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The effects of required amplitude and practice on frequency stability and efficiency in a cyclical task

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From an ecological point of view, motor learning emerges from the interplay of constraints on action, which shape behaviour towards the optimal solution, and practice, conceived as an active exploration of the work-space, to search this optimal solution. In the experiment reported here, we studied this interplay for a cyclical task performed on a ski-simulator. Our aim was to assess the respective effects of amplitude and practice on frequency variability and efficiency. On the basis of previous empirical findings, amplitude was expected, beyond a critical value, to constrain and stabilize the frequency of the movement. Three groups of participants practised during four sessions at three different amplitudes (15, 22.5 and 30 cm). The results showed that participants moving at large amplitude displayed more stable and more consistent frequencies. Nevertheless, there was no interaction effect between target amplitude and practice. On the other hand, movement economy and harmonicity increased with practice, but were not affected by amplitude. Finally, the results of transfer tests showed that the effects of large amplitude on frequency variability were not resistant to a subsequent decrease in target amplitude. These results suggest that constraints and practice act independently on motor behaviour, and that a high constraint could be detrimental to the development of effective search strategies.

Keywords: frequency variability, learning, practice effect.

Introduction

In the ecological approach to motor behaviour, coordination is conceived as an emergent property of a complex set of interrelated constraints (Kugler *et al.*, 1980, 1982; Kugler and Turvey, 1987). From this perspective, a constraint on action is defined as a reduction in the degrees of freedom. Constraints shape or limit behaviour by reducing the action possibilities.

Newell (1986) categorized these constraints into those found in (1) the organism, (2) the environment and (3) the task at hand. The organismic constraints include such physical characteristics as weight, height and body shape, together with psychological and emotional attributes. The environmental constraints arise from the physical environment (gravity, ambient temperature, etc.), as well as from the cultural environment, which tends to promote some kinds of action and to prohibit others (see Reed, 1993). Finally, task constraints include the physical characteristics of the task at hand (implements, machines, etc.) and the instructions that are given to participants about their goal or the particular coordination they must perform. The interaction between these three categories of constraints determines both the possible and the optimal patterns of coordination in the task. According to Newell (1986), the relative impact of these three categories of constraints on the pattern of coordination varies according to the specific circumstances.

Several studies of self-optimization in cyclical activities offer good examples of these principles (Sparrow, 1983). Some experiments have shown that a given set of constraints determines an optimal solution for energy expenditure. For example, Hogberg (1952) observed, for a given running speed (16 $\text{km}\cdot\text{h}^{-1}$), a U-shaped relationship between step amplitude and oxygen consumption. A similar relationship was noted by Holt *et al.* (1991) between stride frequency and oxygen consumption when walking at a fixed speed. Similar results

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were obtained by Salvendy (1972) in various cyclical tasks. Holt *et al.* (1991) showed that a model based on the mechanical properties of the body (i.e. organismic constraints) allowed the accurate prediction of the optimal stride frequency during walking, as the resonant frequency of a single pendulum of equivalent length (see also Kugler and Turvey, 1987). More importantly, when participants were free to choose their pattern of response, they systematically adopted the most efficient one (Corlett and Mahadeva, 1970; Salvendy, 1972; Warren, 1984; Holt *et al.*, 1991).

The dynamical approach to motor coordination highlights behavioural stability as another fundamental characteristic of optimal responses (Schöner and Kelso, 1988; Kelso *et al.*, 1993; Kelso, 1995). Using this framework, the dynamics of the coordination are captured at an abstract (mathematical) level by the equation of motion of a collective variable, whose dynamics can be represented by a potential function, punctuated by attractors (stable equilibrium points of the system) and repellers (unstable equilibrium points). Stability and instability play a crucial role in the dynamics of the collective variable. The system tends to join the attractors of the potential (i.e. the points corresponding to the most stable behaviours), and all change in behaviour (so-called 'phase transitions') is determined by a destabilization of the previous coordination.

For example, when individuals have to move their index fingers or hands rhythmically, they can perform stably in only two phase-locked modes, either in-phase (homologous muscle groups contracting simultaneously) or anti-phase (homologous muscle groups contracting in an alternating fashion; see Kelso, 1995). These two coordination modes are the two attractor states of the relative phase between the two effectors. When participants, initially moving in the anti-phase mode, are instructed to increase cycling frequency, an involuntary abrupt shift to the in-phase mode occurs at a critical frequency. Just before this transition from the anti-phase mode to the in-phase mode, a dramatic increase in relative phase variability is observed.

Note that stability, in this framework, does not signify rigidity or stereotype. Rigidity can occur when a skill is acquired in a very closed and reproducible environment. In this case, the individual could experience difficulty coping with an unexpected perturbation. Stability, from a dynamical point of view, refers to the capacity of the system to return quickly to its attractor state after a perturbation. A skilled pattern is highly stable, but remains flexible and adaptable.

Stability and efficiency have rarely been studied simultaneously. Nevertheless, Holt *et al.* (1995) hypothesized that they could constitute two fundamental characteristics of optimal behaviour, and showed that walking at the preferred frequency was characterized both by maximal efficiency and by a minimal variability in head displacement and the relative phase between joints. Candau *et al.* (1998) recently reported a strong relationship between efficiency and step variability in running.

Motor learning, in this ecological framework, is conceived as the search for the optimal solution in the perceptual-motor workspace (Fowler and Turvey, 1978; Newell *et al.*, 1989). This workspace represents a hypothetical interface between perception and action, determined by the interplay of the current set of constraints with action. In line with the previous discussion, increases in efficiency and behaviour stability constitute expected outcomes of motor learning. Such trends were evidenced in several learning experiments for efficiency (Kamon and Gormley, 1968; Sparrow, 1983; Sparrow and Irizarry-Lopez, 1987; Durand *et al.*, 1994) and stability (Higgins and Spaeth, 1972; Hoffman, 1974; Marteniuk and Romanov, 1983; Darling and Cooke, 1987; Zanone and Kelso, 1992).

Learning emerges from a complex interplay between practice and constraints. Practice allows participants to repeat the search process; constraints channel this search by reducing the action possibilities. Furthermore, in most ecological tasks, learning cannot be simply conceived of as the exploration of a static workspace. Practice leads to a progressive improvement in skill, allowing participants to incorporate additional constraints. In other words, the perceptual workspace evolves qualitatively with practice, and the discovery of a first solution allows the enrichment of the set of constraints and the relaunching of the search process.

These principles were adequately illustrated in a learning experiment by Durand *et al.* (1994) on a ski-simulator. This apparatus (see Fig. 1) consists of a platform that moves on wheels over a pair of bowed rails to the left and right of its central position. Two rubber springs ensure that, after a disturbance in either direction, the platform returns to this central position. The apparatus allows participants to perform slalom-like cyclical movements. It has been used in many experiments, especially in the analysis of the evolution of motor coordination and performance with practice (e.g. den Brinker *et al.*, 1986; Van Emmerik *et al.*, 1989; Vereijken and Whiting, 1990; Vereijken, 1991; Vereijken *et al.*, 1992a,b, 1997).

Durand *et al.* (1994) studied the evolution of amplitude and frequency among five participants during six sessions of practice. They observed a gradual increase in movement amplitude, associated with a progressive convergence of frequencies around a mean value of 1.1 Hz (Fig. 2a). [Durand *et al.* (1994) based their calculation of frequency on the duration of half-cycles (from a reversal point to the opposite). As such, they reported a convergence of frequencies around a mean value of 2.2 Hz. This value must be divided by 2 to agree with the more conventional assessment of frequency, based on the duration of the complete cycle.] During the first session, large differences in individual frequencies were observed (from 0.7 to 1.3 Hz). Moreover, a significant increase in efficiency was noted across sessions.

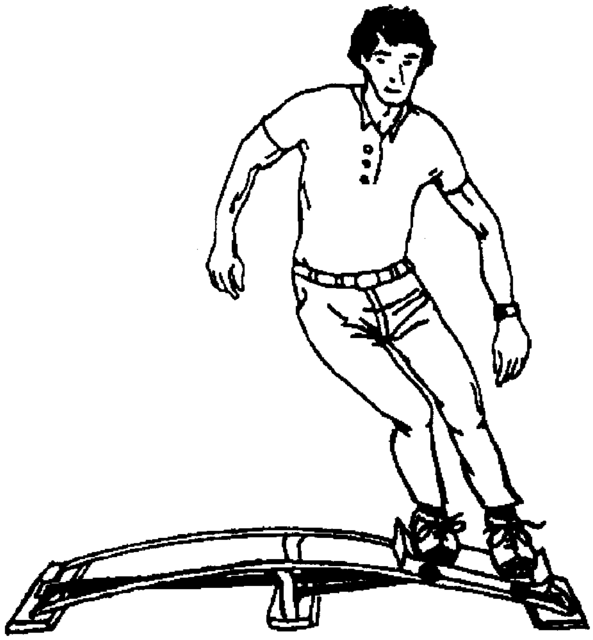


Fig. 1. The ski-simulator apparatus (see text for details). From Whiting *et al.* (1992).

These results were consistent with the preceding assumption that the participants would tend, with practice, to adopt a frequency close to the resonant frequency of the system, resulting in a progressive increase in efficiency. The progressive convergence of frequencies was congruent with the views of learning based on search strategies (Newell *et al.*, 1989), leading the participants to discover increasingly optimal solutions.

Deligniéres *et al.* (1996) suggested a possible alternative interpretation after a broader analysis of the data of Durand *et al.* (1994). They showed that the convergence in frequencies around 1.1 Hz appeared to occur beyond a threshold in amplitude of approximately 30 cm. At the outset of the experiment, some participants showed either very high or very low frequencies associated with low amplitudes. They did not join the optimal frequency before they were able to reach an amplitude of 30 cm. Other participants were able, from the outset of the experiment, to reach an amplitude close to 30 cm. From the very first trials, these participants adopted a frequency close to 1.1 Hz. These observations are illustrated in Fig. 2b, which represents the evolution of the relationship between amplitude and frequency for the five participants in the experiment.

These observations suggest that the increase in amplitude could be conceived as generating a set of constraints that reduce the degrees of freedom of the system, and direct participants towards the adoption of the resonant frequency. From this point of view, the convergence of frequencies might mainly be due to the increase in amplitude, progressively allowed by practice.

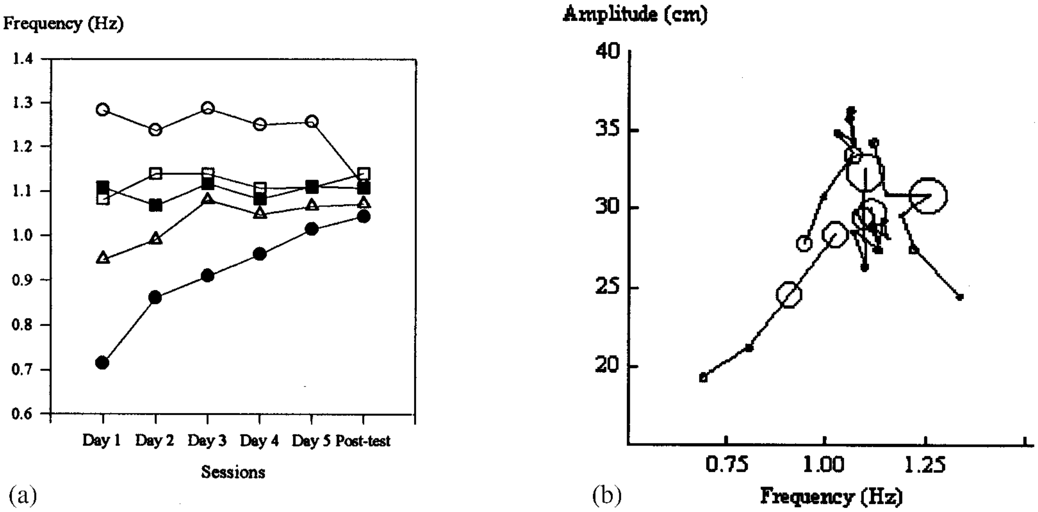


Fig. 2. (a) Evolution of individual frequency over five sessions of practice and a post-test on the ski-simulator (from Durand *et al.*, 1994). ○, participant 1; □, participant 2; △, participant 3; ●, participant 4; ■, participant 5. (b) Representation of the evolution of the relationship between amplitude and frequency, during the same experiment. The data were submitted to a cluster analysis. Each cluster is represented by a bubble, and the diameter of the bubble corresponds to the number of successive points that have been grouped together by the cluster analysis. Data from the five participants are superimposed in the chart. The figure illustrates the convergence of frequencies beyond an amplitude of 30 cm (from Geoffroi *et al.*, 1995).

Durand *et al.* (1994) did not distinguish between amplitude and practice effects, as gains in amplitude appeared as a result of practice. The main aim of the present study was to assess the effects of amplitude and practice on the ski-simulator, manipulated as independent factors. Amplitude was imposed by a target value assigned to each experimental group, and practice was devoted to the optimization of the skill at this fixed amplitude.

The effects of these two factors were analysed for movement efficiency and behavioural stability (measured via frequency variability). A main effect of both factors was expected, as (a) practice was conceived as a search for optimal (and stable) solutions, and (b) amplitude was hypothesized to modulate the availability of these optimal solutions in the workspace. Interaction effects were also expected, which might reveal a possible enhancement of the effects of practice through specific amplitude requirements. Clearly, practice at large amplitude was expected to be more effective in terms of efficiency and stability.

Methods

Participants

Fifteen participants (mean ± *s*: age 23.8 ± 2.3 years, body mass 71.0 ± 6.5 kg, height 177 ± 7 cm) volunteered for the experiment. All participants were occasional skiers, but none of them had previous experience on the ski-simulator. They signed an informed consent form and were not paid for their participation.

Task

The task was executed on a slalom ski-simulator (Skier's Edge; see Fig. 1). The participant's feet were strapped to the platform. The tension of the belts was controlled with a dynamometer at the beginning of each session, and adjusted to obtain a displacement of 4 cm of the platform from the central position with a tangential force of 100 N.

Procedure

The participants were assigned at random to one of three experimental groups. They were asked to perform slalom ski-like movements on the apparatus, with an amplitude of 15 cm (group 1), 22.5 cm (group 2), or 30 cm (group 3). Two fibreglass sticks were adjusted in the vertical direction on both sides of the apparatus to reach the required amplitude. The maximum reachable amplitude on the apparatus was around 50 cm. The choice of these moderate target amplitudes was based on three considerations:

1. As each participant might have had the same amount of practice at the target amplitude, it was necessary that the required amplitude was reachable from the outset of the experiment.
2. The results of Durand *et al.* (1994) suggested that an amplitude of 30 cm was sufficient to obtain a convergence and a stabilization of frequencies.
3. These target amplitudes were sufficiently low to avoid wear of the rubber belts.

Four practice sessions were conducted on 4 consecutive days. Each session consisted of four 4-min trials, with a 4-min break between them. The participants performed individually. They were not given a demonstration, but they were told to oscillate regularly at their target amplitude and to adopt the most comfortable frequency.

As we expected practice at large amplitude to be more effective for learning, transfer tests were proposed for the participants in group 3. At the end of their last session, these participants performed two 4-min transfer trials at amplitudes of 15 and 22.5 cm, respectively. These trials were performed in a random order, with a 4-min break between them. The rationale for these tests was to allow an analysis of the effect of a decrease in target amplitude in participants who practised with a large target amplitude, and to compare these participants, at similar amplitudes, with the participants who practised at low and medium target amplitudes.

Dependent variables

The position of the middle point of the platform was measured by a potentiometer (Radiospares, 20-K resistance and 0.25% linearity) and sampled at a frequency of 100 Hz. One revolution of the potentiometer reflected 12.5 cm of movement of the platform. The data were stored on a personal computer for further analysis.

The position data were first filtered with a Fast Fourier Transform. A peak-finding algorithm was used to localize the reversal points of the movement. 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. Mean amplitude was computed for each 30-s interval, giving eight successive measurements for each trial. Cycle frequency (in Hz) was defined as the inverse of the duration of a complete cycle. Individual mean frequency was then calculated for each 30-s interval.

Intra-individual frequency variability was defined as the standard deviation of frequency, and was calculated for each 30-s interval. Inter-individual frequency variability was defined as the standard deviation, within each group, of individual mean frequencies, and was calculated for each 30-s interval.

Two distinct assessments of energy economy were realized, based on (1) the dynamics of the platform and (2) physiological data. An index of *harmonicity* was calculated, defined as the Pearson-product correlation ($r_{x,\ddot{x}}$) between position (x) and its second-order derivative ($\ddot{x}$). According to Guiard (1993), an ideal mass-spring system, fully exploiting the relative forces, should tend to a simple harmonic motion. In the case of complete harmonicity, x is a sine function of time, and $r_{x,\ddot{x}}$ must be equal to -1 (as the second-order derivative of a sine function is also a sine function but negative). $r_{x,\ddot{x}}$ was calculated for each 30-s interval, and a Fisher Z-transformation was applied before statistical analysis.

Oxygen intake was measured continuously using a Cosmed K2, a portable telemetric system that measures $\dot{V}_E$ (the volume of expired air in litres per minute) and $\dot{V}O_2$ (volume of oxygen consumed in litres per minute). The participants wore a face mask that was connected to an analysis and transmitter unit (weighting 400 g). The data were sent telemetrically to a receiver unit and stored for further analysis. The data were averaged by the system for each 30-s interval.

Physiological efficiency was assessed by computing the *movement cost*, defined by the ratio $\dot{V}O_2$/(amplitude × frequency) (Durand *et al.*, 1994). Because of the latency of aerobic processes, the $\dot{V}O_2$ results were not considered valid during the first 2 min of each trial. Movement cost was then calculated for each 30-s interval during the last 2 min of each trial.

Statistical analysis

For the practice data, amplitude, frequency, intra-individual frequency variability, and harmonicity were analysed by four-way analyses of variance of group (3) × session (4) × trial (4) × interval (8), with repeated measures on the three last factors. Inter-individual variability was analysed by a three-way analysis of variance of group (3) × session (4) × trial (4), with repeated measures on the two last factors. For this analysis, interval values were treated as cases. Movement cost was analysed by a four-way analysis of variance of group (3) × session (4) × trial (4) × interval (4).

Transfer trials ('22.5 cm' and '15 cm' conditions) were compared with the last trial performed by group 3 in the '30 cm' condition using a one-factor analysis of variance (condition), with three levels of repeated measures. Then, two one-way analyses of variance were performed to compare groups 3 and 2 (using the '22.5 cm' data for group 3 and the last trial performed by group 2) and groups 3 and 1 (using the '15 cm' data for group 3 and the last trial performed by group 1). Because of technical problems storing the data, $\dot{V}O_2$ measures were not available for these transfer tests. Analyses were then performed on amplitude, frequency, intra- and inter-individual frequency variability, and harmonicity.

To protect against possible violations of the compound symmetry and sphericity assumptions, the significance of F-ratios was adjusted according to the Huyn-Feldt procedure.

Results

The results are presented in two sections, first for the practice sessions and then for the transfer trials.

Practice trials

Amplitude. A main effect of group was obtained ($F_{2,12} = 63.4$, $P < 0.001$). The mean (± s) values were 17.0 ± 2.95 cm for group 1, 25.5 ± 2.15 cm for group 2 and 32.5 ± 1.32 cm for group 3. Pairwise comparisons indicated that all means differed significantly from each other. There was no main effect of session or trial. The trial × group interaction was significant ($F_{6,36} = 3.42$, $P < 0.05$), with a significant linear trend ($F_{2,12} = 3.91$, $P < 0.05$). This effect indicated that, within each session, amplitude tended to increase slightly over trials for group 3, and to decrease symmetrically for group 1.

Frequency. This analysis revealed a significant effect of group ($F_{2,12} = 8.68$, $P < 0.01$). The mean (± s) values were 1.18 ± 0.14 Hz for group 1, 0.84 ± 0.15 Hz for group 2 and 0.94 ± 0.08 Hz for group 3. Pairwise comparisons indicated that frequency was higher for group 1 than for the other two groups. Because den Brinker *et al.* (1984) reported a significant linear relationship between body mass and preferred frequency on the ski-simulator, we performed a covariance analysis controlling for body mass. The effect of group remained significant in this covariance analysis ($F_{2,11} = 8.52$, $P < 0.01$).

There was no effect of session, but there was a significant effect of trial ($F_{3,36} = 19.4$, $P < 0.001$), with a significant linear trend ($F_{1,12} = 24.9$, $P < 0.001$). Within each session, mean frequency tended to increase from the first to the fourth trial. A main effect was also obtained for interval ($F_{7,84} = 4.04$, $P < 0.05$), with a significant quadratic trend ($F_{1,12} = 4.98$, $P < 0.05$). In general, frequency tended to decrease during the four first intervals of each trial, and then remained stable until the end of the trial.

Intra-individual frequency variability. There was a significant effect of group ($F_{2,12} = 9.97$, $P < 0.01$). The mean (± s) values were 0.033 ± 0.017 Hz for group 1, 0.021 ± 0.005 Hz for group 2 and 0.023 ± 0.009 Hz for group 3. Pairwise comparisons indicated that frequency variability was higher for group 1 than for the other two groups (Fig. 3). Intra-individual frequency variability was higher for participants practising at low amplitude.

A significant effect was obtained for session ($F_{3,36}$ = 3.72, $P < 0.05$), with a significant linear trend ($F_{1,12}$ = 4.95, $P < 0.05$), indicating that frequency variability tended to decrease linearly from the first to the last session. Finally, there was a significant effect of interval ($F_{7,84} = 6.77$, $P < 0.001$), with significant linear and quadratic trends ($F_{1,12} = 8.13$, $P < 0.05$ and $F_{1,12} = 14.2$, $P < 0.01$, respectively). Within each trial, frequency variability was higher during the first minute than during the following intervals.

Inter-individual frequency variability. A main effect of group was obtained ($F_{2,21} = 399$, $P < 0.001$). The mean (± s) values were 0.151 ± 0.019 Hz for group 1, 0.166 ± 0.020 Hz for group 2 and 0.078 ± 0.027 Hz for group 3. *Post-hoc* comparisons indicated that group 3 (high amplitude) had smaller inter-individual variability than groups 1 and 2 (Fig. 4). There was also a significant effect of session ($F_{3,63} = 56.4$, $P < 0.001$), with a significant cubic trend ($F_{1,21} = 158$, $P < 0.001$), indicating that inter-individual variability increased from the first session to the second, and then decreased to the end of the experiment. A main effect was obtained for trial ($F_{3,63} = 89.3$, $P < 0.001$), with a significant linear trend ($F_{1,21} = 160$, $P < 0.001$), indicating that, within each session, inter-individual variability increased linearly from the first trial to the last.

The group × session interaction was significant ($F_{6,63} = 119$, $P < 0.001$), with a significant linear trend ($F_{2,21} = 162$, $P < 0.001$). *Post-hoc* comparisons indicated that differences between group 3 and the other two groups were only significant from the third session. There was also a significant session × trial interaction ($F_{9,189} = 19.4$, $P < 0.001$), with a significant linear trend ($F_{1,21} = 70.1$, $P < 0.001$). *Post-hoc* comparisons showed that the increase in inter-individual frequency variability was higher during the first two sessions than during the last two.

Movement cost. There was no effect of group, but there was a significant main effect of session ($F_{3,36} = 3.46$, $P < 0.05$), with a significant linear trend ($F_{1,12} = 4.65$, $P < 0.05$). Movement cost decreased linearly from the first session to the fourth (0.71, 0.70, 0.65 and 0.63 $\mathrm{ml \cdot kg \cdot s^{-1}}$, respectively). There was also a main effect of trial ($F_{3,36} = 5.92$, $P < 0.01$), with a significant linear trend ($F_{1,12} = 10.4$, $P < 0.01$). Movement cost decreased linearly from the first trial to the fourth (0.69, 0.68, 0.67 and 0.66 $\mathrm{ml \cdot kg \cdot s^{-1}}$, respectively). The session × trial interaction was significant ($F_{9,108} = 2.25$, $P < 0.05$), with a significant linear trend ($F_{1,12} = 4.72$, $P < 0.05$). The decrease in movement cost, within each session, was progressively reduced from the beginning to the end of the experiment (Fig. 5).

Harmonicity. There was no effect of group ($F_{2,12} = 3.42$, $P = 0.067$), but there was a main effect of session ($F_{3,36} = 12.2$, $P < 0.001$), with significant linear and

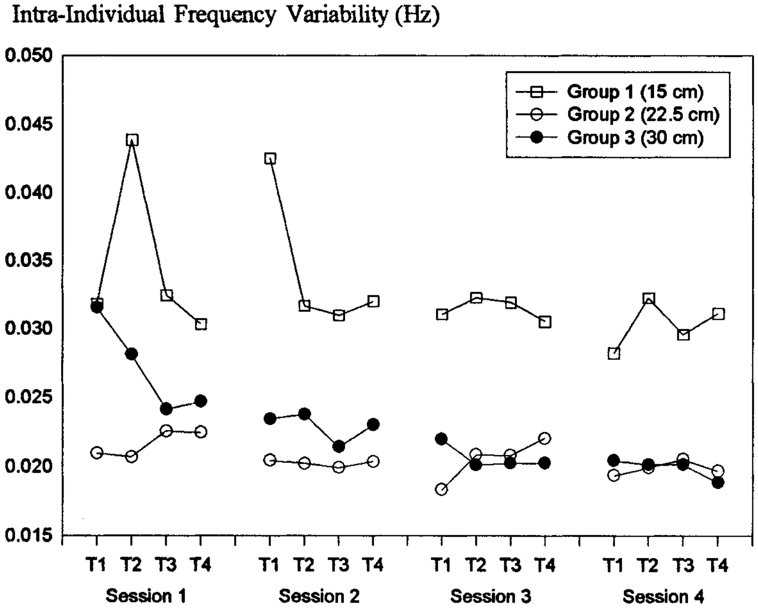


Fig. 3. Evolution of intra-individual frequency variability for the three experimental groups over the four sessions of practice.

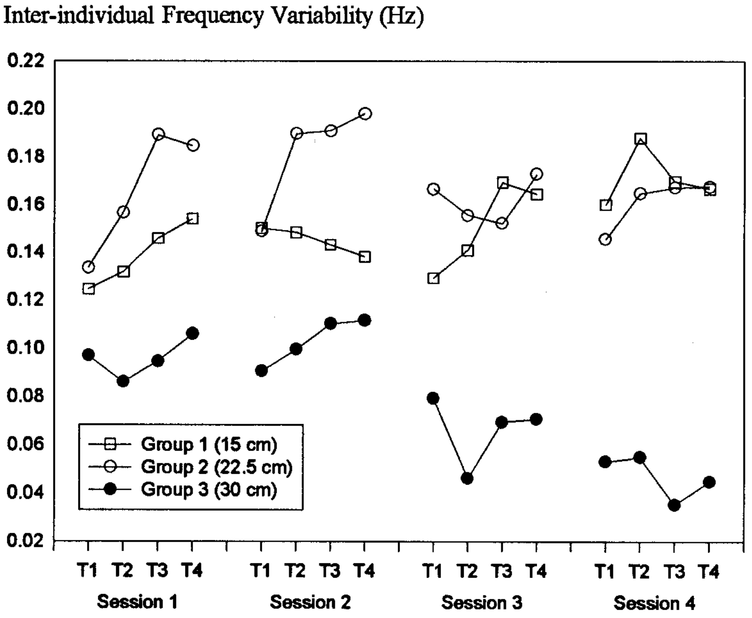


Fig. 4. Evolution of inter-individual frequency variability for the three experimental groups over the four sessions of practice.

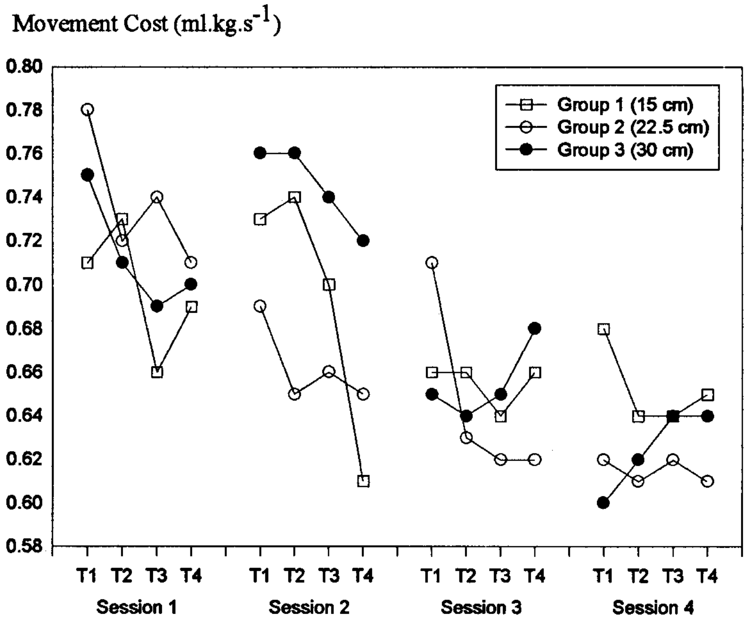


Fig. 5. Evolution of movement cost for the three experimental groups over the four sessions of practice.

quadratic trends ($F_{1,12} = 15.5$, $P < 0.01$ and $F_{1,12} = 15.3$, $P < 0.01$, respectively). Harmonicity increased significantly from the first to the second session, and then remained unchanged until the end of the experiment. Mean $Zr_{x,\dot{x}}$ for the four sessions was −1.87, −2.00, −2.03 and −2.02, respectively. There was also a significant effect of trial ($F_{3,36} = 24.6$, $P < 0.001$), with significant linear and quadratic trends ($F_{1,12} = 33.3$, $P < 0.001$ and $F_{1,12} = 13.9$, $P < 0.01$, respectively). Harmonicity increased significantly from the first to the second trial of each session, and then remained unchanged until the end of the session (Fig. 6). Mean $Zr_{x,\dot{x}}$ for the four trials was −1.88, −1.99, −2.02 and −2.05, respectively. Finally, the session × trial interaction was significant ($F_{9,108} = 4.55$, $P < 0.001$), with a significant linear trend ($F_{1,12} = 25.4$, $P < 0.001$), indicating that the increase in harmonicity was more important within the first session than within the others.

Figure 7 illustrates the evolution of Hooke portraits during the experiment, for one representative participant each from groups 1 and 3. Acceleration of the platform was plotted against position. At the beginning of the experiment, these portraits showed a systematic pause in acceleration at the extreme of each swing. At the end of the experiment, a linear relation was obtained.

Transfer tests

Amplitude. The within-individual analysis indicated a significant effect of target amplitude ($F_{2,8} = 324$, $P < 0.001$), with a significant linear trend ($F_{1,4} = 389$, $P < 0.001$). The mean (± *s*) values were 32.3 ± 0.70 cm for the '30 cm' condition, 25.7 ± 1.72 cm for the '22.5 cm' condition and 16.6 ± 1.87 cm for the '15 cm' condition. Pairwise comparisons indicated that all means differed significantly from each other. An interval effect was also obtained ($F_{7,28} = 5.77$, $P < 0.001$), with significant linear and quadratic trends ($F_{1,4} = 13.7$, $P < 0.05$ and $F_{1,4} = 11.2$, $P < 0.05$, respectively). Whatever the target amplitude, mean amplitude tended to decrease linearly during the first three intervals, and then remained constant until the end of the trial. Between-individuals analyses revealed no main effects or interactions for the comparisons of groups 3 and 2 and of groups 3 and 1.

Frequency. No main effects or interactions were evidenced by the within-individual analysis. The between-individuals analyses revealed no main effects or interactions for the comparisons of groups 3 and 2 and of groups 3 and 1.

Intra-individual frequency variability. The within-individual analysis indicated a significant effect of target amplitude ($F_{2,8} = 7.38$, $P < 0.05$), with a significant linear trend ($F_{1,4} = 13.4$, $P < 0.05$). The mean (± *s*) values were 0.019 ± 0.005 Hz for the '30 cm' condition, 0.024 ± 0.013 Hz for the '22.5 cm' condition and 0.035 ± 0.016 Hz for the '15 cm' condition. Pairwise comparisons indicated that all means differed significantly from each other. Intra-individual variability increased as target amplitude decreased. There was no effect of interval and no interaction effect. Finally, no main effects or interactions were evidenced by the two between-individuals analyses, indicating that intra-individual variability was not significantly different between groups, at equivalent target amplitudes.

Inter-individual frequency variability. The within-individual analysis revealed a significant effect of target amplitude ($F_{2,14} = 241$, $P < 0.001$), with significant linear and quadratic trends ($F_{1,7} = 254$, $P < 0.001$ and $F_{1,7} = 102$, $P < 0.001$, respectively). The mean (± *s*) values were 0.045 ± 0.008 Hz for the '30 cm' condition, 0.121 ± 0.034 Hz for the '22.5 cm' condition and 0.271 ± 0.046 Hz for the '15 cm' condition. Pairwise comparisons indicated that all means differed significantly from each other. A decrease in amplitude led to a systematic increase in inter-individual variability.

The comparison between groups 2 and 3 (with a target amplitude of 22.5 cm) indicated a significant difference ($F_{1,14} = 8.54$, $P < 0.05$), in that the inter-individual variability was larger for group 3 than for group 2 (0.166 *vs* 0.134). A significant difference was also evidenced in the comparison between groups 1 and 3 (with a target amplitude of 15 cm: $F_{1,14} = 39.7$,

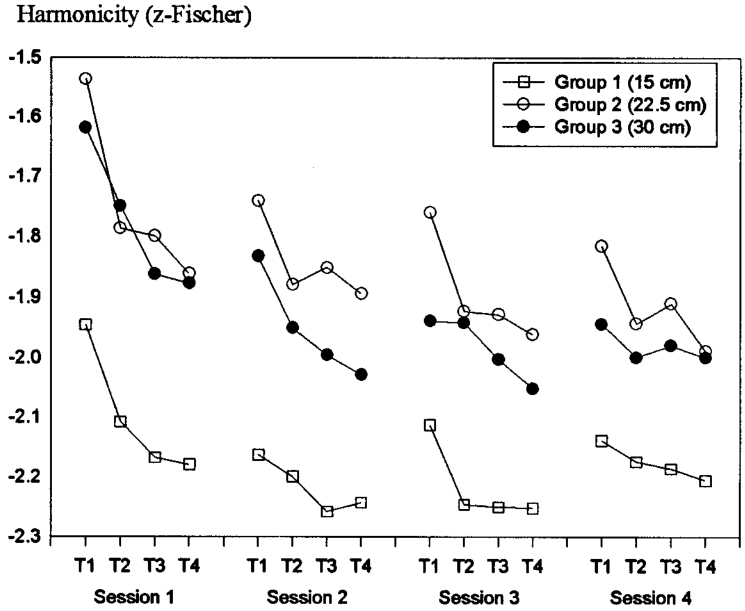
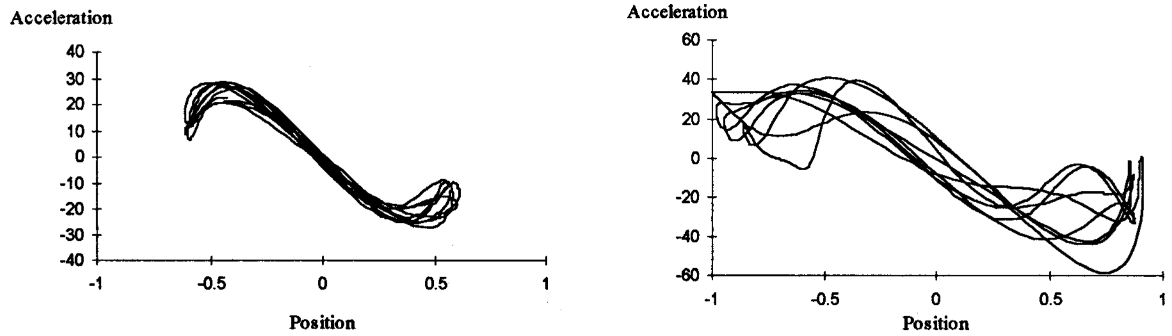
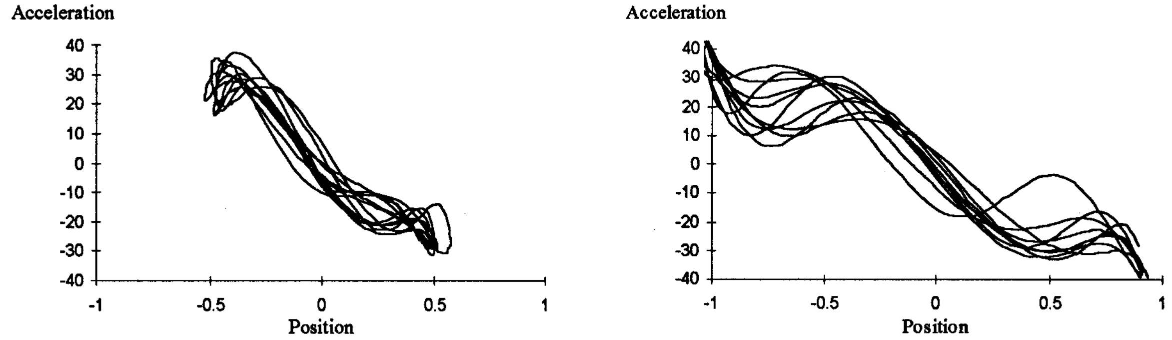


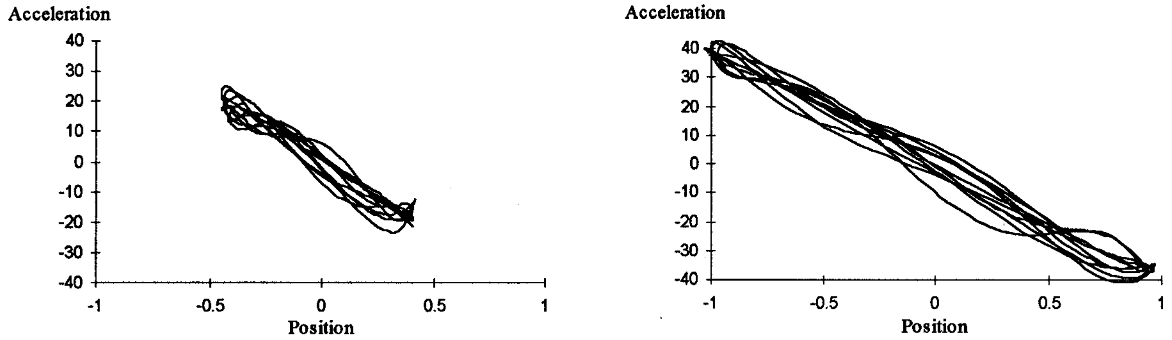
Fig. 6. Evolution of harmonicity for the three experimental groups over the four sessions of practice.



Session 1 - Trial 1 ($r_{x,\ddot{x}} = -0.902$) Session 1 - Trial 1 ($r_{x,\ddot{x}} = -0.856$)



Session 1 - Trial 4 ($r_{x,\ddot{x}} = -0.949$) Session 1 - Trial 4 ($r_{x,\ddot{x}} = -0.969$)



Session 4 - Trial 4 ($r_{x,\ddot{x}} = -0.971$) Session 4 - Trial 4 ($r_{x,\ddot{x}} = -0.988$)

Fig. 7. Evolution of the Hooke portraits, from the beginning to the end of the experiment, for two representative participants. (Left-hand panels) participant from group 1; (right-hand panels) participant from group 3.

$P < 0.001$), as the inter-individual variability was larger for group 3 than for group 1 (0.271 *vs* 0.167).

Harmonicity. No main effects or interactions were evidenced by the within-individual analysis, or by the two between-individuals analyses.

Discussion

The main aim of the present study was to assess the effects of amplitude and practice, considered to be independent factors, on frequency variability and efficiency. Participants were asked to practise at a fixed amplitude (15, 22.5 or 30 cm) over four sessions.

The amplitude results showed that all participants were able to satisfy our requirements in terms of target amplitude. The absence of session, group × session and group × session × trial effects indicated that each group (but especially group 3) was able to reach its target amplitude from the first trial. We consider, therefore, that the amount of practice at the target amplitude was equal for each group. The mean amplitude produced by each group was slightly higher than the respective target amplitudes. This was because of the flexibility of the fibreglass sticks, which allowed the participants to pursue their movements beyond the contact.

Readers might be surprised to observe such amplitudes with novices on the ski-simulator. In most previous experiments using this apparatus, mean amplitude was confined during the first trials between 10 and 20 cm (see, for example, den Brinker *et al.*, 1986; Van Emmerik *et al.*, 1989; Vereijken *et al.*, 1992a,b). As noted previously, all our participants were occasional skiers. Nevertheless, our movement cost and harmonicity results indicated that they did not adopt, at the start of the experiment, an ‘expert’ behaviour. On the other hand, participants in previous experiments were not asked to reach specific amplitudes, but to swing ‘as much as possible’. The results of most goal-setting experiments have shown that specific goals lead to better performances than ‘do-your-best’ conditions (Barnett and Staniceck, 1979; Hall *et al.*, 1987; Weinberg *et al.*, 1988; Boyce and Wayda, 1994).

Our main hypotheses for frequency variability were clearly validated. As target amplitude increased, frequency became more consistent among participants and more stable within participants. Similar trends were obtained with practice. These results are consistent with our previous statements – practice can be considered as a search for optimal solutions and amplitude constraints tend to channel this search process.

Because effective channelling ought to facilitate the search process, an interaction between amplitude and practice was expected. Such an interaction was obtained for inter-individual variability. With practice, participants within each group tended to converge to a common frequency, a trend that was more marked in the group which oscillated at large amplitude. Inter-individual variability could be considered a measure of the importance of apparatus constraints, in the overall set of constraints which shaped behaviour. Our results suggest that this was more salient at large amplitudes.

Conversely, den Brinker *et al.* (1984) emphasized the influence of body mass (an organismic constraint) in determining the preferred frequency on the ski-simulator. This was clearly not the case in the present experiment, or in that of Durand *et al.* (1994), which was performed using the same apparatus. Moreover, large differences appear in mean preferred frequency from one experiment to another. Vereijken (1991) reported values around 0.7 Hz. Recently, Wulf performed two experiments in which participants produced frequencies around 0.45 Hz (Wulf and Weigelt, 1997; Wulf *et al.*, 1998). Preferred frequencies on our own ski-simulator were higher, about 1.1 Hz in the experiment by Durand *et al.* (1994) and 0.84–1.18 Hz in the present study. Differences in belt stiffness, as well as in the setting of belt tension, could explain these discrepancies in preferred frequencies. Even on very similar apparatus, slight differences in mechanical properties might lead to large discrepancies in the hierarchy of the system of constraints.

Surprisingly, an interaction between amplitude and practice was not obtained for intra-individual frequency variability, which can be considered a measure of the attractive power of individual resonant frequency. Amplitude seemed to channel participants towards a stable oscillatory behaviour, but practice did not take advantage of this channelling effect. In this respect, the effects of amplitude and practice were clearly independent.

This independence was confirmed by the results for movement cost and harmonicity, which indicated a systematic decrease in movement cost and an increase in harmonicity among sessions, and among trials within each session. The session × trial interaction showed that progress in efficiency and harmonicity was more important at the beginning of practice, and evolved asymptotically during the experiment.

Inspection of the Hooke portraits (Fig. 7) suggests that the participants learned progressively to exploit the reactive forces of the system. The linear relationships obtained at the end of the experiment between position and acceleration revealed a clear harmonic motion of the platform and showed that the potential energy stored in elastic rubbers during the displacement of the platform was immediately restored after the reversal point. Hooke portraits in the early phases of the experiment revealed strong non-linearities, especially near the reversal points of the movement. The displacement of the platform appeared more as a concatenation (sequencing) of discrete movements rather than as a cyclical motion (Guiard, 1993).

More importantly, these practice effects on harmonicity and movement cost were not affected by target amplitude. In other words, the optimization of the skill appeared to be independent of the amplitude of the movement.

The results of the transfer tests merit a detailed examination. Clearly, the decrease in target amplitude induced a systematic increase in intra-individual frequency variability. This result was not surprising, as the effects of amplitude and practice, during the first part of the experiment, appeared to be independent. Note, however, that mean intra-individual variability for group 3 did not differ from that of the other two groups, at similar target amplitude and after an equivalent duration of practice. One might consider that the effects of practice at large amplitude were effectively transferred in trials at smaller amplitudes. Nevertheless, these results suggest that practice at large amplitude did not result in substantial benefits compared with practice at smaller amplitudes. The same reasoning can be used for the harmonicity results.

Group 3 showed significantly higher inter-individual variability than the other two groups, at similar target amplitudes and after an equivalent duration of practice. Remember that we showed in the first part of this experiment that practice, on the ski-simulator, led to a convergence of frequencies among participants, and that this convergence was higher with a large target amplitude. The transfer results suggest that the participants who practised at large amplitude were less able, at smaller amplitudes, to converge towards the optimal oscillatory frequency of the system.

As proposed by Newell (Newell *et al.*, 1989; Newell, 1991), motor learning can be viewed as learning to search for optimal solutions in a perceptual-motor workspace. From this point of view, skilled individuals do not, over trials, repeat the expert behaviour itself, but the search process which leads to the expert behaviour (Bernstein, 1967). On the other hand, constraints tend to shape behaviour towards the optimal solution; more precisely, high constraints tend to facilitate the search process for the optimal solution. Then, when faced with such constraints, one might suppose that participants do not need to develop effective search strategies to discover the optimal solution (Davids *et al.*, 1994). Conversely, low constraints might oblige participants to develop more sophisticated search strategies. Such a hypothesis could explain why inter-individual variability was higher in transfer tests for group 3 than for the other two groups, at similar target amplitudes.

In conclusion, we can confirm that amplitude, on the ski-simulator, constrains the frequency of movement. Participants moving at high amplitude display more stable and more consistent frequencies. This could be seen as strengthening a system of constraints, leading to the stabilization of oscillatory behaviour of the system. In addition, practice led to a stabilization of frequency, but the effects of amplitude and practice were clearly independent. Furthermore, transfer tests showed that practice at high amplitude was not beneficial in terms of learning. More generally, our results suggest that a set of constraints that guide too strictly the solution of the motor problem prevents participants from developing effective search strategies.

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