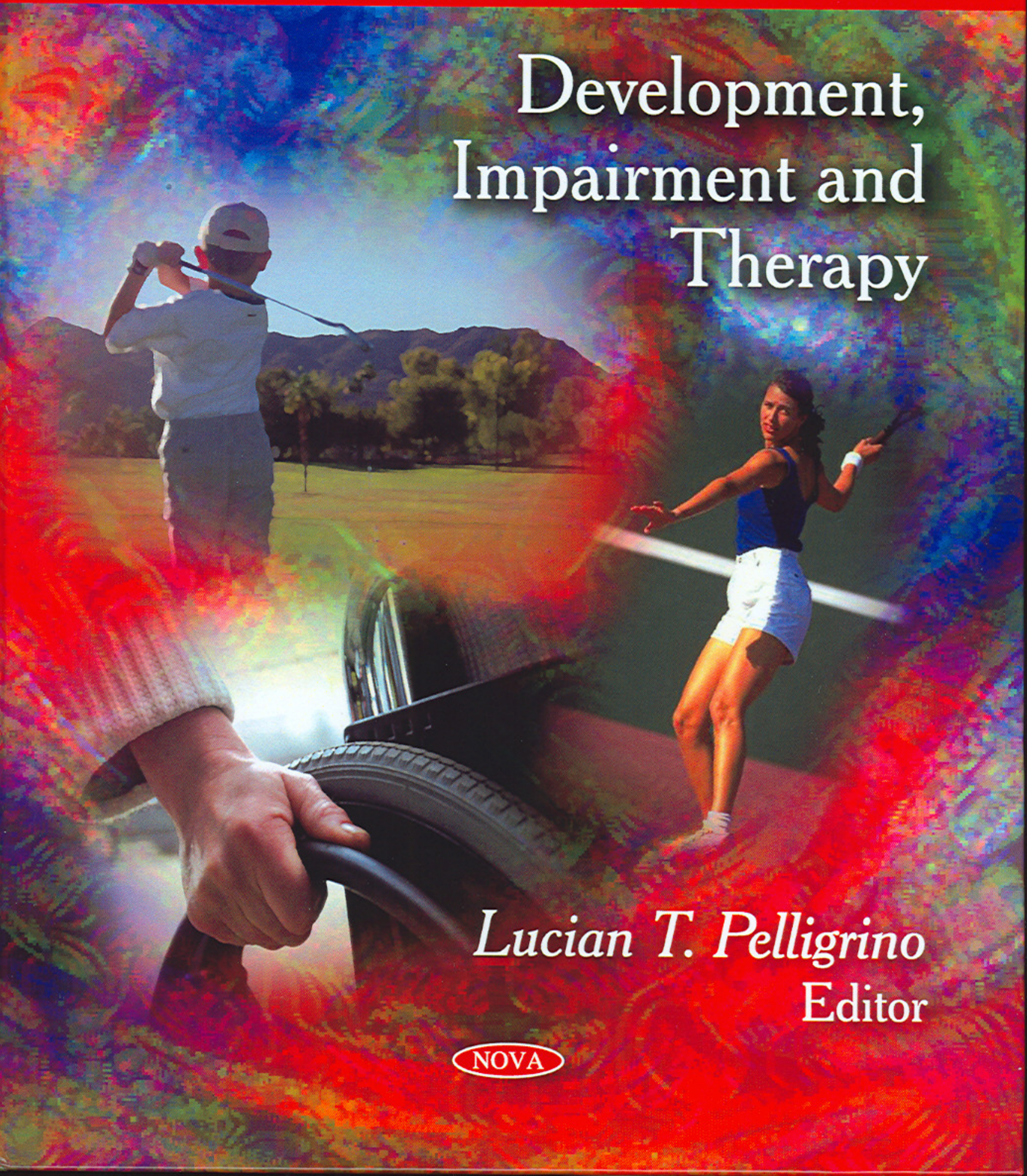
Handbook of Motor Skills

Development, Impairment and Therapy



Lucian T. Pelligrino
Editor

NOVA

In: Handbook of Motor Skills
Editor: Lucian T. Pelligrino
ISBN: 978-1-60741-811-5

Chapter 6

IMPLICIT MOTOR LEARNING IN DISCRETE AND CONTINUOUS TASKS: TOWARD A POSSIBLE ACCOUNT OF DISCREPANT RESULTS

S. Chambaron*[1]*, B. Berberian*[1]*, L. Delbecque*[2]*,
***D. Ginhac*[3] *and A. Cleeremans*[1]**

[1] Unité de Recherche Conscience, Cognition,
Computation (CO3) - Université Libre de Bruxelles, Belgique
[2] Service d'Analyse des Données (SAD) -
Université Libre de Bruxelles, Belgique
[3] Laboratoire d'Electronique, Informatique et Image (LE2I) –
Université de Bourgogne, France

ABSTRACT

Can one learn implicitly, that is, without conscious awareness of what it is that one learns? Daily life is replete with situations where our behavior is seemingly influenced by knowledge to which we have little access. Riding a bicycle, playing tennis or driving a car, all involve mastering complex sets of motor skills, yet we are at a loss when it comes to explaining exactly how we perform such physical feats. Thus, while it is commonly accepted and hence unsurprising that we have little access to the cognitive processes involved in mental operations, it also appears that knowledge itself can remain inaccessible to report yet influence behavior. Reber, who coined the expression "implicit learning" in 1967, defined it as "the process whereby people learn without intent and without being able to clearly articulate what they learn" (Cleeremans, Destrebecqz, & Boyer, 1998).

The research described in this chapter is positioned at the confluence of two different domains: Implicit Learning on the one hand, and Skill Acquisition on the other. The two domains have remained largely independent from each other, but their intersection nevertheless constitutes a field of primary import: the *implicit motor learning* field. The hallmark of implicit motor learning is the capacity to acquire skill through physical practice without conscious recollection of what elements of performance have improved. Unfortunately, studies dealing with implicit motor learning are not very abundant (Pew, 1974; Magill & Hall, 1989; Wulf & Schmidt, 1997; Shea, Wulf, Whitacre, & Park,

2001). These studies provide an apparently straightforward demonstration of the possibility of unconsciously learning the structure of a complex continuous task in a more efficient way than explicit learning allows. Nevertheless, other evidence seems to challenge this view. Indeed, recent studies (Chambaron, Ginhac, Ferrel-Chapus & Perruchet, 2006; Ooteghem, Allard, Buchanan, Oates & Horak, 2008) suggest that taking advantage from the repetition of continuous events may not be as easy as previous research leads us to believe. Indeed, these studies have suggested that sequence learning in continuous tracking tasks might be artefatctually driven by peculiarities of the experimental material rather than by implicit sequence learning per se.

Consequently, a central goal of this chapter will be to reconcile these discrepant results so as to better characterize the conditions in which implicit motor learning occurs. Moreover, understanding what facilitates or prevents learning of regularities in motor tasks will be useful both in sport and in motor rehabilitation fields.

INTRODUCTION

Can one implicitly learn a motor sequence, that is, without conscious awareness of what it is that one learns? Over the past few decades, a large number of studies has been conducted in the domains of implicit learning (for reviews see Cleeremans, 1993; Berry, 1997; Stadler & Frensch, 1998; Shanks, 2003) and motor learning (for reviews see Famose, 1995; Schmidt, 1988; 1993; 1999). However, few studies have addressed issues that involve the two fields, and the two domains have remained largely independent from each other, most likely because of historical contingencies. Their intersection nevertheless constitutes a field of primary import: the *implicit motor learning* field.

The goal of this chapter is to explore the question of implicit motor learning, and is thus positioned at the confluence of two different domains: Implicit learning on the one hand, and Skill acquisition and Motor learning on the other hand. We begin by reporting on research about implicit processes and particularly findings about implicit learning. In a second part, we will focus on skill acquisition and on the distinction between discrete and continuous abilities. The next two sections discuss the notion of implicit motor learning and suggest discrepancies between results obtained in discrete and continuous tasks. The closing section of this chapter describes an attempt to reconcile these discrepant results in order to better characterize the conditions in which implicit learning occurs in both discrete and continuous tasks. In this perspective, we will introduce some recent neuroimaging studies. To conclude, we briefly discuss the relevance of such findings for both sport psychology and rehabilitation.

IMPLICIT LEARNING

Daily life is replete with examples of situations where our behavior is seemingly influenced by knowledge to which we have little access. Riding a bicycle, playing tennis or driving a car, for instance, all involve mastering complex sets of motor skills, yet we are at a loss when it comes to explaining exactly how we perform such physical feats. Such "implicit motor control" has been demonstrated by an elegant experience led by Fourneret and Jeannerod (1998). By giving erroneous visual feedback about the trajectory of a hand movement, these authors observed that participants (who could not see their hands) were nevertheless able of reaching voluntarily the desired result when drawing a straight line on a computer screen. The movement of correction necessary for this achievement was produced unconsciously, the participants being (1) neither conscious to have produced a movement of correction, (2) nor conscious of having perceived some disturbance. In other words, the change is detected, this detection results in an adapted behavior but participants are neither conscious of the change itself nor of having adapted to it. Since then, many studies have confirmed that motor control can be achieved independently of conscious perception of movement, even for voluntary actions (for a discussion see Johnson and Haggard, 2005; see also Day & Brown, 2001; Goodale, Pélisson, & Prablanc, 1986; Desmurget, Epstein, Turner, Prablanc, Alexander, & Grafton, 1999; Varraine, Bonnard, & Pailhous, 2002).

Importantly, dissociations between our ability to report on cognitive processes and the behaviors that involve these processes are not limited to motor skills, but extend to higher-level cognition as well. Thus, most native speakers of a language are unable to articulate the grammatical rules that they nevertheless follow when uttering expressions of the language. Likewise, expertise in domains such as medical diagnosis or chess, as well as social or aesthetic judgments, involves intuitive knowledge that one seems to have little introspective access to. In particular, the last years have seen a great increase in research reporting on the implicit process involved in perception. For example, recent findings about implicit change detection (Fernandez-Duque, Grossi, Thornton, & Neville, 2003; Fernandez-Duque & Thornton, 2000, 2003; Laloyaux, Destrebecqz, & Cleeremans, 2006; Laloyaux, Devue, Doyen, David & Cleeremans, 2007; Thornton & Fernandez-Duque, 2000, 2002) have suggested the continued existence of visual information that is normally inaccessible to the mechanisms underlying conscious change detection. Thus, visuomotor systems can be controlled by stimuli that are not seen consciously (Bridgeman, Hendry, & Stark, 1975; Fourneret & Jeannerod, 1998), familiarity of unrecognized faces can influence skin conductance (Bauer, 1984), and forced-choice guessing of unseen stimuli can be better than chance (Fernandez-Duque & Thornton, 2000; Merikle & Daneman, 1998; Laloyaux, Destrebecqz, & Cleeremans, 2006).

Moreover, if it is commonly accepted and hence unsurprising that we have little access to the cognitive processes involved in mental operations, it also appears that learning itself can remain inaccessible to report yet influence behavior. Arthur Reber, who coined the expression "implicit learning" in 1967, defined it as "the process whereby people learn without intent and without being able to clearly articulate what they learn". Since then, implicit learning has become a major topic of interest for psychologists (for reviews, see Cleeremans, Destrebecqz, & Boyer, 1998; Shanks, 2005; Perruchet & Pacton, 2006). This growing interest for implicit learning stems from its crucial role in the acquisition of natural language and in the development of other cognitive, social and motor abilities. Another interesting feature of implicit learning is that it has proven to be relatively insensitive to age (e.g., Howard & Howard, 1989; 1997; 2001; Curran, 1997; Kotchoubey; Haisst; Daum; Schugens & Birbaumer, 2000) and is preserved in a number of neuropsychological disorders (e.g., McDowall & Martin, 1996; Smith, Siegert, McDowall, & Abernethy, 2001; Zilmer & Spiers, 2001; Stevens, Schwarz, Schwarz, Ruf, Kolter & Czekalla, 2002). As a consequence, the phenomenon is a focus of investigation not only for laboratory researchers, but also for those oriented towards educational or clinical objectives.

Most of the implicit learning literature has focused on three main experimental paradigms. The first is the serial reaction time (SRT) tasks designed on the basis of the Nissen and Bullemer (1987) paradigm. In a typical experiment, participants are presented with a sequence of visual stimuli displayed on a computer screen, and asked to respond by pressing a corresponding sequence of keys. Unknown to them, a specific sequence of stimulus locations recurs throughout the experiment. It was found that participants respond faster to such material than to random material. The reaction time speedup suggests that subjects have learned the patterns. The second paradigm, first investigated by Reber (e.g., 1967), involves artificial grammar learning. In a typical situation, participants are first exposed to a set of consonant letter strings generated based on a finite state grammar, without being asked to learn the rules or even without being informed of the structured nature of the material. A subsequent test is performed in order to reveal whether participants have learned about the grammar. Finally, tasks involving the control of complex and interactive systems find their origin in Broadbent's studies (e.g., Broadbent, 1977). Participants are placed in front of a computer simulating a complex system, such as a city transport system, and they are unaware that the parameters of the system are governed by a linear equation. The task consists of controlling the system, that is to say, participants have to manipulate a number of parameters in order to reach and maintain a predefined target state of the system. In each of these three situations, performance of participants trained with the repeated, or *rule-based* material has been found to be better than chance, or alternatively better than performance observed in participants trained on randomly generated materials, despite the fact that people are often unable to verbalize the learned regularities.

Although relevant research on these situations has led to important conclusions about implicit learning, it is worthwhile to examine whether those conclusions generalize over new experimental settings.

MOTOR LEARNING

Motor learning is defined as a set of processes associated with practice leading to a relatively permanent change in the capability for responding (Schmidt and Lee, 1999). In other words, motor learning is the process of improving the motor skills, the smoothness and accuracy of movements. It is obviously necessary for complicated movements such as speaking or playing the piano, but it is also important for calibrating simple movements like reflexes, as parameters of the body and environment change over time.

Whereas initial theoretical views of motor learning suggested that the motor commands and the sensory feedback were all that are needed to be stored in memory for learning to occur (Adam, 1987), more recent points of view highlight the important role of cognition in motor skills (Magill. 1993; Schmidt, 1988). Indeed, in order to accomplish a task, subjects must be able to anticipate, to plan, to regulate and to interpret the elements of their environment.

Moreover, different classifications of tasks suggest that the tasks are performed fundamentally differently, and that these tasks are learned with major different principles or methods. It is striking to note that almost no effort has been directed towards understanding the commonalities and differences between the learning processes involved in mastering the "continuous" skills requiring sensori-motor coordination and the "discrete" skills involved in more cognitive tasks such as Reber's Artificial Grammar Learning situation. Notice that movement behaviors have been classified in various ways. Here, we are interested in the distinction between discrete versus continuous skills. Discrete movements are those that feature a recognizable beginning and end (Schmidt, 1988). Kicking a ball, throwing, striking a match and shifting gears in a car are examples. Discrete skills can be very rapid, requiring only a fraction of second to complete (e.g., kicking, blinking an eye), but they can also require considerable time for completion. Discrete skills can also be quite cognitive in nature. Indeed, a common laboratory task is the well-known Serial Reaction Time paradigm (Nissen & Bullemer, 1987). In the standard SRT task, a target appears on successive trials in one of four possible locations on a computer screen, and participants are asked to react to the appearance of the target by pressing as fast as possible a key that spatially matches the location of the target. Unknownst to participants, the sequence of events typically consists in the repetition of the same sequence (e.g., a 12-trial sequence). A contrario, continuous movements are defined as movements that have no recognizable beginning and end (Schmidt, 1988), with behavior continuing until the movement is arbitrarily stopped. Example are swimming, running and steering a car. Continuous tasks tend to have longer movement times than do discrete tasks. A common class of continuous skills is the tracking tasks. The tracking task is characterized by a moving target that subject intends to follow with a device (joystick, computer mouse…). The subject attempts to keep tracking the moving target via certain limb movements. A very common laboratory task is the continuous tracking task. In this task, participants are asked to track a continuously moving target that follows a specific trajectory such sine-cosine wave patterns for example. Unknown to the participants, some segments of the target trajectory are predictable. To sum up, continuous tasks require continuous adjustment of the response based on a continually changing stimulus, whereas discrete tasks require discrete, punctuate responses.

Consequently, the differences between these two kinds of skills could have an impact on learning. Indeed, models of sequence learning, in general, assume that performance is facilitated in virtue of the fact that participants become progressively better able to anticipate the location where the next stimulus will appear, thus making it possible for them to achieve better motor preparation, and hence faster reaction times, for the next response. Such improved motor preparation is assumed to result from participants' progressive learning about the relationships between each sequence element and the temporal context in which it occurs. Different models make different assumptions about the nature of the representations that link each element with its temporal context. For instance, the Simple Recurrent Network (SRN, see Elman, 1990; Cleeremans & McClelland, 1991) assumes that such links are learned continuously over training as the network progressively learns to use self-developed increasingly richer representations of the contextual information to predict the location at which the next element will appear. In contrast, models such as Perruchet's PARSER (Perruchet & Vinter, 1998) assume that participants parse the sequence of successive locations that the stimulus visits into non-overlapping chunks that represent frequently observed fragments of the training material. These different assumptions have different consequences on the implicit vs. explicit nature of the acquired representations: Whereas models such as the SRN assume that preparation for the next event is largely implicit to the extent that it does not depend on declarative representations of the links between the temporal context and each sequence element, models such as PARSER assume in contrast that participants form episodic, declarative representations of such links. Consequently, it is interesting to find out if the SRN model, with its principle of anticipation, can be applied to continuous displacements. This model uses discrete components to predict the next location of a stimulus, so how can the SRN explain learning in continuous tasks? Actually, a series of experiments are in progress to bring new elements of response.

After presenting the characteristics of discrete and continuous skills, we will now focus on learning in discrete and continuous tasks. The next section will first present what implicit motor learning is. Secondly, it will describe relevant studies in the domain.

IMPLICIT MOTOR LEARNING

The hallmark of implicit motor learning is the capacity to acquire skill through physical practice without conscious recollection of what elements of performance have improved. According to Maxwell et al. (2000), implicit motor learning is characterized by "the acquisition of a motor skill without the concurrent acquisition of explicit knowledge about the performance of that skill". A classic example illustrating this process is learning to ride a bicycle. Unfortunately, studies dealing with implicit motor learning are not very abundant (Pew, 1974; Magill & Hall, 1989; Wulf & Schmidt, 1997; Shea, Wulf, Whitacre, & Park, 2001). These studies provide an apparently straightforward demonstration of the possibility of unconsciously learning the structure of a complex continuous task in a more efficient way than explicit learning allows. Such findings are in line with those obtained in implicit learning studies, using for instance the Serial Reaction Time paradigm (SRT). An impressive number of studies using the SRT task (Cleeremans & McClelland, 1991; Destrebecqz & Cleeremans, 2001; Howard & Howard, 1989; Reed & Johnson, 1994; Shanks, Wilkinson, & Channon, 2003; Willingham, Greeley, & Bardone, 1993) have shown that reaction times improve selectively for the repeated sequence.

Congruently, studies of implicit learning in continuous tasks provide an apparently straightforward demonstration of the possibility of unconsciously learning the structure of a complex continuous task in a more efficient way than explicit learning permits. In Pew (1974) and in Wulf and Schmidt (1997), participants were asked to track a moving target by acting on a hand-driven lever. The target moved along a horizontal axis, according to the y-value of a polynomial function. The experimental sessions consisted of a succession of trials, with each trial divided into three segments. Typically, the first and the third segment were generated by a function in which the coefficients were randomly drawn on each occasion, hence generating pseudo-random target displacements. The same function served to generate the second segment, but the coefficients were now fixed, and hence, the movement described by the target around the middle of each trial was the same across the whole training session. The tracking accuracy of participants improved only on the repeated segment. Shea, Wulf, Whitacre, and Park (2001) generalized these results to a situation in which participants had to track the target by moving the platform of a stabilometer on which they were standing.

The robustness of these results suggests that human participants are particularly prone to detect and exploit such sequential regularities. In sum, participants seem able to implicitly learn regularities embedded both in continuous tasks (*i.e*, a tracking task) and in discrete tasks (*i.e* SRT task).

Nevertheless, other evidence seems challenge this view. Indeed, recent studies (Chambaron, Ginhac, Ferrel-Chapus & Perruchet, 2006; Ooteghem, Allard, Buchanan, Oates

& Horak, 2008) suggest that benefiting from the repetition of continuous events may not be as easy as previous researches lead us to believe. In an attempted to replicate prior results in continuous tracking tasks, Chambaron et al. (2006) found that participants failed to learn the repeated segment in several experiments in which the design of the studies by Wulf and collaborators was followed, except that a different repeated segment was used for each subject in order to ensure a sound control over the idiosyncratic properties of this segment. A plausible explanation for the discrepancy between these different results could be relied on the properties of the repeated segment. In particular, Wulf and collaborators used the same repeated segment in most of their experiments. Unfortunately, the speed of displacement and the acceleration of the target in this segment were found to be lower than in the random segments used to assess the baseline. In other worlds, a possible alternative is that much of the evidence for implicit learning in a continuous tracking task could be due to the selection of a repeated segment that is especially easy to track. Such an alternative is supported by recent result of Ooteghem and collaborators (2008) which shows that sequence learning in continuous tracking tasks might be driven in part by peculiarities in the repeated segment and not implicit sequence learning per se Implicit learning in discrete and continuous motor tasks

IMPLICIT LEARNING IN DISCRETE MOTOR TASKS: CONSENSUAL RESULTS

Although several tasks have been used to investigate implicit learning (e.g.,artificial grammar learning task proposed by Reber, 1967, dynamic control task used by Berry and Broadbent, 1984) , the motor sequence learning tasks are increasingly popular. In the most typical paradigm, usually coined as the Serial Reaction Time (SRT) task developed by Nissen and Bullemer (1987), a target stimulus appears on successive trials at one of a limited number of positions. Participants are asked to react to the appearance of the target by pressing a key that spatially matches the location of the target on a keyboard. Unknown to participants, the sequence of events is not random. It usually consists of the continuous cycling of the same sequence. Learning is attested by the fact that reaction times (RTs) progressively decrease with practice of the repeated sequence and suddenly increase when a random sequence is unexpectedly inserted (Destrebecqz & Cleeremans, 2001; Reed & Johnson, 1994; Shanks & Johnstone, 1999). This indicates that participants have acquired knowledge about the structured nature of the repeated sequence. However, even if it has been shown that participants have demonstrated sequence learning, the debate about the nature of the acquired knowledge (implicit versus explicit) remains open, but we do not develop these considerations here.

Moreover, several reasons justify the current success of the SRT paradigm. There is no doubt that sequential behavior is involved in virtually any real-world abilities, from language processing to the organization of movements, thus ensuring good ecological validity to sequential tasks. The use of a visual-motor implementation makes a quantitative assessment of learning easy to obtain, and robust learning has proven to be possible within a short time in a large variety of populations, from children (Vinter & Perruchet, 2000) to elderly people (Howard & Howard, 1997). Another advantage of the SRT task over some other tasks of implicit learning is that participants are in truly incidental conditions of learning, because the effect of regularities can be assessed without participants having been informed about the presence of hidden regularities (Cleeremans, 1993; Destrebecqz & Cleeremans, 2001). Finally, it has been shown that the reliability of SRT tasks is pretty good when compared with other tasks of implicit learning (Salthouse, McGuthry & Hambrick, 1999). This latter property is essential when the aim of the researcher is to compare the learning abilities of different samples of participants, and moreover when the residual learning abilities of patients need to be assessed on an individual basis.

Since the initial study by Nissen and Bullemer (1987), SRT tasks have been the object of a huge number of investigations, which have led to both the emergence of a number of variants and the growing sophistication of methodological controls (e.g., Curran & Keele, 1993; Perruchet, Bigand & Benoit-Gonnin, 1997; Ziessler & Nattkemper, 2001; Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004; Osman, Bird & Heyes, 2005; Chambaron, Ginhac, & Perruchet, 2008). Nevertheless, all the studies agree that implicit learning in discrete tasks is remarkably robust whatever the procedural or methodological modifications carried out in the SRT task. We can thus conclude that a consensus emerges concerning the robustness of implicit sequential learning.

Do the results obtained with discrete tasks generalize to continuous motor tasks? This is the object of the next section.

IMPLICIT LEARNING IN CONTINUOUS MOTOR TASKS: DISCREPANT RESULTS

The studies exploring implicit motor learning in continuous tracking tasks (Pew, 1974, Exp. 1; Shea, Wulf, Whitacre, and Park, 2001; Wulf and Schmidt, 1997) are of particular interest. In the studies by Pew (1974) and by Wulf and Schmidt (1997), participants were asked to track a moving target by acting on a hand-driven lever. The target moved along a horizontal axis, according the y-value of a polynomial function. The experimental sessions consisted of a succession of trials, with each trial divided into three segments. Typically, the first and the third segment were generated by a function in which the coefficients were randomly drawn on each occasion, hence generating pseudo-random target displacements. The same function served to generate the second segment, but the coefficients were now fixed, and hence, the movement performed by the target around the middle of each trial was the same across the entire training session (in another condition, the repeated segment was the third one). Participants' tracking accuracy improved over the experiment, but only for the repeated segment. Shea et al. (2001) generalized those results to a situation in which participants had to track the target by moving the platform of a stabilometer on which they were standing. In a first experiment, in each of four successive practice sessions, participants performed two blocks of seven 75-s trials. Unknown to the subjects, each trial was divided into three 25-s segments. The target moved pseudo-randomly during the first and the last segments of each trial, whereas the middle segment was the same throughout the four sessions. A fifth session included a retention test, in which it appeared that Segment 2 was completed with fewer errors than Segments 1 and 3. In a subsequent interview, none of the participants mentioned that a segment had been repeated, even when they were directly questioned about this possibility. Furthermore, participants responded randomly when they were informed about the repetition of a segment and asked to identify whether this was the first, second, or third segment. Finally, the participants were unable to select the repeated segment better than chance would predict when this segment was displayed again among randomly generated segments in a subsequent forced-choice recognition test. These results essentially replicated those obtained by Pew (1974) and Wulf and Schmidt (1997) in a simpler task involving manual pursuit tracking. These studies also showed that the participants selectively improved the accuracy of their tracking on the repeated segment, although they were found to be unaware of the repeated segment and its location within a trial in subsequent recall and recognition tests. Shea et al.'s (2001) Experiment 2 used the same task as that in Experiment 1, except that the random segment was now the middle segment, and the repeated identical segments were the initial and final ones. The authors manipulated the information given to the participants about the structure of the task. Half of the participants were informed that the first third of each trial was repeated, whereas the other half were informed that the repetition concerned the last third of each trial. In a subsequent interview, only one out of the 16 participants mentioned that another segment was repeated in addition to the one designated during the instructions. Thus this design made it possible to compare performance in instructed and non-instructed conditions, without any confound due to the position of the repeated segments within the sequence. It turned out that explicit instructions produced better performances in the early phase of practice, although not at a significant level. However, this pattern was reversed with practice. In the retention test in Session 5, there were significantly fewer errors on the repeated-unknown segment than on the repeated-known segment. Thus these results show that explicit information about the structure of the task has a detrimental effect on performance.

These studies provide an apparently straightforward demonstration of the possibility of unconsciously learning the structure of a complex task in a more efficient way than explicit learning allows.

Although the occurrence of learning in this situation is not surprising given the close parallel between continuous tracking tasks and other implicit learning situations, and especially SRT tasks (Rosenbaum, Carlson, & Gilmore, 2001), there is at least one intriguing point of departure between the results collected in the new and in the classical situations. With the latter, most studies report some degree of explicit knowledge about the regularities of the material when this knowledge was investigated in post-experimental tests (e.g., Dulany, Carlson, & Dewey, 1984; Perruchet, Bigand, & Benoit-Gonin, 1997; Shanks & St.John, 1994; Shanks & Perruchet, 2002). Studies on continuous tracking report a different outcome. In Shea et al. (2001) for instance, none of the participants mentioned that a segment had been repeated in a subsequent interview, even when they were directly questioned about this possibility. Furthermore, participants responded randomly when they were informed about the repetition of a segment and asked to identify whether this was the first, second or third segment. Finally, the participants were unable to select the repeated segment better than chance would predict when this segment was displayed again among randomly generated segments in a subsequent forced-choice recognition test. These results essentially replicate those previously obtained by Pew (1974) and Wulf and Schmidt (1997). These studies also suggested that the participants were unaware of the repeated segment and of its location within a trial in subsequent recall and recognition tests.

In an earlier comment, Perruchet, Chambaron, & Ferrel-Chapus, (2003) suggested that this discrepancy could be due to the fact that the knowledge explored in the post-experimental tests in pursuit tracking experiments did not match the knowledge that was actually responsible for the behavioural improvement. The features explored in the post-experimental tests were (1) the fact that the very same segment is repeated throughout the study phase and (2) the location of this segment within the overall sequence (first, second, or third segment). Perruchet et al. (2003) demonstrated that neither of those features is necessary for performance improvement and, furthermore, they pointed out that neither of these features was actually learned in conventional SRT tasks. Rather, participants in SRT tasks gain knowledge of small chunks composed of 2 or 3 trials (e.g., Buchner, Steffens, & Rothkegel, 1998; Perruchet & Amorim, 1992).

What about the possibility that the conclusions made based on SRT tasks are in fact tightly linked to a very specific experimental setting? A prior study of Chambaron and colleagues (2006) indeed suggests that benefiting from the repetition of events may not be as easy as SRT research leads us to believe. They found that participants failed to learn the repeated segment in several experiments in which the design of the studies by Wulf and collaborators was followed, except that a different repeated segment was used for each subject in order to ensure sound control over the idiosyncratic properties of this segment. A plausible explanation for the discrepancy between Chambaron's results and those of Wulf and collaborators is that most of the experiments by Wulf and collaborators used the same repeated segment, and that the speed of displacement and the acceleration of the target in this segment were found to be lower than in the random segments used to assess the baseline. In support of this hypothesis, Chambaron and colleagues obtained positive results when using this same repeated segment for all participants. Overall, these results suggest that much of the evidence for implicit learning in a continuous tracking task could be due to the selection of a repeated segment that is particularly easy to track. The consequences of this for our concern are straightforward: Learning from event repetitions may not be as easy as studies involving SRT tasks seem to suggest. Such a finding is supported by recent results from Ooteghem and collaborators (2008). These authors examined changes in the motor organization of postural control in response to continuous, variable amplitude oscillations evoked by a translating platform and explored whether these changes reflected implicit sequence learning. Results showed similar improvements for the random and repeated segments, indicating that participants did not exploit the sequence of perturbations to improve balance control. They concluded that implicit sequence learning does not occur for compensatory posture control under conditions where other regularities exist in the perturbation environment. Finally, they argued that sequence learning in continuous tracking tasks might be driven in part by peculiarities in the repeated segment and not by implicit sequence learning per se.

IMPLICIT MOTOR LEARNING: TOWARD A POSSIBLE ACCOUNT OF DISCREPANT RESULTS

A large body of neuroimaging studies has explored motor skill learning. Studies in animals and humans have shown that motor cortical regions, the cerebellum, and the basal ganglia are significantly involved in learning skilled movements (Graybiel, 1995; Thach, 1996; Doyon, 1997; Karni et al., 1998; Van Mier, 2000). Current models suggest that different networks of cortical and subcortical regions are preferentially involved in the early and late phases of skill acquisition (Karni et al., 1998; Hikosaka et al., 1999; Van Mier, 2000; Doyon and Ungerleider, 2002). Neuroimaging studies of motor sequence learning have shown decreasing cerebellar activation as a task is learned, accompanied by increased activation in the basal ganglia, primary motor cortex (M1), and in the supplementary motor area (SMA) (Grafton et al., 1994; Jenkins et al., 1994; Karni et al., 1995; Doyon et al., 1996, 1999; Van Mier et al., 1997; Toni et al., 1998).

Recently, Doyon, Penhune and Ungerleider (2003) showed that changes in the brain depend not only on the stage of learning (Doyon and Ungerleider, 2002) but also on whether subjects are required to learn a new sequence of movements (motor sequence learning) or to learn to adapt to environmental perturbations (motor adaptation). This model of Doyon and collaborators proposes that the cortico-striatal and cortico-cerebellar systems contribute differentially to motor sequence learning and motor adaptation. It is therefore interesting to ask whether different cerebral systems are also involved in learning in discrete vs. continuous tasks.

Concerning continuous tasks, a convincing study by Maquet and collaborators (Maquet, Schwartz, Passingham, & Frith, 2003) seems to contrast with earlier results obtained by Chambaron et al. (2003, 2006). In this study, subjects were trained on a pursuit task in which the target can move along the two dimensions, that is to say on the horizontal and vertical axes. This task was a particular version of the pursuit task (Frith, 1973) in which the target trajectory was predictable on the horizontal axis but not on the vertical axis. Moreover, in this study, the authors were also interested in the impact of sleep deprivation on the learning. Participants were tested during a functional magnetic resonance imaging (fMRI) scanning session. Functional magnetic resonance imaging revealed task-related increases in brain responses to the learned trajectory, as compared with a new trajectory. According to the findings obtained by Maquet and collaborators, positive learning results were obtained using a two-dimensional tracking task. Such results contrast with previous results obtained by Chambaron et al. (2003, 2006). Thus it seems that the introduction of a second dimension in the experimental material makes it possible for participants to learn about the regularities contained in the target's movements. Adding a second dimension seems permit a better identification because, we can suppose that, it is a more "ecological" situation. This is an argument leading to a possible explanation of discrepant in continuous tasks.

Consequently, it is interesting to ask if different cerebral systems are involved in learning of discrete and continuous tasks. To further investigate this issue, we (Chambaron, Ginhac, Cleeremans and Peigneux, in prep) have attempted to test subjects in comparable SRT and continuous tracking situations, using strictly identical material in which the 2D target trajectory (tracking) or stimulus moves (SRT) were predictable on one of the two dimensions: axes. In other words, a perfect matching exists between these two tasks concerning the design; only the nature of the task differs. For half of the participants, the target trajectory was predictable on the horizontal but not on the vertical axis, and vice versa for the other half. The subjects will perform both the tracking task and the SRT task in the scanner. A mirror box will allow them to view the display. Subjects will be simultaneously shown the positions of a moving target and of a joystick. By manipulating a custom made joystick with their non-dominant hand (left hand), the subjects can move the position of the joystick on the screen. The left hand is chosen to ensure that performance on the tasks does not rely on preexisting motor skills such as writing or drawing. Participants do not know that the trajectory followed by the target is manipulated in a similar way as in Maquet, Schwartz, Passingham, & Frith

(2003). The trajectory followed by the target was easily predictable along the horizontal axis but very difficult to predict along the vertical axis. With such a protocol, we will be able to explore the neural bases of learning in discrete and continuous conditions. Thus, we can hypothesize that two distinct cerebral systems are implied in these two kinds of tasks. If this indeed proves to be the case, we would be able to understand why discrepant results exist in the literature. Succeed in reconciling these discrepant results in order to better characterize the conditions in which implicit learning occurs in both discrete and continuous tasks would be an important result. Indeed, understand what facilitates or prevents learning of regularities in motor tasks will be useful both in sport and in motor rehabilitation fields.

CONCLUSION

The main goal of this chapter was to explore the field of implicit motor learning. As we mentioned, an abundant literature exists concerning both implicit learning and motor learning, but the literature concerning specifically implicit motor learning is more limited. We have reported on the main findings in these domains. Whereas consensual results emerge when discrete tasks are used, continuous tasks have led to divergent findings. Consequently, neuroimaging studies represent an interesting way of understanding (and maybe resolving) these discrepancies.

Theories and results stemming from the fields of implicit learning and of motor learning represent a valuable source of support for problems encountered in rehabilitation. Indeed, a large portion of the rehabilitation experience after stroke relies on implicit learning. Boyd and Winstein (2006) concluded that for healthy participants, explicit information appears helpful for learning. A contario, after stroke, some forms of explicit information are less beneficial for the patients. Consequently, it is important that therapists adapt their interventions to facilitate motor skill learning. It is likely that to optimize rehabilitation outcomes alternative methods of prescriptive information may be more useful to the learner than are explicit instructions. Clearly, success in exploring and circumscribing conditions enabling better implicit motor learning in healthy people and after stroke represent a challenge both for researchers and therapists. Obviously, much more research is needed in the behavioral and neuroimaging domains.

REFERENCES

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin. 101*, 41-74.

Bauer, R. (1984). Autonomic recognition of names and faces in prosopagnosia: A neuropsychological application of the guilty knowledge test. *Neuropsychologia. 22*, 457-469.

Berry, D. C. (1997). *How implicit is implicit learning*. Oxford: Oxford University Press.

Berry, D. C. & Broadbent, D. E. (1984). On the relationship between task performance and associated verbalizable knowledge. *Quarterly Journal of Experimental Psychology. 36A*, 209-231.

Bischoff-Grethe A., Goedert K.M., Willingham D.T., Grafton S.T. (2004). Neural substrates of response-based sequence learning using fMRI. *Journal of Cognitive Neurosciences. 16(1)*,127-138.

Boyd, L.A. & Winstein, C.J. (2006). The interaction between explicit knowledge, task demand and focal brain damage on implicit motor sequence learning. *Journal of Neurologic Physical Therapy.* 30, 46-57.

Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision Res. 15*(6), 719-722.

Broadbent, D. E. (1977). Levels, hierarchies, and the locus of control. *Quarterly Journal of Experimental Psychology. 29*, 181-201.

Buchner, A., Steffens, M.C. & Rothkegel, R. (1998). On the role of fragmentary knowledge in a sequence learning task. *Quarterly Journal of Experimental Psychology. 51A*, 251-281.

Chambaron, S., Ginhac, D., Ferrel-Chapus, C. & Perruchet, P. (2006) Implicit learning of a Repeated Segment in Continuous Tracking: A Reappraisal. *The Quarterly Journal of Experimental Psychology.* 59A, 845-854.

Chambaron, S., Ginhac, D., Cleeremans, A., & Peigneux, P. (in prep). Learning discrete and continuous regularities in two-dimensional settings.

Chambaron, S., Ginhac, D., & Perruchet, P. (2008) gSRT-Soft: A generic software and some methodological guidelines to investigate implicit learning through visual-motor sequential tasks. *Behavior Research Methods. 40(2)*, 493-502.

Cleeremans, A. (1993). Mechanisms of implicit learning : Connectionist models of sequence processing. Cambridge: MIT Press.

Cleeremans, A., Destrebecqz, A., & Boyer, M. (1998). Implicit learning: news from the front. *Trends in Cognitive Sciences. 2*, 406–416.

Cleeremans, A. & McClelland, J. L. (1991). Learning the structure of event sequences. *Journal of Experimental Psychology-General, 120*, 235-253.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research*, *60*, 24–41.

Curran, T., and Keele, S.W. (1993)Attentional and non attentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition. 19*, 189-202.

Day, B. L., & Brown, P. (2001). Evidence for subcortical involvement in the visual control of human reaching. *Brain. 124*(Pt 9), 1832-1840.

Desmurget, M., Epstein, C. M., Turner, R. S., Prablanc, C., Alexander, G. E., & Grafton, S. T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nat. Neurosci. 2*(6), 563-567.

Destrebecqz, A. & Cleeremans, A. (2001). Can sequence learning be implicit? New evidence with the Process Dissociation Procedure. *Psychonomic Bulletin & Review.* 8 (2), 343-350.

Doyon J (1997) Skill learning. In: The cerebellum and cognition (Schmahmann J, ed), pp 273-294. San Diego: Academic

Doyon J, Owen A, Petrides M, Sziklas V, Evans A (1996) Functional anatomy of visuomotor skill learning in human subjects examined with positron emission tomography. *Eur. J. Neurosci. 8*:637-648.

Doyon, J., Penhune, V., and Ungerleider, L. (2003) Distinct contributions of the cortico-striatal and cortico-cerebellar systems to motor skill learning, *Neuropsychologia. 41*, 252–262.

Doyon J, Song A, Lalonde F, Karni A, Adams M, Ungerleider L (1999) Plastic changes within the cerebellum associated with motor sequence learning: an fMRI study. *NeuroImage. 9*:S506.

Doyon, J., & Ungerleider L. Functional anatomy of motor skill learning. (2002) In: L. Squire and D. Schacter, Editors, *Neuropsychology of Memory.* Guilford Press, New York , 225–238.

Dulany, D. E., Carlson, R. A. & Dewey, G. I. (1984). A case of syntactical learning and judgement : How conscious and how abstract? *Journal of Experimental Psychology-General. 113*, 541-555.

Elman, J. (1990) Finding structure in time. *Cognitive Science. 14,* 179-211.

Famose, J. P. (1995). L'apprentissage moteur. In R. Thomas (Ed.), *Sciences et techniques des activités physiques et sportives*. Paris: P.U.F.

Fernandez-Duque, D., Grossi, G., Thornton, I. M., & Neville, H. J. (2003). Representation of change: separate electrophysiological markers of attention, awareness, and implicit processing. *J .Cogn. Neurosci. 15*(4), 491-507.

Fernandez-Duque, D., & Thornton, I. M. (2000). Change detection without awareness: Do explicit reports underestimate the representation of change in the visual system? *Visual Cognition. 7*(1-3), 323-344.

Fernandez-Duque, D., & Thornton, I. M. (2003). Explicit mechanisms do not account for implicit localization and identification of change: An empirical reply to Mitroff et al. (2002). *Journal of Experimental Psychology: Human Perception and Performance. 29*(5), 846-858.

Fourneret, P., & Jeannerod, M. (1998). Limited conscious monitoring of motor performance in normal subjects. *Neuropsychologia. 36*(11), 1133-1140.

Frith, C. (1973) Learning rhythmic hand movements. *The Quarterly Journal of Experimental Psychology. 25,* 253–259.

Goodale, M. A., Pelisson, D., & Prablanc, C. (1986). Large adjustements in visually guided reaching do not depend on vision of the hand or perception of target dispalcement. *Nature. 320*, 748-750.

Grafton S, Woods R, Tyszka M (1994) Functional imaging of procedural motor learning: relating cerebral blood flow with individual subject performance. *Hum. Brain Map.* 1:221-234.

Graybiel, A.M. Building action repertoires: memory and learning functions of the basal ganglia, *Curr. Opin. Neurobiol. 5,* 733–741.

Hikosaka O, Nakahara H, Rand M, Sakai K, Lu X, Nakamura K, Miyachi S, Doya K (1999) Parallel neural networks for learning sequential procedures. *Trends Neurosci. 22*:464-471

Howard, D.V. & Howard, J.H. (1989). Age differences in learning serial patterns: Direct versus indirect measures. *Psychology and Aging. 4*, 357-364.

Howard, J.H., Jr., & Howard, D.V. (1997). Age differences in implicit learning of higher-order dependencies in serial patterns. *Psychology and Aging. 12*, 634-656.

Howard, D.V., & Howard, J.H., Jr. (2001). When it does hurt to try: Adult age differences in the effects of instructions on sequential pattern learning. *Psychonomic Bulletin and Review.* 8(4), 798-805.

Jenkins I, Brooks D, Nixon P, Frackowiak R, Passingham R (1994) Motor sequence learning: a study with positron emission tomography. *J. Neurosci. 14*:3775-3790

Johnson, H., & Haggard, P. (2005). Motor awareness without perceptual awareness. *Neuropsychologia. 43*(2), 227-237.

Karni A, Meyer G, Jezzard P, Adams M, Turner R, Ungerleider L (1995) Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature. 377*:155-158

Karni A., Meyer G., Rey-Hipolito C., Jezzard P., Adams M.M., Turner R., Ungerleider L.G. (1998). The acquisition of skilled motor performance: fast and slow experience-driven changes in primary motor cortex. *Proc. Natl. Acad. Sci. U.S.A. 95*:861– 868

Kotchoubey, B., Haisst, S., Daum, I., Schugens, M., & Birbaumer, N. (2000). Learning and self-regulation of slow cortical potentials in older adults. *Experimental Aging Research. 26*(1), 15-35.

Laloyaux, C., Destrebecqz, A., & Cleeremans, A. (2006). Implicit change identification: a replication of Fernandez-Duque and Thornton (2003). *J. Exp. Psychol. Hum. Percept. Perform, 32*(6), 1366-1379.

Laloyaux, C., Devue, C., Doyen, S., David, E., & Cleeremans, A. (2008). Undetected changes in visible stimuli influence subsequent decisions. *Conscious Cogn. 17*(3), 646-656.

Magill, R.A. (1993). Motor Learning. Concepts and applications. Madison, Wisconsin: Brown & Benchonrk.

Magill, R. A. & Hall, K. G. (1989). *Implicit learning in a complex tracking skill.* Paper presented at the 30th annual meeting of the psychonomic society, Atlanta.

Maquet, P., Schwartz, S., Passingham, R., & Frith, C. (2003). Sleep-Related Consolidation of a Visuomotor Skill: Brain Mechanisms as Assessed by Functional Magnetic Resonance Imaging. *J. Neurosci. 23,* 1432-1440.

Maxwell, J.P., Masters, R.S.W. & Eves, F.F. (2000) From novice to know-how: A longitudinal study of implicit motor learning. *Journal of Sports Sciences. 18,* 111–120

McDowall, J. and Martin, S. (1996) Implicit learning in closed head injured subjects: evidence from an event sequence learning task. *New Zealand Journal of Psycholoy. 25*, 1-6.

Merikle, P. M., & Daneman, M. (1998). Psychological investigations of unconscious processing. *Journal of Consciousness Studies. 5*, 5-18.

Nissen, M.J. & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology. 19*, 1-32.

Osman, M., Bird, G., & Heyes, C.M. (2005) Action observation supports effector-dependent learning of finger movement sequences. *Experimental Brain Research. 165(1)*, 19-27.

Ooteghem, K., Frank, J.S., Allard, F., Buchanan, J.J., Oates, A.R., & Horak, F.B. (2008). Compensatory postural adaptations during continuous, variable amplitude perturbations reveal generalized rather than sequence-specific learning. *Experimental Brain Research. 187(4),* 603-11.

Perruchet, P. & Amorim, M. A. (1992). Conscious knowledge and changes in performance in sequence learning : Evidence against dissociation. *Journal of Experimental Psychology-Learning Memory and Cognition. 18*, 785-800.

Perruchet, P., Bigand, E. & Benoit-Gonnin, F. (1997a). The emergence of explicit knowledge during the early phase of learning in sequential reaction time. *Psychological Research. 60*, 4-14.

Perruchet, P., Chambaron, S., & Ferrel-Chapus, C. (2003). Learning from implicit learning literature: Comment on Shea, Wulf, Whitacre, and Park (2001). *The Quarterly Journal of Experimental Psychology. 56A,* 769-778.

Perruchet, P. & Vinter, A. (1998). PARSER: A model for word segmentation. *Journal of Memory & Language. 39*, 246-263.

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: Two approaches, one phenomenon. *Trends in Cognitive Sciences.* 10, 233-238

Pew, R.W. (1974). Levels of analysis in motor control. *Brain Research. 71*, 393-400.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior. 5*, 855-863.

Reed, J. & Johnson, P. (1994). Assessing implicit learning with indirect tests : Determining what is learned about sequence structure. *Journal of Experimental Psychology-Learning Memory and Cognition. 20*, 585-594.

Rosenbaum, D. A., Carlson, R. A. & Gilmore, R. O. (2001). Acquisition of intellectual and perceptual-motor skills. *Annual Review of Psychology. 52*, 453-470.

Salthouse, T. A., McGuthry, K. E., & Hambrick, D. Z. (1999). A framework for analyzing and interpreting differential age patterns: Application to three measures of implicit learning. *Aging, Neuropsychology, & Cognition. 6*, 1-18.

Schmidt, R. A. (1988). *Motor control and learning: a behavioral emphasis.* (2nd ed.). Champaign, IL.: Human Kinetics Publishers.

Schmidt, R. A. (1993). *Apprentissage moteur et performance*. Paris: Vigot.

Schmidt, R. A. & Lee, T. D. (1999). *Motor Control and Learning: A Behavioral Emphasis, 3ème édition*. Champaign, IL: Human Kinetics.

Shanks, D. R. (2003). Attention, awareness, and implicit learning. In L. Jimenez (Ed.), *Attention and implicit learning.* (Vol. 48, pp. 11-42). Amsterdam and Philadelphia: John Benjamins.

Shanks, D. R. (2005). Implicit learning. In K. Lamberts and R. Goldstone, *Handbook of Cognition.* (pp. 202-220) . London: Sage.

Shanks, D. R., Johnstone, T. (1999). Evaluating the relationship between explicit and implicit knowledge in a sequential reaction time task. *Journal of Experimental Psychology: Learning, Memory, & Cognition. 25,* 1435-1451.

Shanks, D. R. & Perruchet, P. (2002). Dissociating between priming and recognition in the expression of sequential knowledge. *Psychonomic Bulletin & Review. 9*, 362-367.

Shanks, D. R. & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences. 17*, 367-447.

Shanks, D. R., Wilkinson, L., & Channon, S. (2003). Relationship between priming and recognition in deterministic and probabilistic sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition. 29*, 248–261.

Shea, C.H., Wulf, G., Whitacre, C.A., & Park, J-H. (2001). Surfing the implicit wave. *The Quarterly Journal of Experimental Psychology. 54A*, 841-862.

Smith, J., Siegert, R., McDowall, J., & Abernethy, D. (2001). Preserved implicit learning on both the serial reaction time task and artificial grammar in patients with Parkinson's disease. *Brain and Cognition. 45*, 378-391.

Stadler, M. A. & Frensch, P. A. (1998). Handbook of Implicit Learning and Implicit Memory. In P. A. Frensch & M. A. Stadler (Eds.). Thousand Oaks: SAGE.

Stevens A, Schwarz J, Schwarz B, Ruf I, Kolter T, Czekalla, J. (2002) Implicit and explicit learning in schizophrenics treated with Olanzapine and with classic neuroleptics. *Psychopharmacology. 160*, 299-306.

Thach, W. On the specific role of the cerebellum in motor learning and cognition: clues from PET activation and lesion studies in man, *Behav. Brain Sci. 19* , 411–431.

Thornton, I. M., & Fernandez-Duque, D. (2000). An implicit measure of undected change. *Spatial Vision. 14*(1), 21-44.

Thornton, I. M., & Fernandez-Duque, D. (2002). Change blindness and transsacadic integration. In J. Hyönä, D. P. Munoz, W. Heide & R. Radach (Eds.), *Progress in Brain Research.* (Vol. 140). Amsterdam: Elsevier.

Toni I, Krams M, Turner R, Passingham R (1998) The time course of changes during motor sequence learning: a whole-brain fMRI study. *NeuroImage. 8*:50-61.

Van Mier H (2000) Human learning. In: *Human brain mapping: the Systems.* (Mazziota J, ed), pp 605-662. Academic.

Van Mier H, Ojemann J, Miezin F, Akbudak E, Conturo T, Raichle M, Peterson S (1997) Practice-related changes in motor learning measured by fMRI. *Soc. Neurosci.. Abstr. 23*:1051.

Varraine, E., Bonnard, M., & Pailhous, J. (2002). The top down and bottom up mechanisms involved in the sudden awareness of low level sensorimotor behavior. *Brain Res. Cogn. Brain Res. 13*(3), 357-361.

Vinter, A., Perruchet, P. (2000). Unconscious learning in children is not related to age: Evidence from drawing behavior. *Child Development.* 71, 1223-1240.

Willingham, D. B., Greeley, T., & Bardone, A. (1993). A dissociation of awareness and performance using a more sensitive declarative measure: Reply to Perruchet and Amorim. *Journal of Experimental Psychology: Learning, Memory, and Cognition. 19*, 1424-1430.

Wulf, G., & Schmidt, R.A. (1997). Variability of practice and implicit motor learning, *Journal of Experimental Psychology: Learning, Memory and Cognition. 23*, 987-1006.

Ziessler, M. & Nattkemper, D. (2001): Learning of event sequences is based on response-effect learning: Further evidence from a serial reaction task. *Journal of Experimental Psychology: Learning, Memory and Cognition. 27*, 595-613

Zilmer, E. & Spiers, M. (2001). *Principles of Neuropsychology.* Belmont, CA: Wadsworth.

Handbook of Motor Skills

Development, Impairment and Therapy

Lucian T. Pelligrino
Editor

www.novapublishers.com

ISBN-13 : 978-1-60741-811-5
ISBN-10 : 1-60741-811-8

9 781607 418115