An Enactive Approach to Perception-Action and Skill Acquisition in Virtual Reality Environments

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ABSTRACT

We describe in this chapter basic principles underlying human skill acquisition, and envisage how virtual environment technology can be used to shorten the route toward expertise. The emphasis is put on *coordination* — between segments, muscles, sensory modalities, and between the agent and the environment — and on enaction, a form a knowledge that is gained by doing, i.e., through the active interaction between action and perception, in real or virtual environments. Examples are taken from the SKILLS FP6 european integrated project.

Keywords: Enaction, skill acquisition, perception-action, virtual environment

SKILLED COORDINATED BEHAVIOR

Generally speaking, skill can be defined as the capacity acquired by learning to reach a specified goal in a specific task with the maximum of success and a minimum of time, energy or both. This simple definition available in any textbook on motor control and learning suggests that skill cannot be considered as a general and abstract ability, but rather as a specific and learned capacity operating in an limited ensemble of situations. A number of criteria can be analyzed for evaluating the level of skill, and have to be integrated in a formal definition of skill.

1. The accuracy of the outcome, with respect to the assigned goal: this criterion is the most commonly used, and measured in terms of errors to the target goal (spatial and /or temporal).

2. The consistency of responses over successive trials: Skilled movement outputs are stable and reproducible. Stability can be traditionally measured by assessing for instance the standard deviation of a set of successive outcomes. More contemporary approaches however focus not only on the amplitude of variability but also on its temporal structure, suggesting that consistency should not be understood in terms of ‘behavioral stereotype’ but, as proposed by Bernstein (1967), as “repetition without repetition”, i.e., as the propensity of experts to regulate small details of the ongoing actions in order to reach a stable performance.

3. Efficiency, i.e. the ability to reach the desired goal at minimal cost: Efficiency can be understood at various levels, including the cognitive level (the use of automatic processes allowing a decrease in mental load), the metabolic level (a reduced metabolic cost in expert to reach the same performance), or the neuro-muscular level (reduction of co-contraction and more phasic muscular activation in experts). These various levels are not independent from each other and generally reveal the same trend toward economy as skill acquisition progresses.

4. Flexibility and adaptability: Skilled behavior copes with endogenous and exogenous uncertainties. This flexibility suggests that skill is not specific to a particular task, but rather to an ensemble of similar tasks, which raises the fundamental problem of skill generalization and transfer. Flexibility and adaptability are crucial and complementary aspects to the stability properties described above. Variability is often functional, not necessarily reflecting noise in the neuro-muscular system for instance, but as a consequence of continuous and functional adaptations operating at the level of perception-action loops.

5. The elaboration of a coordinative structure: Skills are characterized by a delicate spatio-temporal organization of sub-movements, including task specific synergies among body segments, joint angles, and end-effectors, and also between the agent and the environment. A skilled movement is never performed in the exact same way, and always possesses a certain degree of variability; however a pattern of organization — order — is common to each sample. The spatio-temporal patterns of coordinated motor activity are low dimensional, due to the dynamic interactions of the many degrees of freedom of the system, and accordingly can often be described by one or few collective variables. To be proficient, or ‘dexterous’, the coordinative structure (e.g., Turvey, 1990) has to resist unavoidable internal and external perturbations, and thus must possess stability.

PERCEPTION-ACTION AND SKILL LEARNING

The components of a skilled action briefly outlined above include the set of end effectors and segments-joints effectors, but also include the perceptual systems that are used to guide task performance. Human and other biological organisms are informationally coupled to their environments, in various task-specific perception-action cycles (e.g., Kugler & Turvey, 1987). On the perception-action side, complementary markers of skill performance and skill acquisition are of interest to build efficient virtual reality platforms.

1. Movements are sources of information. Physical properties of the agent - environment system relative to its layout have specific consequences on ambient energies. Although not depending on movement for their existence, these invariant patterns within energies emerge unequivocally only with a flux, “the essentials become evident in the context of changing nonessentials” (Gibson, 1979). Movements themselves are structured and have unequivocal consequences in the informational flow. Accordingly, information resides in the stimulation, that is, in the structure of ambient energies (e.g., optics, acoustics, etc.) that stimulate our perceptual systems.

2. Information, when perceived, is used to regulate movements. In natural or virtual interaction, (multisensory) stimulation is specific to reality, indicating that a lawful relationship (i.e., 1:1) exist between both parts. The specification relation can be formalized in the form Force = f(flow), meaning that the net force acting on the observer (external + internal forces) is specified in the structure of energy flows. First assumed to be modal (e.g., within the structure of one single energy), this equation is now considered to be intermodal (Stoffregen & Bardy, 2001). According to the circular causality principle, motor performance is achieved by the means of control laws. These laws are relations between the informational (perceptual) variables and the free parameters of the action system (motor variables) that are relevant for the ongoing action (Warren, 1988).

3. Learning consists in discovering and optimizing the information-movement coupling. Because information is both created by the movement and regulating the movement, finding the coupling function between the two components is one key problem that learners have to solve. For instance driving a car on a turning road implies maintaining the current direction of the car aligned continuously with the direction of the road. The current direction of the car being given by the optical focus of expansion at the driver’s eye, a simple and efficient way of accomplishing this action (going from A to B on a turning road) is to move the steering wheel so as to maintain the focus of expansion in the middle of the road. Learning how to drive a car on a turning road imply discovering and stabilizing the coupling function between movements of the hands on the steering wheel and the optic flow created by these movements.

4. Learning implies stabilizing control laws. Control laws are expressed in the form: $\bullet\, fint = g\,(\bullet\, flow)$, where $\bullet\, fint$ refers to the changes in internal forces applied by the observer, and $\bullet\, flow$ to the corresponding changes in flow energy (e.g., optical or inertial flow) specifying the (changes in) relationship between the observer and the environment. In the car driving example, the control law for driving a car on a turning road can be written in the form: Intensity of force on the steering wheel = f (focus of expansion / road). This example is a simple one. There

are many control laws that need to be simultaneously stabilized during the acquisition of skilled behaviors — both within and between perceptual modalities.

SKILL DECOMPOSITION

As evidenced in the previous two paragraphs, the various transformations in coordination and perception-action that accompany the acquisition of expertise involve many skill elements, both at sensori-motor and cognitive levels. A specific skill — e.g., juggling, rowing, drilling, reaching, tracking, assembling etc. — can thus be decomposed in a series of skill elements. Within the SKILLS European project (www.skills-ip.eu), several sensori-motor and cognitive skills have been identified throughout six VR training platforms. Table 1 below summarizes these main skill elements call “sub-skills”.

Table 1 Skill elements at both sensori-motor and cognitive levels

Sensori-motor sub-skills	
Balance and postural control	The regulation of posture (segments, muscles, joints, etc…) and balance (static, dynamic, etc…) that allows the distal/manual performance to be successfully achieved. It is captured by inter-segmental and inter-muscular coordination, as well as center-of-pressure variables.
Bimanual coordination	The functional synchronization in space and time of the arms/hands/fingers. Bimanual coordination is captured by the relative phase between the coordinated elements and its stability.
Hand – eye coordination	The synchronization of eye / gaze / effector with reference to the main information perceptually detected. It is assesses by gain, relative phase, and in general coupling variables between eye, gaze, and hand.
Interpersonal coordination	The coupling between two or more persons. It emerges from a nexus of components including sociality, motor principles, and neuroscience constraints. It is assessed by the relative phase between persons.
Perception-by-touch	The coetaneous component of the haptic modality. Various receptors embedded in the skin provide information about mechanical properties (*vibration*, *compliance* and *roughness)*, *temperature* and *pain*. It is evaluated by psychophysical methods.
Prospective control	The anticipation of future place-of contact and time-to-contact based on spatio-temporal information contained in optic, acoustic, or haptic energy arrays. It requires the coupling between movement parameters and information contained in various energy arrays, and is measured by time-to-contact and related variables.

Proximo-distal coupling	The spatio-temporal coordination of proximal, gross components with distal manipulatory components. It refers to the organization of the body underlying arm movements, or to the synergy between arm postures and hand movements. It is assessed by cross-relational variables.
Respiratory-movement coupling	The synchronization of breathing and movement (segments, muscles, joints, etc…) that allows efficient performance. It is measured by amplitude, phase and frequency synchronization patterns.
Fine force control	The online regulation of the internal forces applied on the surface to successfully reach the goal (drilling, pasting, navigating, etc…). It depends on the properties of the surface in relation to the forces developed by the effectors, and is evaluated by the ratio between the two.
Cognitive sub-skills	
Control flexibility and attention management skills	The ability to change response modes and performance strategies, to apply and manage new attention policies in order to cope with task demands and/or pursue new intentions and goals. It is measured by adjustments to changes in task demand and attention allocation.
Coping strategies and response schemas	A vector of importance or attention weights computed over the many sub-elements of a task, which are associated with the achievement of a specific goal. They are measured by the number and type of strategies to cope with variations in task demands and changes of intention.
Memory organization, structure and development of knowledge schemas	Level of formulated and organized multi hierarchy, task specific memory and knowledge bases that facilitate encoding, retrieval and the conduct of performance. Measured by speed and accuracy of encoding, response and decision-making performance, and number, diversity and speed of generating alternative solutions.
Perceptual Observational	The ability to detect, sample and extract task relevant information from the environment and perceive static patterns and dynamic regularities. Measured by speed, efficiency, amount of conscious supervision, and use of higher-level structures and redundancies.
Procedural skills	Sequences of ordered activities that need to be carried out in the performance of tasks. Performance of every task can be subdivided into a large number of procedures, the competence in the performance of which is developed with training. Evaluated by speed and efficiency of performance, type of supervision (un/conscious).

The first nine sub-skills (upper section of Table 1) are from the sensori-motor repertoire while the last five sub-skills (lower section of Table 1) are from the cognitive repertoire. In general, sensorimotor sub-skills are skills that relate to the relationship between perceptual components and motor components, and cognitive skills are related to higher-level cognitive activities that orient, formulate, monitor and regulate the sensori-motor performance. The distinction is partly arbitrary as the two categories are largely interdependent. This is because of the natural embodiment of cognitive phenomena into sensori-motor dynamics, an embodiment at the heart of the SKILLS project. Although there are several views on embodied cognition (see Wilson, 2002 for a review), the term generally refers to the basic fact that a) cognition is largely for action, and b) off-line cognition (cognition decoupled from the environment) is largely body-based. Consistent with these claims is the fact that perceptual inputs (e.g., vision) can elicit covert motor representations in the absence of any task demand. There is also increasing evidence coming from brain imaging studies that the perception of objects automatically affords actions that can be made towards them (Grezes & Decety, 2002). Similarly, the fact that when individuals observe an action, an internal replica of that action is automatically generated in their premotor cortex (Buccino et al., 2001), suggests that embodied cognition plays a role in representing and understanding the behavior of conspecifics, such as in learning from imitation.

Hence perception is not a perceptual process, preceding symbolic representations of actions to be performed. What one perceives in the world is influenced not only by, for instance, optical and ocular-motor information, but also by one’s purposes, physiological state, and emotions. Perception and cognition are embodied; they relate body and goals to the opportunities and costs of acting in the environment (Varela et al., 1991; Proffit, 2006). The taxonomy of skill elements reported in Table 1 is only a convenient way to help researchers and engineers to elaborate technological tools able to accelerate the learning of these skill elements.

ENACTING SKILL ACQUISITION IN VR

Contemporary multimodal virtual reality simulators can be used to accelerate the acquisition of complex skills. It is the aim of the SKILLS EU integrated project to develop training accelerators and training protocols able to speed up the mastering of the various skill elements described in the previous section. What these demonstrators have in common is their potential to *enact* useful — sensori-motor or cognitive — on line or off line information at given moments in time and in a training context, in order to take advantage of the well-known general principles underlying skill acquisition in real life and transfer them to virtual or mixed contexts. In this final section we present three basic examples of how this enactment can be realized (see the SKILLS related chapters for more examples).

DESTABILIZING SPONTANEOUS COORDINATION MODES

As stated previously, learning occurs on the basis of pre-existing coordination modes (between segments, between muscles, or between the agent and the environment. These initial solutions attract the spontaneous behavior, and seem highly resistant to change. The initial attractors of the system exhibit a strong stability, preventing the exploration of the workspace and the adoption of other behaviors more efficient in the long run (Nourrit et al., 2003). A solution for shortening this initial stage is to find tricks helping the destabilization of initial attractor states. This hypothesis was initially examined by Walter and Swinnen (1994) in a bimanual coordination task. In participants who had to learn a 1:3 frequency ratio, they found that slowing down the movement facilitated learning. In oscillation skills, movement frequency is indeed often considered as a control parameter of the coordination (e.g., Kelso, 1984). This adaptive tuning was supposed to reduce the exclusiveness of the spontaneous 1:1 coordination mode, and to allow an effective exploration of other less natural ratios. A related method is currently used in the SKILLS project with virtual juggling of a three-ball cascade (see Figure 1). In this ongoing experiment, jugglers are guided by on line vibro-tactile and auditory information contributing to breaking the spontaneous 1:1 coordination between hands and transforming it into more complex, multi-rhythmic and multimodal, 2:3 ball-hands coordination. Together, these scenarios indicate that control parameters and on line information can be used to accelerate learning through an information-induced destabilization of the initial coordination state.

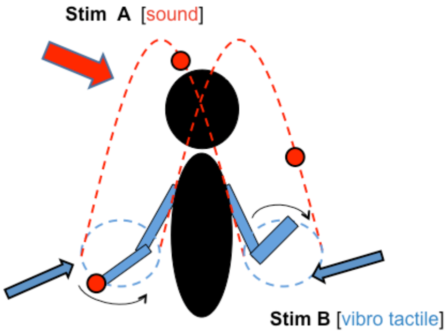

FIGURE 1. Online multimodal information (auditory, vibrotactile) used during virtual juggling in order to destabilize initial 1:1 bimanual coordination and learn a more complex 2:3 multi-rhythmic hand-ball coordination.

INCREASING PATTERN AVAILABILITY

A complementary principle is obviously to increase the availability of the expert coordination mode. Here also, one solution is to use adequate control parameters. This procedure was explored in the domain of rehabilitation. For example Wagenaar and Van Emmerick (1994) showed that during walking at preferred speed, healthy participants had their pelvis and trunk moving out-of-phase, while Parkinson’s patients had their pelvis and trunk moving mostly in-phase. When velocity was increased, differences between healthy controls and patients decreased. This result suggests that an appropriate tuning of a relevant control parameter can induce the emergence of the desired coordination pattern during rehabilitation. This example is of interest for the acquisition of complex skills because it reveals that accelerators can be very simple when the dynamics of the perceptuo-motor workspace is known (location of attractors and repellors, disappearance of attractors in patients etc…). It also reveals that slowing down a movement during the acquisition phase is not always a good solution for accelerating learning.

When the desired pattern is not potentially available, and does not emerge as a result of control parameter manipulation, the pattern can nevertheless be required by means of instructions or by presenting a model. In the first case the pattern is described by verbal explanations, in the second case a model is directly provided (by a real or a virtual trainer). For example, Faugloire et al. (2009) demonstrated that on-line postural feedback, by means of a Lissajous plot (position vs. position), allows a quicker learning of a complex postural coordination pattern. In this experiment participant had to learn a coordination pattern with a 90° phase offset between the ankles and the hips. In this case, the expected Lissajous plot is an ellipse (see Figure 2).

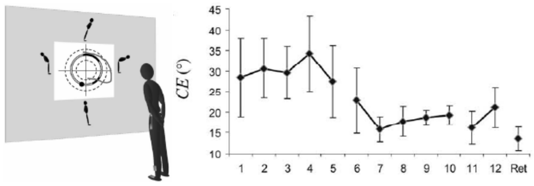

FIGURE 2 Accelerator for learning a new postural pattern (left); Constant error (required - produced pattern) during the acquisition period (right). Data are averaged over participants (Faugloire et al., 2009).

In the initial trials, participants were attracted towards spontaneous coordination modes, especially in phase and anti-phase, yielding straight lines in the Lissajous plots. With time and practice, the competition between the spontaneous patterns and the new pattern progressively turned in favor of the new pattern, with reminiscent presence however of the intrinsic dynamics of the postural system. Interesting for our purpose is the complementary finding that learning persisted over time, suggesting that the accelerator had long-term effects. Similar methods are currently employed within the SKILLS project in various demonstrators (e.g., rowing and juggling).

GUIDING THE EXPLORATION OF THE WORKSPACE

According to Newell et al. (1989), learning is the result of an active exploration of the workspace defined by organism, task and environment constraints interacting with each other. This workspace can be conceived as a landscape characterized by zones of stability (especially that corresponding to the expert pattern). Novices have to explore this landscape in order to discover the optimal zones (i.e. the “valleys”, see Figure 3). This exploration can be guided by on line information, especially concerning task requirements, and efficiency gradients. Providing augmented feedback can help learners in their search for optimal solutions. This augmented feedback should be particularly efficient when targeted onto the order parameter representing the macroscopic controlled variable in the task. Enriched multimodal information, using various channels (auditive, visual, haptic,.) can also be delivered in order to guide a more efficient exploration of the workspace.

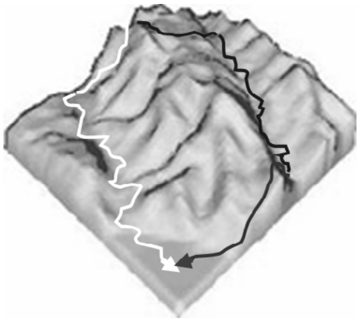

FIGURE 3 Exploring the workspace during learning a new perception-action skill in search for optimal solutions (attractors in the workspace). Multimodal information can be given online to the trainee to find the optimal solution.

CONCLUSION

Demonstrators can be conceived as technological implementation of learning accelerators. The above analysis suggests that according to the nature of the task at hand, but also to the level of advancement of the learning process, different accelerators can be selected. As such, a precise evaluation of the goal of the demonstrator (helping novices, training experts, etc.), and a deep analysis of the task (nature of the workspace, spontaneous coordination mode, expert behavior to be learned) should be undertaken before conceiving the appropriate implementation.

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