



Contributions from associative and explicit sequence knowledge to the execution of discrete keying sequences



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ABSTRACT

Research has provided many indications that highly practiced 6-key sequences are carried out in a *chunking mode* in which key-specific stimuli past the first are largely ignored. When in such sequences a deviating stimulus occasionally occurs at an unpredictable location, participants fall back to responding to individual stimuli (Verwey & Abrahamse, 2012). The observation that in such a situation execution still benefits from prior practice has been attributed to the possibility to operate in an *associative mode*. To better understand the contribution to the execution of keying sequences of motor chunks, associative sequence knowledge and also of explicit sequence knowledge, the present study tested three alternative accounts for the earlier finding of an execution rate increase at the end of 6-key sequences performed in the associative mode. The results provide evidence that the earlier observed execution rate increase can be attributed to the use of explicit sequence knowledge. In the present experiment this benefit was limited to sequences that are executed at the moderately fast rates of the associative mode, and occurred at both the earlier and final elements of the sequences.

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1. Introduction

1.1. Motor skill representations

The question how serial motor skills are represented in the brain has inspired researchers for many decades. Consistent with behavioristic thinking, the classic chaining theory claimed that serial motor skills are based on associating the response-produced feedback stimuli from each movement with the ensuing movement (Bain, 1868; James, 1890; Skinner, 1934). However, the insight developed that chaining theory cannot account for relationships between non-adjacent items in serially organized behavior (Lashley, 1951). With the advent of cognitive psychology in the late 1950s, it became clear that knowledge is based on a combination of sensorimotor and symbolic (e.g., verbal) representations that are hierarchically or linearly associated to make up more complex representations (Paivio, 1963). Keele (1968) used this idea in his proposal that muscle commands can be planned before movement begins using a representation called a motor program. Later, the well-known schema theory further worked out this motor programming idea by combining two types of representations, the

abstract General Motor Program defining a class of movements, and the Recall Schema containing parameters like speed and size to scale the General Motor Program into an executable motor program (Schmidt, 1975). In his neuropsychological theory of motor skill learning, Willingham (1998) assumed that motor sequences rely on a skill-dependent mixture of egocentric representations (e.g., relative to the head, shoulder, or trunk) and allocentric spatial representations (i.e., relative to a particular object in the outside world). At about the same time, Hikosaka et al. (1999) inspired many serial motor studies with their neurocognitive proposal of a fast learning effector-independent system using allocentric and eye- and hand-centered egocentric spatial coordinates, and a slowly learning effector-dependent motor system (e.g., Seidler, Bo, & Anguera, 2012; Shea, Kovacs, & Panzer, 2011; Wühr & Heuer, 2014). Representations in the motor system would code joint angles (a type of coding that may well be responsible for indications that movement control occurs in terms of successive body postures, Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001).

A particularly fruitful sequence learning paradigm involves the serial reaction time (RT) task (Nissen & Bullemer, 1987; for reviews see Abrahamse, Jiménez, Verwey, & Clegg, 2010; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). Research with this task demonstrated that sequential motor skills may be based on knowledge that is not accessible to consciousness, that is, on *implicit* sequence knowledge. Still, there always appeared to be a few participants who do develop

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awareness of the order of the movements, in that they can verbalize that order. These participants are said to possess *explicit* sequence knowledge. This knowledge is used when, for example, we are typing our PIN on the basis of an explicitly recalled number (Fendrich & Arengo, 2004).¹ Explicit sequence knowledge may develop also because repeated execution of externally guided movement sequences allows participants to test hypotheses about the order of the sequence elements (Rünger & Frensch, 2008). Aware participants are often found to execute movement sequences a little faster than participants without awareness (Curran & Keele, 1993; Mayr, 1996; Rüsseler et al., 2003). The fact that an execution benefit of explicit knowledge is not always observed has been attributed to a lack of time to translate explicit knowledge into actual movement (Cleeremans & Sarrazin, 2007; Destrebecqz & Cleeremans, 2001).

There is considerable consensus now that serial motor skill relies on a task-, age-, and practice-dependent mixture of verbal, spatial, and motor representations (Panzer, Gruetzmacher, Ellenbürger, & Shea, 2014). This redundant way of coding movement allows flexible adjustment of these serial motor skills to a variety of situations (Shea et al., 2011). This view was recently worked out in the Cognitive framework for Sequential Motor Behavior (C-SMB; Verwey, Shea, & Wright, 2015).

1.2. A processing architecture

In our own empirical work, we have focused especially on the cognitive system that processes the various representations that underlie sequential movement series. Following a number of theoretical approaches that all assume that central processing and motor processing involve independent cognitive systems (Allport, 1980; Keele et al., 2003; MacKay, 1982; Pew, 1966; Schmidt, 1975), we argued that with the execution of relatively short (i.e., *discrete*) movement sequences a distinction can be made between a central and a motor processor (Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Verwey, 2001). According to this *Dual Processor Model*, the central processor selects and loads movement representations into a short-term motor buffer, either one by one or on the basis of an integrated representation (Verwey, 1996). The motor processor then reads the individual movements from this motor buffer and executes each of them. If the central processor is not occupied by another task it can speed up execution by triggering, in parallel to the motor processor, the individual responses on the basis of stimuli (Verwey, 2001, 2003b), or cognitive sequence representations (Ruitenberg, Abrahamse, De Kleine, & Verwey, 2012).

The Dual Processor Model assumes that the various representations underlying serial motor skills are processed in different ways. First, a distinction can be made between external and internal execution modes (Verwey, 2001). External control involves guidance of movement sequences by the central processor reacting to element-specific stimuli (Hikosaka et al., 1999; Tubau, Hommel, & López-Moliner, 2007). This external control encompasses two execution modes (Verwey & Abrahamse, 2012). In the so-called *reaction mode*, a movement sequence is carried out by merely reacting to successive stimuli. However, when a movement series is carried out over and over again the sequence may continue to involve reacting to stimuli while processes and representations required for each response are gradually primed by the processes used to produce earlier responses. This priming of individual response movements probably occurs at all processing levels, and involves perceptual, egocentric and allocentric spatial, symbolic, and motor representations (Abrahamse et al., 2010; Goschke & Bolte, 2012). This way of producing movement sequences has recently been

named the *associative mode* and is believed to be responsible for improvement in the serial RT task (Verwey & Abrahamse, 2012).

In the case of internal sequence control, each individual movement is assumed to be selected on the basis of a memory representation called a *motor chunk* (Rhodes, Bullock, Verwey, Averbach, & Page, 2004; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1996). The use of these motor chunks is referred to as the *chunking mode* (Verwey, 2003b; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011). The above discussion suggests that in principle these motor chunks may include a mixture of motor and various spatial codes. However, the motor component in the motor chunks is likely to become dominant over the slower spatial representations because the motor representations can be more rapidly applied by the motor system (Verwey et al., 2015).

Given that participants may also be using verbal sequence knowledge to produce movement sequences, it is important to realize that research on serial verbal learning demonstrated that participants initially learn the first and last items of a series after which their explicit knowledge of the series gradually extends to the items in the middle (if at all) (for an overview see, Johnson, 1991). For instance, in an eight word list error rate increased from 5% at Position 1 to 18% at Positions 5 and 6, and then reduced to 10% at Position 8 (Figure 1 in Johnson, 1991). This phenomenon appears to hold for any task in which participants are required to give a response to a stimulus in a list, and it therefore is likely that this occurs with the development of explicit sequence knowledge in discrete sequence production (DSP) sequences too. A recent DSP task study did indeed show that explicit knowledge of two 6-key sequences was stronger for the initial two and last two responses than for the third and fourth responses (Verwey & Wright, 2014). However, this awareness correlated with execution rate only in the first, relatively slow, practice block. In unfamiliar DSP task sequences, too, the second and last responses have been reported to be relatively fast (De Kleine & Van der Lubbe, 2011; De Kleine & Verwey, 2009; Verwey, 2010; Verwey, Abrahamse, & De Kleine, 2010; Verwey, Abrahamse, & Jiménez, 2009). The fast second response in DSP sequences further appears to be relatively vulnerable to conditions that require cognitive processing, like concatenating sequences in a new order, and reversing stimulus-sequence mappings (Verwey, 2001), suggesting a high cognitive contribution to especially that response. Taken together, these findings suggest that in DSP sequences participants develop explicit knowledge especially of the first and last key presses, but that this speeds up keying sequences only when they are carried out at a moderate execution rate because translating explicit knowledge takes too long to speed up execution that already is based on the rapidly executed motor representations.

In line with the possibility to produce movement sequences in different execution modes, several studies demonstrated that participants can intentionally switch between these modes. One of those studies reported that when participants were responding to an unfamiliar stimulus series to produce 6-key sequences, and that sequence unexpectedly appeared to be familiar, execution rate increased (Verwey, 2003b). The finding that the response time distributions of the moderately fast key presses included two or three peaks strongly suggested that participants switched from the reaction to the associative and/or the chunking mode. More recently, Jiménez, Méndez, Pasquali, Abrahamse, and Verwey (2011) found indications that color coding in a serial RT task induced application of motor chunks in that short key pressing segments were carried out in bursts. Yet, when the colors were removed execution occurred again in the associative mode instead of in the chunking mode. Furthermore, Verwey and Abrahamse (2012) first had participants execute keying sequences in the chunking mode. Then these participants were exposed to a mixed-familiar condition in which 75% of the sequences included two deviating stimuli (called *deviants*) in an otherwise familiar sequence, while the remaining 25% of the sequences did not include deviants. The results suggested that when the participants expected these deviants the sequences were executed again in the associative mode (for replications, see

¹ The verbal expression of sequence knowledge may not always indicate explicit knowledge, but may rely also on a reconstruction that is based on a playing off implicit sequence knowledge (Verwey et al., 2010; Verwey & Wright, 2014).

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