Journal of Sports Sciences, 2004, **22**, 867–874

Taylor & Francis healthsciences

Influence of a stressing constraint on stiffness and damping functions of a ski simulator's platform motion

THIBAULT DESCHAMPS,[1,2]* DÉBORAH NOURRIT,[2] NICOLAS CAILLOU[2] and DIDIER DELIGNIÈRES[2]

[1]*Faculty of Sport Sciences and Physical Activities, University of Nantes, JE 2438 'Motricité, Interactions, Performance', 25 bis boulevard Guy Mollet, BP 72206, 44322 Nantes Cedex 3 and* [2]*Faculty of Sport Sciences and Physical Activities, University of Montpellier I, EA 2991 Sport–Performance–Santé, 700 avenue du Pic Saint Loup, 34090 Montpellier, France*

Accepted 7 October 2003

The aim of this study was to assess the effect of stress on a previously acquired motor coordination. Following a longitudinal learning experiment, four participants performed oscillations on a ski simulator, either in normal or stressful conditions. The results showed that the amplitude of the oscillations decreased under stress, but no significant effect was seen regarding coordination, suggesting the strong resistance to stress of overlearned behaviour. Nevertheless, for one participant, a transient regression towards a former stage of learning was observed. This result was consistent with the regression hypothesis formulated by Fuchs (1962).

Keywords: coordination dynamics, damping, progression–regression hypothesis, stiffness, stress.

Introduction

The influence of stress on motor performance has been widely studied from a cognitive standpoint (Sanders, 1983; Humphreys and Revelle, 1984; Jones and Hardy, 1989; Gaillard, 1993). According to these authors, the environmental stressors affect the energetical state of the organism, which, in turn, alters the efficacy of the information-processing mechanisms underlying motor performance. A number of concepts were proposed to account for this energetical state, such as activation, arousal and anxiety, and the relationship between this state and performance has mainly been discussed in relation to the seminal inverted-U hypothesis advocated by Yerkes and Dodson (1908). Despite recent refinements of the theory (Sanders, 1983; Fazey and Hardy, 1988), these approaches remain confined at the cognitive level, and appear unable to support any hypothesis about the effect of stress on more qualitative features of motor behaviour, such as motor coordination.

The application of non-linear dynamical systems theory to motor coordination over the last two decades has resulted in a new understanding of the emergence of motor behaviour (for a review, see Kelso, 1995). It has been shown, in particular, that the motor system can be characterized by its intrinsic dynamics – in other words, the preferential coordination modes adopted in a given situation. For example, in a bimanual coordination task, two coordination modes (in-phase and anti-phase) emerge spontaneously: the other phase relations between the two limbs appear more difficult to perform. These intrinsic attractors are not equally stable: the in-phase coordination mode appears to be intrinsically more stable than the anti-phase mode, and when the system is prepared in anti-phase, an increase of the oscillation frequency leads beyond a so-called critical frequency, to a transition to the in-phase mode. In other words, frequency constitutes a control parameter, which may induce dramatic changes in the system's behaviour.

Within this dynamical framework, Court *et al.* (1998) suggested that stress could also act as a control parameter, determining the destabilization of the current mode of coordination, and a possible transition towards a more stable attractor of the system. They showed, using a bimanual coordination task with highly anxious participants, that the critical frequency was

* Address all correspondence to Thibault Deschamps, Faculty of Sport Sciences and Physical Activities, EE, Motricité, Interactions, Performance', University of Nantes, 25 bis boulevard Guy Mollet, BP 72206, 44322 Nantes Cedex 3, France. e-mail: thibault.deschamps@staps.univ-nantes.fr

Journal of Sports Sciences ISSN 0264-0414 print/ISSN 1466-447X online
DOI: 10.1080/02640410410001675478

lower in stressful than in normal conditions. Beuter and Duda (1985) reported such an influence in a stepping motion performed in stressful conditions: dynamical analysis revealed that the movement was less smooth and more jerky under stress than in normal conditions.

In a similar vein, Lee (1998) proposed a dynamical interpretation of the progression–regression hypothesis of Fuchs (1962). In a tracking task, Fuchs demonstrated that learning evolved through successive stages, characterized by the use of progressively higher-order derivatives of information (i.e. velocity, acceleration, jerk). Under stress, the learner tended to regress towards a less complex mode of control, previously exploited during the course of learning. In other words, the learner tended to revert to a previously acquired and overlearned behaviour.

There is wide agreement for considering learning as a progression through a hierarchy of qualitatively distinct behaviours (Newell, 1991; Zanone and Kelso, 1992). The dynamical approach to motor learning considers this progression as a succession of phase transitions, from the initial to the expert mode of coordination (Vereijken, 1991; Delignières *et al.*, 1998). Similarly, according to Lee (1998), 'the regression under stress is a control parameter-induced, short-term phase transition to previously acquired (and overlearned) behaviour of the motor system' (p. 335).

To test this hypothesis in terms of motor coordination, it is necessary to consider a task in which the history of learning is known. Such an opportunity was recently offered in our laboratory, in a longitudinal experiment of skill acquisition (Nourrit *et al.*, 2003). In this experiment, five participants performed 390 one-minute trials on a ski simulator. The experiment lasted for 13 weeks, with three sessions of 10 trials per week. Analyses focused on the movements of the platform of the apparatus, in particular the amplitude of the movement, its frequency and the nature of the stiffness and damping functions, revealed by a dynamical analysis (Beek and Beek, 1988). In such a dynamical analysis, the system is conceived as a self-sustained oscillator. The stiffness function expresses the elastic properties of the system, and the damping function the manner by which energy is lost by friction, and actively re-injected for sustaining oscillations. The results allowed us to identify three successive stages in the acquisition of the skill:

A first stage was characterized by a significant increase in movement amplitude, from 10 to 30 cm. Frequency was relatively low, around 1.0 Hz. This stage was characterized by a highly non-linear Duffing stiffness function, including cubic and quintic terms, and a Rayleigh damping behaviour, leading to the following model:

$$\ddot{x} + c_{10}x + c_{30}x^3 + c_{50}x^5 + c_{01}\dot{x} + c_{03}\dot{x}^3 = 0 \qquad (1)$$

The stiffness function, expressed by the terms x, x^3 and x^5, suggested a complex evolution of elasticity within each cycle: the system acted as a kind of softening, then hardening, spring. The Rayleigh function, composed of the terms $\dot{x}$ and $\dot{x}^3$, is a well-known damping behaviour, characterized by an early injection of energy in the oscillation cycle. This coordination dynamics was interpreted as a way participants can benefit from a kind of dwelling time, within each oscillation, to realize the postural adjustments necessary for managing the reversal points of the movement (Nourrit *et al.*, 2003). Among participants, this first stage lasted 50–100 trials.

A second stage was initiated by a sudden increase in frequency, from 1.0 to 1.4 Hz on average. During this stage, a progressive linearization of the stiffness function was observed (i.e. a decrease, in absolute terms, of the coefficients c_{30} and c_{50}). The damping coefficients c_{01} and c_{03} decreased significantly during this stage, suggesting a modification of the initial damping behaviour. A cycle-to-cycle analysis revealed a bi-stable regime, characterized by an alternating exploitation of a Rayleigh and a van der Pol behaviour. The van der Pol behaviour is a qualitatively different damping strategy, characterized by a later injection of energy in the oscillation cycle. This damping behaviour allows oscillations to be performed at high frequency, while preserving a large amplitude. Among participants, this second stage lasted 50–175 trials.

Finally, a third stage was characterized by the stabilization of a quasi-linear stiffness and of a van der Pol damping function, leading to the following equation:

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

During this stage, participants were able to reach large amplitudes (around 40 cm), while sustaining a high oscillation frequency (around 1.4 Hz). This coordination dynamics was considered as the typical 'expert' behaviour (Nourrit *et al.*, 2003).

The aim of the present experiment was to test the regression hypothesis in the domain of motor coordination, by using the same participants and the same task. The task was performed either in normal conditions (on the floor) or in stressful, dangerous conditions (the ski simulator was placed at a considerable height). We hypothesized that, in the stressful conditions, participants would exhibit a regression towards a previous stage of learning, for example a resurgence of a Rayleigh damping behaviour.

Methods

Participants

Four males aged 29.5 ± 6.45 years (mean ± *s*) volunteered to participate in the experiment. All participants provided informed consent in accordance with the ethical rules outlined by the scientific committee of the Faculty of Sport Sciences, University of Montpellier I. All participants had previously taken part in the study of Nourrit *et al.* (2003), which ended 5 months before the present experiment. Thus all participants had quite extensive experience of the ski-simulator (39 sessions of practice) and their behaviour was characterized by a stable Duffing + Van der Pol model. It should be noted that it is difficult to 'produce' experts in this experimental task (see Results and Discussion sections in Nourrit *et al.*, 2003), which explains the very low sample size. It is also stressed that the main regression hypothesis lies in the knowledge of the individual's learning dynamics.

Apparatus

The task was executed on a slalom ski-simulator (Skier's Edge Co., Park City, UT), which consisted of a platform on wheels that moved back and forth on two bowed, parallel metal rails (Fig. 1). 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.

As in the experiment of Nourrit *et al.* (2003), we used a modified version of the original simulator: we replaced the two independent feet supports of the apparatus with a 30 cm wide board, in unstable balance over a sagittal rotation axis (Fig. 2). Our apparatus could then be conceived as a kind of *mono-ski* simulator. For security reasons, the feet were not strapped down. To help participants maintain their feet on the board, two wooden sticks were fixed at its lateral extremities, and the upper surface was covered with a non-skid material.

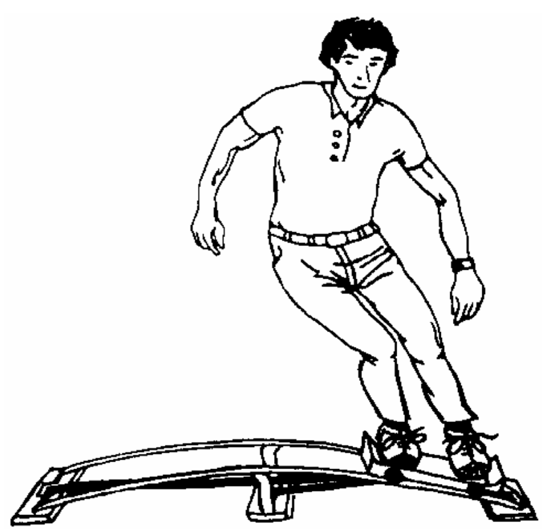

Fig. 1. The ski-simulator.

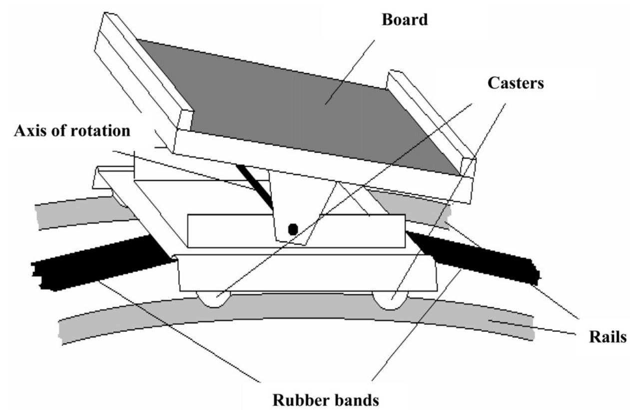

Fig. 2. Details of the arrangement of the simulator in the mono-ski version.

The position data of the midpoint of the platform were measured by a potentiometer and sampled at a frequency of 100 Hz. In the stressful condition, the simulator was fixed on the top of a narrow support 1.80 m high. In this condition, the distance between the floor and the participant's eyes was approximately 3.8 m. Following ethics requirements, safety mats on the floor were arranged all around the experimental device. Moreover, two participants, standing 1 m in front and behind the simulator, were on hand in the case of a fall.

Procedure

One week before the experiment, the participants performed a complete session of ten 1 min trials, to re-accustom themselves with the task. This session had a particular importance, as it constituted a retention test for the earlier experiment of Nourrit *et al.* (2003), and allowed an assessment of the initial skill level of the participants for the present work. The last trial of this session was taken into consideration for this assessment.

Then, the participants completed two experimental sessions, each composed of ten 1 min trials, each separated by 1 min of rest. The first session was performed in stressful conditions and the second on the floor (control condition). Because of technical problems, we were unable to counterbalance the order of the two conditions. All participants began in the stressful condition, following by the control condition 4 days later. The acquisition data were collected over 30 s, from the 15th to the 45th second of each trial. All participants received identical instructions to those given in the previous longitudinal study, namely 'to make movements as ample and frequent as possible' (see Procedure section in Nourrit *et al.*, 2003, p. 155).

Data and statistical analysis

The position time-series were filtered with an inverse Fast Fourier Transform, with a cut-off frequency of 10 Hz. A peak-finding algorithm was used to locate the reversal points of the movement. Cycle frequency (in Hz) was defined as the inverse of the time between two successive right reversals. Cycle amplitude (in 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. Means and standard deviations of amplitude and frequency were computed for each 30 s sample.

The dynamical modelling of the platform's motion was performed according to the following procedure (for further details, see Beek and Beek, 1988; Delignières *et al.*, 1999; Mottet and Bootsma, 1999; Nourrit *et al.*, 2003). In a first step, each sample was summarized in an *average normalized cycle*: each half-cycle was normalized using 21 equidistant points by means of linear interpolation, and then all the same normalized half-cycles (i.e. beginning at the same reversal point) were averaged point by point, thus determining an averaged normalized cycle (42 points).

The first and second derivatives were computed from the averaged normalized cycle, and then rescaled to the interval [−1; 1]. We used the graphical methods proposed by Beek and Beek (1988) to settle on the terms to include in the model. Then the coefficients (c_{ij}) were determined by using a stepwise multiple regression procedure of all relevant terms ($x, x^3, x^5, \dot{x}, \dot{x}^3, x^2\dot{x}, \ldots$) onto $-\ddot{x}$.

An analysis of variance (ANOVA), with repeated measurements on each factor (2 conditions × 10 trials), was carried out with each dependent variable: amplitude, frequency and each coefficient in the model. For each analysis, statistical significance was set at $P < 0.05$. Tukey's HSD was used for *post-hoc* tests when significant effects were identified. If the sphericity assumption in repeated-measures ANOVA was violated (examined using Mauchly's test), then corrected tests of significance were used (Huynh and Feldt, 1970; Huynh and Mandeville, 1979). In that case, paired *t*-tests with a corrected alpha level were used as *post-hoc* comparisons.

Results

During the last trial of the re-accustoming session, each participant reached large amplitudes (39.01, 38.94, 39.56 and 34.71 cm, respectively) and high frequencies (1.45, 1.46, 1.40 and 1.23 Hz, respectively), comparable to those attained at the end of the previous experiment. The dynamical modelling revealed that each participant exploited a Duffing + van der Pol behaviour. The linear damping coefficients c_{01} (−0.196, −0.191, −0.196 and −0.116, respectively) were similar to those obtained at the end of the learning experiment. These values indicated that the van der Pol damping behaviour was highly stable during this retention trial, at least for the first three participants. The coefficient c_{01} obtained for participant 4 suggested a less stable damping behaviour.

For the two experimental sessions, the analysis of amplitude data indicated main effects of condition ($F_{1,3} = 35.47$, $P < 0.05$) and trial ($F_{9,27} = 5.37$, $P < 0.05$). Amplitude was significantly lower in the stressful condition than in the control condition, but in both conditions amplitude tended to increase linearly from the beginning to the end of the session (Fig. 3). Regarding frequency, the ANOVA only revealed an effect of trial ($F_{9,27} = 3.86$, $P < 0.05$): frequency increased from the beginning to the end of both sessions.

For all conditions and all trials, the average normalized cycles were accurately accounted for by a Duffing + van der Pol model:

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

The estimated coefficients respected the sign requirements for the limit cycle sustainability, c_{10}, c_{50} and c_{21} being positive, c_{30} and c_{01} being negative.

The analyses of variance performed on the coefficients of the model did not reveal any significant main effect or interaction (see Table 1). In others words, stress did not induce an increase in the non-linear

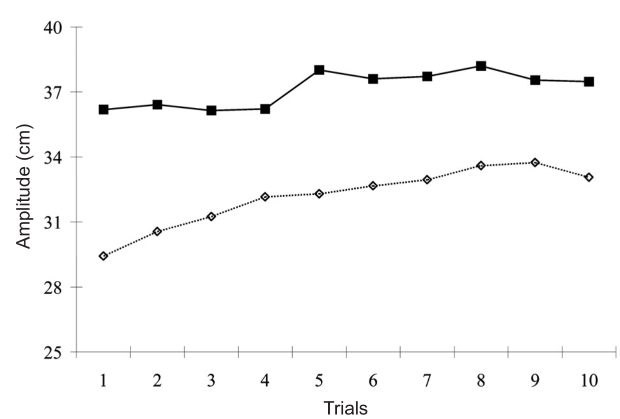

Fig. 3. Evolution of oscillations amplitude according to the height of the ski-simulator (◇, stressful condition; ■, control condition) and the trial's rank.

coefficients in the stiffness function, and did not modify the nature of the damping behaviour. Nevertheless, a closer examination of the results revealed important inter-individual differences. Figure 4 shows the individual evolution of the linear damping coefficient (c_{01}), which constitutes an index of the stability of the van der Pol behaviour. As can be seen, c_{01} showed a particular evolution in the stressful condition for participant 4: during the first part of the session, and especially during trials 3, 4 and 5, this coefficient gave values close to zero (-0.02, -0.004 and 0.001, respectively), suggesting a kind of harmonic behaviour. This apparent harmonicity

Table 1. Averaged absolute values of coefficients for the estimated Duffing + van der Pol model ($c_{10} > 0$, $c_{30} < 0$, $c_{50} > 0$, $c_{01} < 0$ and $c_{21} > 0$) in relation to condition [at height (HC) and on the floor (FC)] for the four participants (mean $\pm$ *s*)

	Participant 1		Participant 2		Participant 3		Participant 4	
Coefficient	HC	FC	HC	FC	HC	FC	HC	FC
c_{10}	0.80 ± 0.08	0.76 ± 0.10	0.57 ± 0.14	0.53 ± 0.13	0.85 ± 0.08	0.80 ± 0.06	0.92 ± 0.10	1.04 ± 0.08
c_{30}	0.09 ± 0.19	0.14 ± 0.25	0.23 ± 0.14	0.45 ± 0.21	0.12 ± 0.23	0.22 ± 0.12	0.14 ± 0.25	0.46 ± 0.16
c_{50}	0.26 ± 0.11	0.34 ± 0.16	0.17 ± 0.10	0.13 ± 0.09	0.25 ± 0.07	0.41 ± 0.09	0.21 ± 0.17	0.38 ± 0.10
c_{01}	0.19 ± 0.02	0.19 ± 0.04	0.17 ± 0.02	0.22 ± 0.02	0.19 ± 0.02	0.25 ± 0.02	0.07 ± 0.05	0.20 ± 0.02
c_{21}	0.25 ± 0.02	0.28 ± 0.06	0.28 ± 0.03	0.31 ± 0.04	0.24 ± 0.03	0.30 ± 0.02	0.01 ± 0.07	0.29 ± 0.03

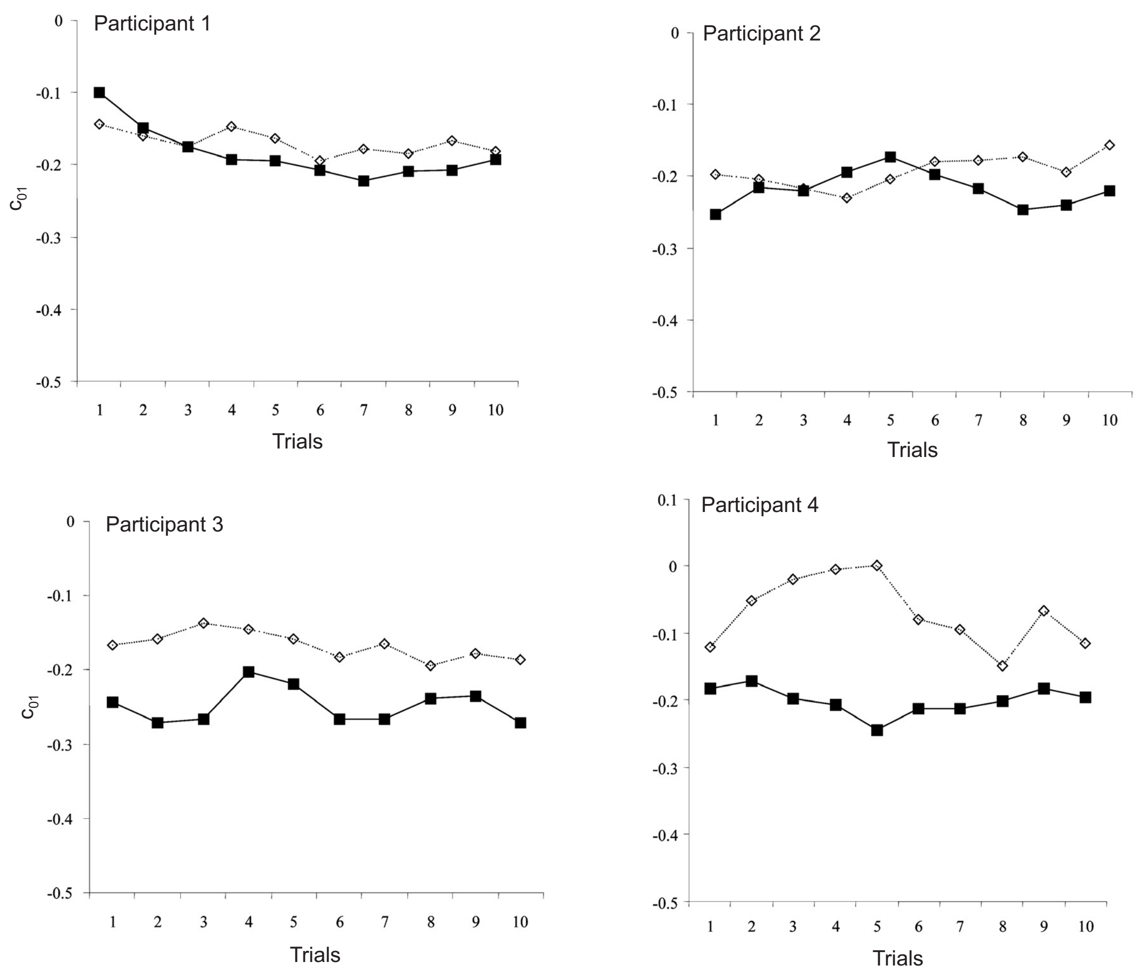

Fig. 4. Evolution of the linear friction coefficient c_{01} estimated over the regressions of the van der Pol model for the 4 participants according to condition (◇, stressful condition; ■, control condition) and the trial's rank.

was typically observed, in the learning experiment (Nourrit *et al.*, 2003), during the transition from the initial Rayleigh behaviour to the final van der Pol behaviour. In the present experiment, it could suggest the possible (punctual) re-emergence of a Rayleigh escapement. Because Rayleigh and van der Pol dissipations act orthogonally in phase space, a harmonic behaviour could result from the simultaneous presence of equally powerful Rayleigh and van der Pol components (Mottet and Bootsma, 1999, p. 243).

This hypothesis was tested by a cycle-to-cycle analysis of these 'harmonic' trials (for further details, see Nourrit *et al.*, 2003). The c_{01} coefficient was estimated for each successive cycle, using the Duffing + van der Pol model of equation (3). With this procedure, the obtaining of a negative coefficient reveals the presence of a van der Pol damping behaviour, whereas a positive estimate indicates a Rayleigh escapement. Similar results were obtained for the three 'harmonic' trials (trials 3, 4 and 5): as can be seen in Fig. 5, the average values obtained seemed to result from a cycle-to-cycle alternation between van der Pol (negative c_{10} values) and Rayleigh (positive c_{10} values) damping behaviours. This result suggests the re-emergence of a bi-stable regime where the Rayleigh and the van der Pol behaviours were simultaneously available and successively exploited.

Discussion

The first results to consider are those obtained during the re-accustoming session, which constituted, 5

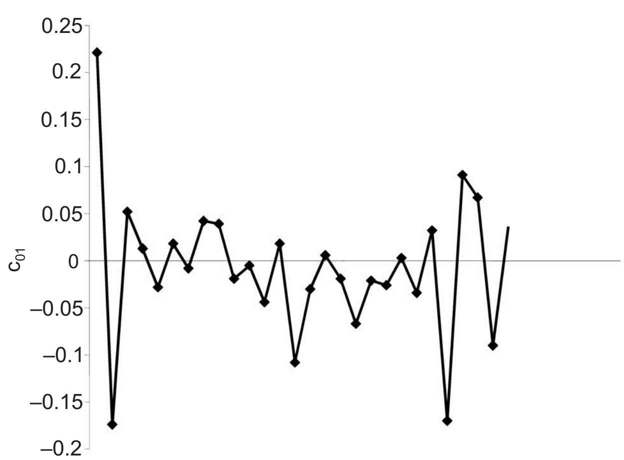

Fig. 5. Evolution of the estimated cycle-to-cycle values of c_{01} when participant 4 performed his 5th trial in the stressful condition. If $c_{01} < 0$, the behaviour describes a van der Pol model. When $c_{01} > 0$, the behaviour describes a Rayleigh model.

months later, a retention test for the experiment of Nourrit *et al.* (2003). The four participants were able to reach the same amplitudes as during the last trials of the previous experiment, and adopted the same van der Pol escapement behaviour. These results show that the coordination mode adopted during the previous work was for all participants highly stable and persistent overn time, and allowed them to achieve a high level of performance. It is important to bear in mind that the present experiment was conducted against the background of a skilled behaviour, stabilized by a large amount of practice. Nevertheless, the results show a lower stability of the van der Pol behaviour for participant 4. It is important to note that this participant stabilized this van der Pol behaviour very late during the previous experiment, after 11 weeks of practice, while the others participants realized the transition quite early, between the third and the seventh week (Nourrit *et al.*, 2003). During the last sessions of the first experiment, similar differences were evidenced between this participant and the others in terms of the values of the linear damping coefficient c_{01} (for example, the values obtained for the 395th trial were -0.226, -0.226, -0.278 and -0.107 for participants 1–4, respectively). Five months later, this gap between participant 4 and the others was still evident.

During the present experiment, participants reached lower amplitudes when the simulator was off than on the floor. In so far as the two conditions were not counterbalanced between the participants, this result should be considered with caution. The increase in amplitude, from one condition to the other, could simply be considered a phenomenon of re-learning, during the 20 trials of the experimental sessions. This explanation is reinforced by the fact that the instructions provided to the participants did not indicate a specific outcome for amplitude. Nevertheless, this interpretation cannot be sustained, when considering the results obtained at the end of the re-accustoming session: clearly, the stressful condition induced a decrease in amplitude and, during the second session in the control condition, the participants were able to reach the same amplitude as at the end of the re-accustoming session. These amplitude data suggest that all the participants were stressed, even if no physiological and/or psychological measure has been recorded of how stressed they were. Future investigations on the control of coordination patterns under stress could be necessary to give evidence about the stress level as reported by Court *et al.* (1998) or Higuchi *et al.* (2002).

This decrease in performance shows that the influence of the stressful condition was not negligible. Participants were influenced by these new constraints, and were not able to realize the same level of performance. Nevertheless, at least for three participants, this decrease in performance was not accompanied by an alteration in coordination. They all maintained a highly stable van der Pol damping behaviour, without any trace of a regression towards a previously adopted behaviour.

First, in sporting contexts, performance needs to be maintained to ensure success. In that case, it could be emphasized that a breakdown in coordination pattern could have been observed if the participants had been required to maintain a certain level of amplitude. For example, frequency-induced transitions from anti-phase to in-phase coordination during rhythmic inter-limb coordination tasks, originally modelled by Haken *et al.* (1985), are accounted for by the decrease in movement amplitude (due to the Rayleigh damping term in the component oscillators) (Peper and Beek, 1998). However, the findings show that the stability of coordination patterns was not fully based on the inverse relation between movement frequency and amplitude. Even when participants were instructed to maintain the required amplitude, loss of stability of the initial pattern and phase transitions has been observed (Peper and Beek, 1999). Peper and Beek assumed that changing the spatiotemporal characteristics of coordination, by means of specific instructions with respect to amplitude of movements, does not alter the coordination dynamics. This point suggests that the component oscillators depend more directly on the movement frequency *per se*.

Secondly, our results suggest that skilled behaviour is highly robust and is able to resist stressful conditions. Note also that there was no significant alteration of the stiffness function, which remained almost linear. This is not surprising, as the linearization of the stiffness function appeared as a quite precocious phenomenon during the learning experiment of Nourrit *et al.* (2003).

The case of participant 4 is very interesting, as he exhibited a transient regression, during at least three trials, towards a bi-stable regime, where the system appeared to 'hesitate' between two concurrent escapement behaviours. This bi-stable regime was typical of the transition observed during the previous experiment (Nourrit *et al.*, 2003). During learning, all participants exhibited this kind of behaviour, which allowed them to leave their initial Rayleigh escapement and then to stabilize the van der Pol damping. It is important to remember that, compared with the other participants, participant 4 remained in this transition phase for longer in the previous experiment, and stabilized the van der Pol behaviour very late on. As a consequence, one can argue that his skill was less than that of the other participants, and his results could represent a good illustration of the regression hypothesis of Fuchs (1962), under stressful conditions.

In conclusion, two points should be highlighted. The first is the apparently strong resistance of skilled coordination under stressful conditions. Even if performance, as measured by movement amplitude, was clearly altered by stress, skilled motor coordination remained generally unchanged. This result provides strong support for the idea developed by some authors, regarding the necessary overlearning or automatization of skills, for coping with dangerous or stressful conditions (Roche, 1969; Wilde, 1988). Secondly, the eventual effect of stress on moderately skilled coordination does not appear as a random destabilization, but rather, as suggested by Fuchs (1962), as a transient regression towards a previously acquired behaviour.

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