The learning of goal-directed locomotion: 
A perception–action perspective

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This study was designed to better understand the process underlying the learning of goal-directed locomotion. Subjects walked on a treadmill in a virtual reality setting and were asked to cross pairs of oscillating doors. The subjects’ behaviour was examined at the beginning of the learning process (pretest), after 350 trials (intermediate test), and after 700 trials (posttest). The data were analysed at three different levels, each representing a specific aspect of the global response: performance outcome, displacement kinematics, and current arrival condition. While some aspects of performance outcome suggested the presence of a ceiling effect in the intermediate test, both displacement kinematics and current arrival condition clearly highlighted continuous transformations of the control mechanism involved. The learning process is best described as (1) the establishing of a relationship between specific information and a movement parameter and (2) the optimization of this relationship. The optimization process is characterized by the further exploration of the available behavioural repertoire and by the refinement of the dialogue between information and movement.

During our daily life activities we are very often engaged in some form of goal-directed action. Actually, when we observe human behaviour it becomes clear that this type of action takes a prominent position in the movement repertoire. Even though we do not need to pay much attention to them, these movements still necessitate a close dialogue between the perceptual and the motor components of behaviour. While we have an idea of the kind of mechanisms underlying the control of such actions, the process allowing for the elaboration of these mechanisms (i.e., how these actions are actually learned) is far from understood. The present study has been designed to explore this learning process.

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According to the ecological approach to perception and action (Gibson, 1979), the control of the above-mentioned goal-directed actions relies on the operation of an information–movement cycle. Every movement, or more particular every displacement, gives rise to a specific optic flow. This specificity translates into the existence of optical invariants that continuously inform the actor about the validity of the produced displacements with respect to the task at hand. This incessant knowledge of the state of the actor–environment system (SAES) (Bootsma, 1998) permits on-line adaptations of the movement through the regulation of the force field (Kügler & Turvey, 1987; Warren, 1988).

To date numerous studies have presented results compatible with the involvement of a control mechanism relying on the operation of the information–movement cycle. This has been the case, for example, for catching tasks (e.g., McLeod & Dienes, 1993; Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994), locomotor pointing tasks (e.g., de Rugy, Montagne, Buekers, & Laurent, 2001; Montagne, Cornus, Glize, Quaine, & Laurent, 2000) or heading tasks (e.g., Warren, Kay, Zosh, Duchon, & Sahuc, 2001). All these studies confirmed the basic assumption in showing continuous functional adaptations of the displacement. McLeod, Reed, and Dienes (2002) (see also McLeod & Dienes, 1993) presented a very instructive illustration of this functioning in the case of catching fly balls. Their experiment was based on Chapman’s (1968) argument that the vertical optical acceleration of the ball can be very useful information for locomotor displacement control in ball catching. Optical acceleration has the potential of being very useful information in the sense that if optical acceleration is positive, the players know that the ball will land behind them. In contrast, if it is negative, they know it will land in front of them, while an optical acceleration of zero informs them that they will be located at the right place at the right time. A player who wants to catch a fly ball only has to zero out the optical acceleration of the ball by producing the appropriate locomotor displacements. McLeod and colleagues (McLeod & Dienes, 1993; McLeod et al., 2002) analysed the catching behaviour of expert players. They showed that the velocity curves produced by a player could easily be differentiated based on the distance to be covered and the remaining time. Nevertheless all the produced displacements were shown to zero out optical acceleration. These results indicated that vertical optical acceleration allows the player to control his or her action on-line to get to the right place at the right time (but see McBeath, Schaffer, & Kaiser, 1995, for a different optical candidate and Tresilian, 1995 for a different control mechanism).

From these experiments it became clear that the existence of adequate optical information allows for a precise control of the action as soon as it is available. Bootsma and collaborators (Bootsma, Houbiers, Whiting, & Van Wieringen, 1991; Bootsma & Van Wieringen, 1990) even took this idea a step further as they showed the information–movement coupling strength to be a function of time to contact—that is, coupling strength increases as time to contact decreases, becoming maximal at contact. Bootsma et al. (1991) described the operation of this control mechanism through the funnel-like type of control metaphor. A weak coupling between information and movement would give rise to a substantially high tolerance of the system, resulting in important inter-trial movement variability far from contact. In contrast, strengthening of the coupling would induce an intertrial variability decrease during the unfolding of the action. Finally the variability would be minimal as contact emanates. Note that this control mechanism will only provoke movement corrections when circumstances call for it—for example, small corrections will not be effectuated long before the final contact time.
as they tend to be lost in movement variability. While this control mechanism is classically described in the literature, the demonstration of its usefulness in goal-directed action (a forehand drive in table tennis) characterized by particularly stringent spatio-temporal constraints (movement times lower than 150 ms) is attractive.

So far, the control mechanism allowing an actor to successfully interact with the environment has been identified as well as how this mechanism is operating. Also, the eventual funnel-like type expression of this control mechanism has been described for a population of top level table tennis players who have probably accumulated thousands and thousands of forehand drives. Conversely little is known about how this mechanism is built up and/or optimized through learning. The intriguing question that remains unanswered then is how experts reach this final stage of proficiency.

Very few studies have been designed to answer this question. The work by Berg, Wade, and Greer (1994) and Scott, Li, and Davids (1997) constitutes isolated attempts to tackle this important issue. These authors examined the influence of the level of expertise on gait regulation in the long-jump approach phase. More precisely, novice long jumpers were compared to expert long jumpers whose regulation behaviour had already been characterized in previous studies (Hay, 1988; Lee, Lishman, & Thomson, 1982). The main variable used to make this comparison was the between-trial variability of the foot–target distance (during the last ten footfalls before the jump) during the run-up phase. The variability pattern exhibited a marked and systematic decrease at four footfalls from the board whatever the level of expertise. These results were said to highlight the occurrence of visually driven adjustments of locomotion in the last four steps before the jump. They were also believed to reflect the similarities between the control mechanisms used by novices and experts. In spite of their apparent elegance, these observations suffer from a number of shortcomings that call for a different type of data analysis. First, one can wonder whether a between-trial analysis is well suited to reveal a control mechanism based on the operation of an information–movement cycle (Montagne et al., 2000). As a matter of fact, this type of classically used (e.g., Scott et al., 1997) analysis can only demonstrate the presence of functional visually driven regulations during the run-up phase. A more refined analysis is necessary to go one step further—that is, to identify the control mechanism involved (Montagne et al., 2000) and more importantly to bring to light the specific influence of learning on this mechanism. Actually, this analysis has to rely (at least partly) on a within-trial analysis. Second, Berg et al. and Scott et al. have chosen to study the influence of learning on the regulation of gait by comparing two groups of totally independent subjects (i.e., novices and experts). While these studies are very instructive a more direct and powerful analysis of the learning process can be performed if the control mechanism of a given group of subjects is studied at different key periods during training. This latter procedure will permit us to more validly and convincingly assign the feasible differences to learning factors.

To put it briefly, while we have a rather clear picture of the mechanism underlying the control of goal-directed action among experts, the learning process provoking this product is unclear. The expert relies on an information–movement coupling cycle to control the action while the strength of the coupling increases as time to contact decreases. The aim of this study is to discover how this control mechanism is set up through learning.

In this study we opted for a locomotor pointing task performed in virtual reality (de Rugy, Montagne, Buekers, & Laurent, 2000). Subjects have to walk in virtual hallways and adapt—if necessary—their walking velocity to successfully cross a pair of oscillating doors (1 Hz). This
task is of special interest as a result of the strong spatio-temporal constraints it imposes to the subject and consequently of the poor performance level exhibited by the subjects. Buekers, Montagne, de Rugy, and Laurent (1999) showed that subjects succeeded in less than 30% of the trials. Moreover the low variability level observed for the locomotor parameters (step length and step duration) expressed the difficulties encountered by the subjects to take into account the information needed to regulate their displacement (Buekers et al., 1999). The present learning experiment has been designed to better understand how subjects set up a control mechanism relying on the information–movement cycle. If the information–movement cycle is ineffective at the beginning of the learning session, the performance level should be rather low, and successful trials should be essentially due to chance or to very-last-moment regulations. After a large amount of practice, the set-up of the control mechanism should give rise to an increase of the success rate due to the appearance of functional on-line adaptations. Finally additional practice should allow subjects to optimize the information–movement cycle. This optimization should express itself by an increase in performance and more parsimonious on-line regulations of the displacement.

Method

Subjects

A total of 7 subjects (mean age of 23 years) volunteered to participate in the present study. All subjects had normal or corrected-to-normal vision and had no previous experience with the task. Informed consent was obtained prior to testing.

Task

Subjects were asked to walk on a treadmill through successive virtual hallways that were presented on a large screen in front of them. In each of these virtual hallways a pair of doors were programmed that continuously opened and closed at a frequency of 1 Hz. These doors had to be correctly crossed by the subjects, implying that the aperture needed to be sufficiently large to permit reliable passing. It must be noted that, although subjects were allowed to accelerate or decelerate to produce the necessary regulations, they were not allowed to stop in front of the doors.

Apparatus

In the following paragraphs we give a concise description of the complete technical report and validation of the apparatus that has been published previously (de Rugy et al., 2000). The apparatus (see Figure 1) consisted of a treadmill (Gymrol, BRL 1800) having a moving belt measuring 0.6 m width by 1.20 m long (upper part). The subject was attached to the treadmill by means of a freely rotating girdle connected to the back of the treadmill via a rigid rod. This construction was required to keep the position of the subject on the belt unchanged, a prerequisite for a valid presentation of the virtual scene. In front of the treadmill a 3-m × 2.3-m projection screen was mounted, on which a virtual scene was projected by means of a Silicon Graphics system. The virtual scene consisted of successive hallways of 17 m long in which sliding doors (each 1.6 m wide × 3.2 m high) were programmed. These doors continuously opened and closed at a frequency of 1 Hz and a velocity of 1.28 m/s, resulting in a maximal door aperture of 1.28 m (0.64 m for each door) every other second. To prevent systematic adaptations, the doors were positioned at a random distance between 10 and 13 m from the entrance of the hallway.
The treadmill was connected to the Silicon Graphics system such that the speed of the movement produced by the subject generated the appropriate environmental flow on the screen. Thus, when the subject progressed by one metre, the visual scene moved into the direction of the subject by one metre, producing actor–environment conditions that fully resembled locomotion in a real-life setting. For reasons of obtaining reliable and realistic locomotor patterns, the initial velocity of the moving belt was adjusted to allow subjects to overcome the inertia produced by the friction forces exerted on the belt. This “aid” was chosen so that the forces generated by the subject would result in a velocity of the moving belt that was practically equivalent to the velocity that would have resulted if the same forces were generated by the subject while walking on a normal surface. The position of the treadmill was measured by means of an optical encoder at a frequency of 100 Hz. This permitted us to calculate the position of the subject in the hallway to the nearest cm. This position was needed to generate the virtual scene and also to continuously calculate the distance of the subjects to the oscillating doors.

**Procedure**

The experiment consisted of nine test sessions conducted on five consecutive days. In total subjects performed 720 trials (door passings). On the morning of the first day each subject performed an initial session during which 30 successive hallways were presented. This session served to familiarize the subject with the task and make sure that a natural locomotion pattern was obtained. Immediately afterwards a pretest of 20 trials was provided. The second session took place in the afternoon and consisted of three training blocks. Note that training blocks always consisted of 30 trials and were not used for further analysis. On the next day two sessions (morning and afternoon) of three training blocks were accomplished. The fifth session took place on the morning of the third day and was initiated by one training block, followed by the intermediate test (20 trials) and another training block. Sessions 6 to 8 were conducted in the afternoon of Day 3 and during Day 4. In Session 9 subjects performed a posttest of 20 trials after completing the last training block. Only the data of the pretest, the intermediate test and the posttest were collected and used for further analysis. Note that the subjects received immediate performance feedback after every door passing. This feedback was provided under the form of a green
(successful trial) or red (failure) square that was projected in the centre of the screen. Actually this feedback information somehow replaced the intrinsic feedback that would have normally been present when a real setting was used (subjects would bump into the door or be caught between them when they arrived at the doors at the wrong moment).

Data reduction and analysis

The data of the pretest, intermediate test, and posttest were analysed at three different levels, each representing a specific aspect of the global response. These dependent variables were related to performance outcome, movement kinematics, and current arrival condition:

1. For performance outcome the percentage of correct door passings and door passing variability (DPV) were calculated. Subjects executed a correct passing when they arrived at the doors when these were passable—that is, between 75% (i.e., 96 cm) of maximal aperture (during the opening phase) and 87.5% (i.e., 116 cm) of maximal aperture (during the closing phase). DPV refers to the standard deviation of the different door apertures at the instant of door crossing and expresses to what degree the subjects are able to produce a more or less stable behaviour. Note that the spatio-temporal window was kept invariant across subjects whatever their anthropometric characteristics. Indexing the task to these characteristics would have entailed a variation in varying the opening–closing velocity and the maximal aperture of the doors to maintain the same temporal window. Since we wanted the opening–closing velocity to be invariant, we opted for a comfortable minimal door aperture allowing for correct passing (0.96 m) and a rather homogeneous population of subjects (shoulder width mean 45 cm, SD 3 cm).

2. For movement kinematics the variability of walking velocity was computed. The velocity profiles were differentiated from the position data of the treadmill. Then, the within-subjects standard deviation of these profiles were computed for 14 successive 0.5-s time-to-passing (TTP) intervals. The rationale for using this variable is related to the observation that for locomotor pointing tasks variability of step length increases as subjects arrive in the proximity of the target (e.g., Buekers et al., 1999; Lee et al., 1982). This variability was shown to be functional as it helped subjects improve performance.

3. Finally, the current arrival condition was used to examine at a trial-by-trial level how subjects regulated their approach. More specific this variable expresses the SAES and how this state changes during the approach. To obtain this variable the evolution of the aperture condition of the doors at arrival was calculated from the current velocity of the subject. First, time-to-passing at a given instant (TTPt) was calculated for each successive position in the hallway, by dividing the given distance from the doors by the current velocity at the given instant (TTPt = Dt/Vt). Second, the successive current arrival conditions (CA1t) were calculated for the computed TTPt values. These values were obtained by extrapolating the current door condition on the basis of the TTPt values. For example, imagine that the doors are completely closed when a subject is at a distance of 2 m from the doors, walking at a velocity of 1 m/s. Keeping the walking velocity stable would result in incorrect passing as the doors (1-Hz opening–closing cycle) would be in the same phase of the cycle (completely closed) 2 s later. In contrast, if the subject would increase his or her speed to 1.33 m/s, he or she would arrive at the doors after 1.5 s—that is, when the doors would be completely open. The implementation of this procedure resulted in a distinct coupling CA1t profile for each individual approach. For reasons of clarity a typical velocity and coupling CA1t profile is presented in Figure 2. The profile shows a trial for which the subject would arrive late if he or she were to keep his or her velocity unchanged. However, given the resulting acceleration the CA1t profile changes, and the subject will verge upon the correct passing moment. It is worth noting that CA1t corresponds to a variable summarizing the current situation of the subject. In this study the time course of this variable is said to reflect the regulation behaviour of the subjects. Our study did not aim at testing the causal function of this variable in the regulation process. The use of this variable would necessitate
not only picking up the optical counterpart of both the time to passage and the current state of the doors but also integrating in some way the oscillating properties of the doors.

Different one-way and two-way analyses of variance (ANOVA) with repeated measures were conducted on performance measures (3 test sessions) and movement kinematics, 3 (test sessions) × 14 (time-to-contact, TTC, intervals). In these latter analyses data were ordered from TTC-14, representing the velocity values at 7 s before crossing, to TTC-1, representing the velocity values at 0.5 s before crossing. Finally, separate one-way ANOVAs with repeated measures (14 TTC intervals) were conducted on variability of CAt in the posttest. The level of significance was set at $p < .05$.

Results

**Performance outcome.** As could be anticipated subjects improved their initial performance level from an initial 24.2% to 62.1% in the intermediate test and 64.2% in the posttest.

As such these data confirm the observation of a previous study (Buekers et al., 1999) reporting a 30% success level for novice subjects. Although subjects were able to double the initial success rate after about 300 practice trials, this fast increase was levelled off during the second part of the training process. This observation was confirmed by the results of the one-way ANOVA, showing a significant main effect for tests, $F(2, 12) = 25.43, p < .05$. Newman–Keuls a posteriori tests revealed significant differences between the pretest and both the intermediate and the posttest, but not between these last two. Although these findings seem to suggest that subjects stop improving after a substantial initial progress, this is not corroborated by the data of the door passing variability, $F(2, 12) = 37.85, p < .05$. Actually subjects became less and less variable as practice continued, a finding surfacing from the significant difference between the pretest (DPV = 0.86 m) and the intermediate test (DPV = 0.61 m), and also between this
latter test and the posttest (DPV = 0.35 m). As illustrated in Figure 3, the high initial door passing variability inclined towards a more regular crossing behaviour during the course of practice.

Movement kinematics. Note that for the calculation of this variable only correct passings were taken into account—that is, 34 trials for the pretest, 87 for the intermediate test, and 90 for the posttest. We opted to limit this analysis to the correct trials because we were interested to find out how subjects arrived at successful behaviour. Moreover, the inclusion of all trials could have masked possible changes occurring when subjects adopted accurate locomotor adaptations. The results of the 3 (tests) × 14 (TTC intervals) analysis provided a first insight into how subjects accomplished the observed performance gain. A significant main effect was
observed for TTC intervals, $F(13, 78) = 20.70$, $p < .05$, indicating that velocity variability changed during the approach. Moreover, the Tests $\times$ Intervals interaction was also significant, $F(26, 156) = 16.15$, $p < .05$. In fact, Newman–Keuls a posteriori tests revealed significant differences between successive intervals for both the intermediate test and the posttest, but not for the pretest. Moreover, as illustrated in Figure 4, the variability increase of the last three intervals was larger for the posttest (0.12, 0.19, and 0.25 m/s) than for the intermediate test (0.09, 0.11, and 0.12 m/s) and the pretest (0.05, 0.06, and 0.06 m/s). These findings reveal (1) the absence of any between-trial variability in walking velocity during the pretest and (2) during the course of practice, the appearance of an increased walking velocity variability when the subjects arrived in the vicinity of the doors. This latter variability increase, expressing the operation of locomotor regulation, was a function of the amount of practice as it was more pronounced in the posttest. This again corroborates the finding that some important behavioural changes took place in spite of the small performance benefit observed during the second part of the experiment. Also note that the regulation was spread out over the last two door cycles.

An interesting phenomenon became apparent as we analysed the velocity data of the intermediate test. Actually subjects had the tendency to use a deceleration strategy to cope with the imposed task constraints. This deceleration preference was so salient that it forced subjects to wait for the next opening cycle, even when a small acceleration would have permitted them to achieve a correct passing. Based on this observation we analysed the number of cycle changes in CA that occurred in both the intermediate test and the posttest. For the former almost one out of two passings (45%) was characterized by a cycle change, whereas this figure dropped to only 10% for the posttest. This result suggests that subjects established a more refined regulation (acceleration and deceleration behaviour) at the end of practice as they were able to remain within the boundaries of a single door cycle.

To further explore these observations an extra analysis was conducted on the velocity variability profiles. We wanted to know whether the larger increase in velocity variability in the posttest was the result of the presence of two types of regulation behaviour. Consequently, we

![Figure 4](image-url)

**Figure 4.** Time course of velocity variability for each test (pretest, intermediate test, and posttest). The variability increases in the last 1.5 s in both intermediate and posttest while it is kept constant in the pretest. Moreover the variability increase is more pronounced in the posttest than in the intermediate test.
differentiated the variability profiles corresponding to the accelerated and the decelerated trials in the posttest, in order to compare each to the variability profile exhibited in the intermediate test. The analysis including decelerated trials revealed a Tests × TTC Intervals interaction, $F(13, 78) = 2.59, p < .05$. Newman–Keuls a posteriori tests showed that the variability profiles were the same up to the last two intervals. In the last second preceding door crossing, the variability was larger in the intermediate test (0.11 and 0.12 m/s) than in the decelerated trials performed in the posttest (0.09 and 0.097 m/s). Conversely the analysis including accelerated trials did not reveal any Test × Intervals interaction, $F(13, 78) = 1.09, p > .05$. The time course of variability is was the same in the intermediate test and in the accelerated trials of the posttest. Consequently, the larger increase in velocity variability in the posttest observed in our first analysis was actually the result of the presence of two types of regulation behaviours.

We also wanted to find out why subjects got to a failure level of almost 40% in both the intermediate test and the posttest. Therefore we compared the time course of the velocity variability of the two types of trial (successful and unsuccessful) in each test. A significant main effect was observed for TTC intervals in the two tests, $F(13, 78) = 12.54, p < .05$ in the intermediate test and, $F(13, 78) = 39.69, p < .05$ in the posttest, indicating that velocity variability changed during the approach. In contrast, the Type of Trials × Intervals interaction failed to be significant, $F(13, 78) = 0.76, p > .05$ in the intermediate test and, $F(13, 78) = 1.75, p > .05$ in the posttest, indicating that a similar velocity variability regardless of the type of trial. These data suggest that the unsuccessful trials resulted from inadequate velocity changes. We turn back to this observation in the following section.

**Current arrival condition.** The time course of CAt can be anticipated as the most informative variable, since it elucidates, how the actor and the environment interact to achieve the required goal. In Figure 5, some representative profiles are presented for the three tests. In the pretest no specific changes can be observed as the coupling CAt profiles tend to remain relatively stable throughout the approach. These data indicate that the subjects walk at a regular pace to the doors, regardless of the current state at the entrance of the hallway. When the current state led to an early arrival, subjects did not decelerate to reduce the temporal error. Accordingly, late arrival did not lead to an increase of the velocity, leaving the temporal error unchanged when the subject arrived at the doors. Apparently this absence of regulations also provoked correct responses as subjects also upheld their walking velocity in the case of favourable initial circumstances, resulting in correct passing behaviour. As we have already mentioned previously, subjects favoured a different strategy (i.e., a velocity decrease in the vicinity of the doors), in the intermediate test. As illustrated in Figure 5, this deceleration resulted in a shift into the next door cycle even when the current situation would rather call for a more parsimonious acceleration. Note that the overall occurrence of a final acceleration phase confirmed previous observations (Buekers et al., 1999). Finally, and conforming to our main hypothesis, the subjects adopted a locomotor behaviour that was in accordance with the functioning of a funnel-like type of control. As Figure 5 shows, the coupling CAt trajectories tend to converge to the required status during the final phase of the approach. In contrast to the intermediate test, subjects did use the acceleration strategy to counter an emanating late arrival. The operation of this funnel-like perception–action mechanism is validated by an analysis of the within-subject variability of the CAt values for the posttest, as it reveals a significant TTC interval effect, $F(13, 78) = 54.10, p < .05$. Newman–Keuls a posteriori tests...
Figure 5. Time course of current arrival conditions (CAt) recorded in seven representative trials performed by the same subject in each test (pretest, intermediate test, and posttest). During the pretest the time course of CA\textit{t} is “flat”. No changes in displacement velocity occur; consequently the state of the door at the instant of crossing is more or less comparable to the one observed several seconds before. During the intermediate test, the successful trials mostly represent regulated trials as illustrated by the convergence of several curves towards the window. Nevertheless the resulting regulations correspond systematically to a deceleration even if the current situation would rather call for a slight acceleration. Finally, during the posttest, all regulations make the curves to converge towards the window in a parsimonious way whatever the initial conditions.
revealed a significant decrease of the variability from TTC-4 onwards. It is worth noting that the CAt values for the intermediate test were not analysed as the large number of door cycle changes renders a valid interpretation impossible.

Parallel to the analysis performed in the previous section, we compared the time course of the variability of the CAt in the successful and unsuccessful trials performed in the posttest. This analysis revealed a significant Type of Trials × Intervals interaction, $F(13, 78) = 7.82, p < .05$ (Figure 6). Newman–Keuls a posteriori tests showed that the CAt variability did not change during the approach in the unsuccessful trials. Conversely, however, for the successful trials a significant variability decrease of was observed from TTC-4 onwards. The invariance of the time course of the variability of the CAt in the unsuccessful trials reveals the inadequate nature of the resulting velocity changes. This result illustrates how difficult it was for subjects to perform coherent locomotor regulations, even after extensive practice. Most certainly these difficulties are provoked by the spatio-temporal cyclical constraints imposed by the task.

Discussion

This experiment was conducted to study the influence of practice on the development of a control mechanism based on the operation of an information–movement cycle. In particular, we wanted to find out how the funnel-like type of control—observed previously in expert behaviour—was learned in the context of goal-directed locomotion tasks. Three tests performed at the beginning (pretest), in the middle (intermediate test), and at the end (posttest) of the training period were selected to characterize the learning process. To obtain a comprehensive idea of the control mechanism, three complementary levels of analysis were used.

First it is important to verify whether a funnel-like type of control was set up at the end of the training period. The results from the posttest reveal an improved performance level as

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**Figure 6.** Time course of current arrival conditions (CAt) variability in the posttest for each kind of trial (successful and unsuccessful). The variability decreases in the last 2 s in the successful trials while it is kept constant in the unsuccessful trials.
compared to both pretest and intermediate test. Interestingly, this performance gain went hand in hand with an increase of the (between-trials) walking velocity variability in the last two seconds preceding door crossings (at least when compared with the pretest). Also note that the observed velocity variability increase was accompanied by a decrease in the CA1 variability, revealing the functional character of these velocity adaptations. Even more important are the findings of the within-trial analysis as they actually demonstrated that the changes in walking velocity resulted in a corresponding reduction of the current arrival error. Put differently, the produced behavioural changes were always in accordance with the behavioural changes required to succeed in the task. Albeit indirect, this result is compelling enough to suggest that the subjects use information allowing for the production of on-line displacement adaptations. One can appropriately argue from this that the control mechanism used during the posttest relies on the use of an information–movement cycle. That is to say, the progressive decrease of the between-trial variability of the current error in the last 2 s corroborates the operation of a funnel-like type of control. This variability decrease is not really surprising in the sense that it results from the convergence of the current error profiles at the end of the trials, which characterize the success in the task. Put differently, the success in a task requiring perceptually driven regulations entails the use of a funnel-like type of control. Nevertheless, the comparison of the current error profiles exhibited in the intermediate test and in the posttest clearly show that the pattern of convergence can differ, even if the success rate is similar. This point will be discussed in more detail in the following paragraph.

While the time scales of the task studied by Bootsma et al. (1991), lasting only a few hundred milliseconds, and our task, lasting several seconds, are largely different, the control mechanisms exhibit some interesting similarities. Nevertheless, it is worth noting that the control mechanism employed by the experts in the table tennis study (Bootsma et al., 1991) is unquestionably much more optimized than the one used by our subjects. This should not be too surprising in view of the large amount of trials accumulated by the experts over the long years of practice they were exposed to. Comparatively, our subjects only received a very small portion of the repetitions needed to obtain the ultimate level of expertise. It would therefore be misleading or even improper to consider our subjects as real experts in the task, as the final success rate (64.2%) corroborates. This performance level could appear rather poor given both the extensive training period (700 trials) and the size of the temporal window imposed (180 ms). It certainly expresses the difficulties experienced by the subjects to deal with a cyclical event. Obviously a direct access to both the temporal vicinity of the doors and the current state of door as such is inadequate. The subject has to integrate one way or the other the cyclical character of the doors to accommodate to the future. The linkage of these two processes is probably one of the key parameters of the optimization of the perceptual side of the control mechanism.

Still, at the end of the training programme subjects were substantially better than at the beginning, revealing at least an important amelioration of the control mechanism. Even if the control mechanism is not fully optimized, it induced a rather appropriate walking behaviour as subjects accelerated or decelerated according to the spatio-constraints imposed by the sliding doors. Apparently they were by that time able to exploit the two suitable types of behaviour leading to possible success. Most probably the smaller increase in velocity variability associated with the deceleration behaviour results from a larger experience of the subjects with a type of regulation behaviour already exhibited during the intermediate test. The application
of this deceleration versus acceleration behaviour permitted subjects to remain within the boundaries of a specific door cycle, in contrast with the intermediate test where door cycle changes were prominent. We return to this issue later as we discuss the results of the intermediate test. For now we can conclude that, conforming with our hypothesis, a funnel-like type of control was indeed observed after a considerable amount of practice.

We now turn to the central question of this study. How does learning influence the acquisition of the funnel-like type of control? The results of both pretest and intermediate test reveal some interesting findings that provide the elements to answer this question.

During pretest, the performance level was rather poor while both between-trial velocity variability and within-trial current error hardly varied when time to passage decreased. As has been documented previously, this velocity invariance is a powerful indication for the absence of displacement regulations. Consequently, the error produced by the subjects at door crossing was almost identical to the current error when the subject entered the hallway. Success only emanated when the initial conditions (i.e., state of the doors, current velocity, and position of the doors) were favourable. Given the nature of the temporal window used in this study (nearly 20% of the door cycle) and the random positioning of the doors in the hallway across the experiment, the success rate produced by the subjects was not very high above chance level. Put differently, these findings speak for the absence of a control mechanism at the beginning of practice. We believe that the perceptual part of the cycle was lacking, as subjects were not attuned to the optical information and/or did not integrate the cyclical character of the oscillating doors. As the valid indications for the required velocity changes were missing, subjects tended to stabilize their walking velocity, resulting in a poor performance level.

The intermediate test performed after a training period of about 300 door crossings revealed some appealing transformations. Actually, the performance level largely improved while, contrary to what was observed in the pretest, the between-trials velocity variability varied as a function of time before door crossing. As mentioned earlier, the variability increase during the last two seconds before door crossing reveals the existence of displacement regulations. But, contrary to what was observed in the posttest, these regulations had a typical character. The within-trial analysis shows that for some trials changes in displacement velocity reduced the current error while in some other trials the reverse was true. In fact this result is mainly due to the systematic application of a deceleration strategy. When the subjects were in advance, the deceleration was consistent with door crossing in that it contributed to the cancellation of the current arrival error. Conversely, when the subjects were late, this deceleration augmented the error until the subject “entered” a new opening–closing door cycle in which the deceleration behaviour became adapted. This systematic deceleration behaviour appeared efficient as it gave rise to a performance level that was only slightly lower than the posttest (e.g., variable error) but considerably better than the pretest (e.g., success rate and variable error).

One can now wonder whether the systematic deceleration behaviour interferes with the operation of an information-movement cycle. The present results clearly contradict this assumption in showing behavioural changes that were in accordance with the functioning of an information-movement cycle. Even if sometimes an acceleration behaviour would have been more parsimonious, the amount of deceleration applied in the distinct trials depended on the required deceleration for correct door crossing. The within-trial analysis also showed
continuous adaptations of the displacement in the last two seconds preceding door crossing. The fact that the acceleration behaviour was absent reveals that at this learning stage, while subjects had access to the information, the spectrum of motor responses had not been fully scrutinized. Nevertheless the matching decrease of time to contact and current arrival error strongly advocates the funnel-like type of control. Yet this funnel-like type of control appears to be incomplete as subjects only exploited half the cycle. Most likely this latter restriction was due to a query for behavioural regularity and simplicity. It is tempting to overlook this idea of simplification against the background of the dynamic systems approach (e.g., Bernstein, 1967) that proposed the concept of “freezing” and “releasing” the degrees of freedom to characterize the learning of inter-limb coordination (Vereijken, 1991). If we apply this metaphor to our data, the deceleration strategy used in the intermediate test represents the freezing phase, whereas the freeing phase is found in the posttest where subjects integrate an additional type of behaviour (i.e., acceleration), to cope with the task. While interesting, these latter thoughts are more or less speculative and should be considered with prudence as they are not based on a thorough comparison of the constituent elements.

The identification of the control mechanisms used at three key periods during the learning process provides the necessary means to better understand the development of the funnel-like type of control. First, at the beginning of practice, the information–movement cycle was not operational—a lack of competence essentially due to the inability of the subject to pick up the adequate information and/or to integrate the cyclical character of the oscillating doors. After a substantial amount of practice (in our experiment in the intermediate test) the funnel-like type of control was possible while its functioning was far from optimal. Our results reveal some limiting factors at the motor side of the system; the systematic deceleration behaviour made the regulations very costly in some situations. In the posttest the funnel-like kind of control was more effective while not fully optimized, as exemplified by the percentage of successful trials. The resulting regulations were in a systematic way concordant with the more parsimonious manner to succeed in the task (i.e., acceleration when the subject was late, deceleration when he or she was early, and constant velocity when he or she was on time) even if the acceleration behaviour is far from being finely tuned. On the basis of our results one can hypothesize that the next learning stage would probably entail integrating more fully the cyclical character of the doors and refining the relationships between information and movement. While the adaptations produced in the posttest were qualitatively coherent with the current situation a more refined dialogue between information and movement would probably guarantee an additional increase in performance.

A final point that is worth noting relates to the already mentioned finding that subjects chose to engage in a cycle shift even when the circumstances did not really ask for it (essentially in the intermediate test). Subjects preferred to resolutely decelerate at the expense of parsimony rather than to mildly accelerate to keep the current status of the system within the boundaries of a given door cycle. Most probably this type of behaviour is driven by the principle of security (de Rugy et al., 2001; Rushton & Wann, 1999) as the subjects favour a strategy affording additional time to solve the temporal problems they are facing. It is interesting to consider this cycle switch behaviour from the perspective of the so-called attractor states described by the dynamical systems approach (Kelso, 1995). According to this account a number of coordination patterns exist that pull (attract) the different elements (limbs) of the system into this preferred overall mode of operation. These attractor states have been
described at the level of both inter-limb coordination (Kelso, 1984) and between-persons coordination (Schmidt, Carello, & Turvey, 1990). This latter observation is of interest for this study, as it seems to imply the operation of a visual element in the functioning of the attractor states. Actually, our results confirm and even broaden this notion as they reveal the existence of optical attractors states—that is, the visual door-cycle properties that drive the information–movement cycle. Indeed, subjects appear to be caught between two optical attractor states—that is, the two successive passable door aperture conditions that envelope their current final arrival condition at the doors (current state of the system). Thus when subjects are in the temporal proximity of the leading door aperture one might readily expect them to be attracted by this optical state and accelerate in order to succeed in the task. In contrast, when subjects find themselves in the proximity of the lagging door, a deceleration appears to guarantee the most parsimonious solution to the problem. This is exactly what happened during the final acquisition phase of the present experiment, as subjects were able to successfully adopt the acceleration and deceleration strategy. However, during the intermediate session this behaviour was obviously far from established, as subjects almost solely turned to the deceleration, most probably for reasons of security (Rushton & Wann, 1999; de Rugy et al., 2001). These findings corroborate the idea that learning can be characterized by a freezing–freeing process in which the degrees of freedom, be they at the level of perception, action, or their interaction, are initially reduced to assure relatively successful stable behaviour. The subsequent release of the degrees of freedom enables subjects to deviate from the acquired stability and generates a more versatile behaviour that has the potential to further enhance the performance level.

REFERENCES


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