correspond to an optimal use of the system's biomechanical properties. The van der Pol behavior is characterized by a delay of forcing, which appears in the second part of the oscillation (Nourrit et al., 2003). Vereijken (1991) showed that the progressive appearance of this delay was a main feature of learning on the ski simulator and suggested that this strategy was the best to act efficiently. Participants first exploit the restoring force of the apparatus and then the system toward the opposite reversal point. In contrast, the Rayleigh behavior is characterized by a precocious forcing, which seems to interfere with the restoring forces in the first part of the half cycle.

It is important to keep in mind that the present results represent a narrower time scale than those of Nourrit et al. (2003). Our participants accumulated 96 min of practice, versus 390 min for the 5 participants of the previous experiment. In Figure 8 is a comparison between the $c_{01(\text{Rayleigh})}$ coefficient evolutions in the two experiments. The coefficient values are averaged over participants and over similar amounts of cumulated practice in the two experiments. Note that the

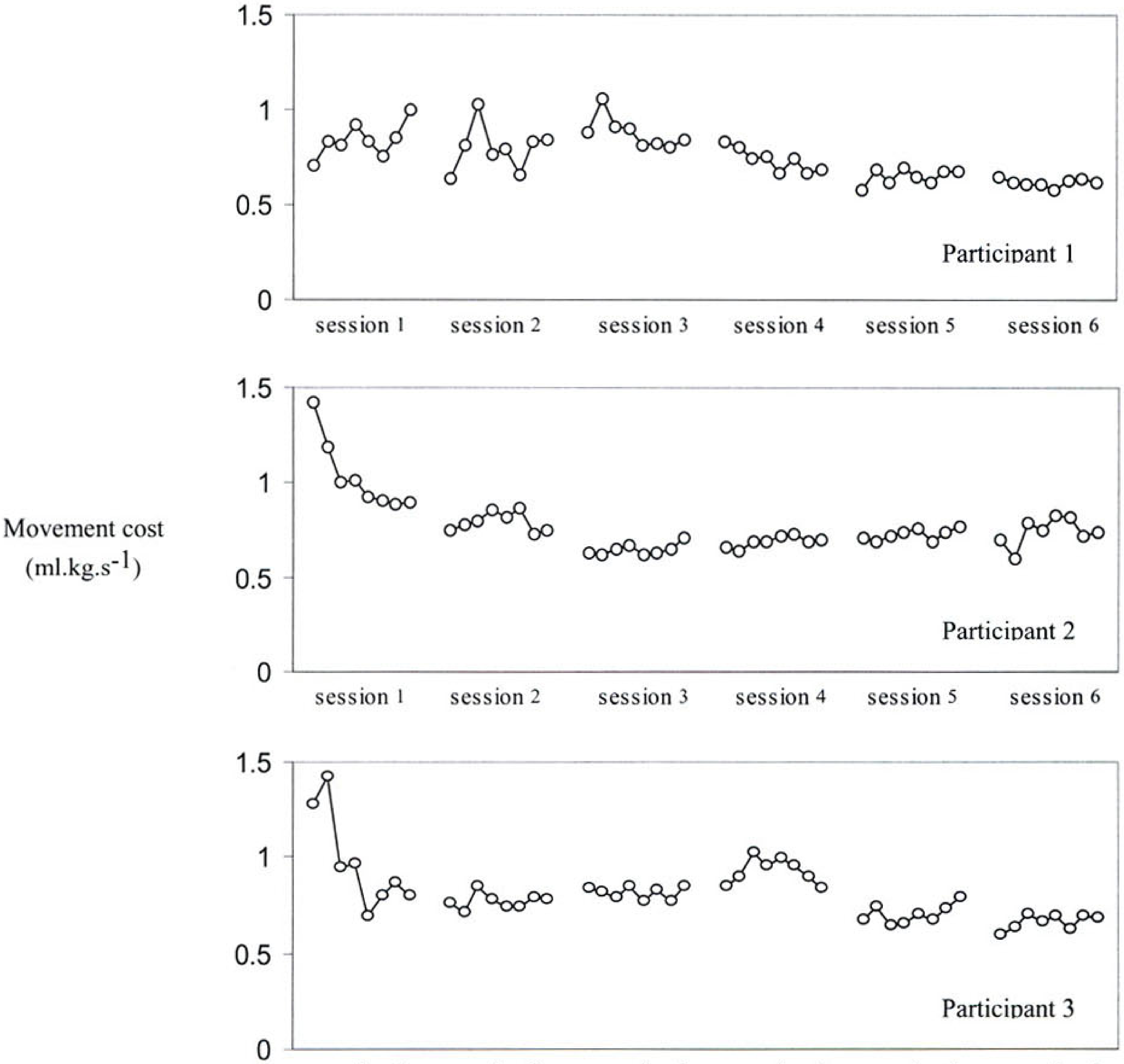

Figure 7. Evolution of movement cost with practice.

two first points of the monoski curve are contaminated by the results of 1 participant in the Nourrit et al. experiment, who strangely adopted a van der Pol behavior during the first two practice sessions.

The most important result is the relatively fast evolution of the coefficient $c_{01\,(\mathrm{Rayleigh})}$ in the present experiment, as compared to the previous one. The first six sessions of the experiment of Nourrit et al. (2003) were characterized by a stable and consistent use of a Rayleigh damping behavior (excepted for the first two sessions for 1 participant). With a similar amount of practice, participants in the present experiment had already adopted a van der Pol-type behavior or entered in the stage of transition leading to the definitive adoption of the van der Pol behavior. These two experiments described the same evolution, but the process appeared to occur more slowly with the monoski version of the simulator than with the conventional version.

In summary, the present experiment confirms that the behavior beginners spontaneously adopt when using the ski simulator for the first time is characterized by a Rayleigh damping function. With practice, learners tend to adopt another forcing behavior, which is characterized by a van der Pol damping function and is more adapted to promote motor efficiency. The transition to the van der Pol behavior could appear very early (see Participant 1), but Nourrit et al. (2003) showed that in a more difficult version of the task this transition could be widely delayed. A number of previous papers pointed out that beginners' spontaneous coordination modes showed resistance to change when learning a novel complex motor skill (Delignières et al., 1998; Nourrit et al., 2003). The present results show that this conclusion has to be normalized according to the task difficulty. The possible emergence of the "expert" behavior early in practice could then explain, as supposed in the introduction, the systematic observation of van der Pol behavior in the Delignières et al. (1999) experiment. This suggests the necessity to strictly control the initial skill level of participants in such experiments.

The generalization of results obtained from only 3 participants could be of concern, especially regarding the important interindividual differences evidenced on several variables. Nevertheless, based on the main hypotheses of the present experiment, we think the results are remarkably consistent among participants: all adopted the same Rayleigh damping behavior at the beginning of practice and presented a precocious evolution toward a van der Pol behavior (as compared with the previous observations by Nourrit et al., 2003).

On the other hand, it is difficult to expect a high interindividual consistency in behavior with such complex tasks. As Bernstein (1967) pointed out, learning requires the coordination of many and often redundant degrees of freedom. This redundancy suggests that the same global dynamics could be achieved using different coordination dynamics at the local level. Hong and Newell (2006) provided an interesting example of this redundancy principle on the ski simulator, in that participants produced both in-phase and antiphase knee motion relations while preserving the global center of mass to platform coupling dynamics. As well, the transition from Rayleigh to van der Pol damping could be achieved in different ways, as revealed by the interindividual differences in the evolution of frequency and stiffness coefficients.

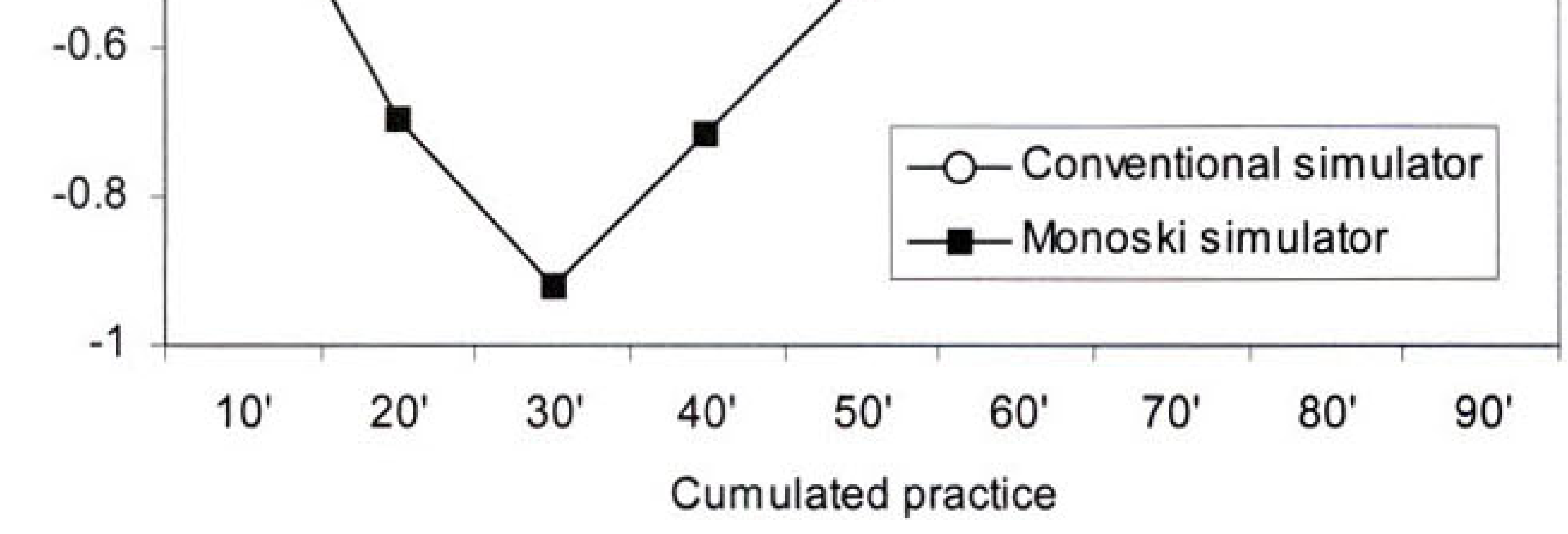

Figure 8. Comparison of the evolution of the $c_{01(\mathrm{Rayleigh})}$ coefficient, in the present experiment (conventional simulator) and in the experiment by Nourrit et al. (2003; monoski simulator). In each experiment, data were averaged over participants and for similar amounts of cumulated practice.

More generally, this experiment confirms some important hypotheses concerning the evolution of behavior when learning complex, whole-body skills. The first is that spontaneous coordination tendencies lead novices to adopt the same kind of behavior when confronted with a novel task. These spontaneous coordination modes are generally characterized by an absolute synchronization of phases and frequencies, allowing a rather simple control of the global dynamics (Delignières et al., 1998; Nourrit et al., 2003). This first coordination mode often permits the performer to reach an acceptable level of task performance.

Second, practice generally induces the adoption of another coordination mode, often more complex in terms of phase and/or frequency relationships (Delignières et al., 1998) but allowing a better adaptation to the mechanical constraints of the task. The adoption of this "expert" coordination mode is revealed by an enhancement of coordination stability and energetic efficiency.

Third, the transition from novice to expert behavior appears as a progressive process achieved through a transition stage during which the participant exploits the two behaviors in alternation. Teulier and Delignières (2005) recently presented a nice illustration of this principle on an experimental swing, in which participants alternatively used 1:1 and 2:1 coordination modes (representing the frequency ratios between forcing and swing oscillations) before the definitively adopting the latter. The present experiment supports these three hypotheses and shows that in some cases participants could quickly abandon their initial behavior and enter the transition stage leading to adoption of the expert coordination mode.

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