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W.B. Verwey

ON PRODUCING SEQUENTIAL MOVEMENTS AND ACTIONS. AN INTEGRATIVE REVIEW AND AN UPDATE OF THE GENERALIZED MOTOR PROGRAM

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TNO Institute for Human Factors

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Fax +31 3463 5 39 77
Telephone +31 3463 5 62 11

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W.B. Verwey

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
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TNO Defence Research
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In dit rapport wordt een overzicht gegeven van de literatuur met betrekking tot de uitvoering van bewegingssequenties in het algemeen en de gevolgen van oefening voor bewegingssequenties in het bijzonder. Een belangrijk uitgangspunt in dit rapport is het idee dat een sequentie van maximaal vijf bewegingselementen geprogrammeerd kan worden door informatie voor elk element in een motor buffer te laden. Vervolgens wordt de inhoud van deze buffer gebruikt om de gehele sequentie snel uit te voeren. Evidentie wordt besproken dat het programmeren zich ook af kan spelen gedurende de uitvoering van eerdere elementen in de sequentie. Ten gevolge van een beperkte informatieverwerkingscapaciteit is dit zichtbaar in een vertraagde uitvoeringssnelheid tenzij de bewegingen in de sequentie sowieso relatief traag worden uitgevoerd als gevolg van biomechanische beperkingen. Als een bewegingssequentie langdurig geoefend wordt ontstaat een geïntegreerde representatie van die sequentie in het geheugen. Deze representatie wordt een 'motor chunk' genoemd. Motor chunks vereenvoudigen het programmeren van een sequentie doordat zij het mogelijk maken dat de motor buffer in één keer geladen kan worden. Individuele bewegingen en bewegingssequenties die door een motor chunk gestuurd worden, worden gekoppeld door 'action plans'. Er wordt een onderscheid gemaakt tussen hiërarchische action plans en hiërarchische sturing in de zin dat processen op verschillende niveaus van informatieverwerking tegelijkertijd actief zijn. Deze ideeën leiden uiteindelijk tot een tentatief 'Stage Model of Sequence Production'.

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CONTENTS Page

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Author: Drs. Ing. W.B. Verwey

Institute: TNO Human Factors Research Institute
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SUMMARY

This report presents a review of the literature on the rapid production of sequences of movements in general and the effects of practice on sequence production in particular. A basic notion in this chapter is that a sequence of up to five movement elements can be programmed in advance by loading information on each element into a short-term motor buffer in a step-by-step manner. Subsequently, the content of this motor buffer is used for rapidly executing the entire sequence. Evidence is discussed that the programming of individual sequence elements may also occur while earlier sequence elements are executed. Due to a limited processing capacity this shows as a reduction in sequence production rate unless the individual elements are already executed slowly because of biomechanical limitations. When a particular movement sequence is practiced extensively an integrated representation of the sequence develops. This representation is termed a motor chunk. Motor chunks facilitate sequence programming in that they allow the motor buffer to be loaded in a single processing step. Individual movements and movement sequences which are controlled by motor chunks are concatenated by action plans. A distinction is made between hierarchical action plans and hierarchical control in terms of processes at different stages that are simultaneously active. Together, these notions lead to the tentative Stage Model of Sequence Production.

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Over het uitvoeren van sequentiële bewegingen en acties. Een integrerende literatuurstudie en een aanpassing van het Generalized Motor Program

W.B. Verwey

SAMENVATTING

In dit rapport wordt een overzicht gegeven van de literatuur met betrekking tot de uitvoering van bewegingssequenties in het algemeen en de gevolgen van oefening voor bewegingssequenties in het bijzonder. Een belangrijk uitgangspunt in dit rapport is het idee dat een sequentie van maximaal vijf bewegingselementen geprogrammeerd kan worden door informatie voor elk element in een motor buffer te laden. Vervolgens wordt de inhoud van deze buffer gebruikt om de gehele sequentie snel uit te voeren. Evidentie wordt besproken dat het programmeren zich ook af kan spelen gedurende de uitvoering van eerdere elementen in de sequentie. Ten gevolge van een beperkte informatieverwerkingscapaciteit is dit zichtbaar in een vertraagde uitvoeringssnelheid tenzij de bewegingen in de sequentie sowieso relatief traag worden uitgevoerd als gevolg van biomechanische beperkingen. Als een bewegingssequentie langdurig geoefend wordt ontstaat een geïntegreerde representatie van die sequentie in het geheugen. Deze representatie wordt een 'motor chunk' genoemd. Motor chunks vereenvoudigen het programmeren van een sequentie doordat zij het mogelijk maken dat de motor buffer in één keer geladen kan worden. Individuele bewegingen en bewegingssequenties die door een motor chunk gestuurd worden, worden gekoppeld door 'action plans'. Er wordt een onderscheid gemaakt tussen hiërarchische action plans en hiërarchische sturing in de zin dat processen op verschillende niveaus van informatieverwerking tegelijkertijd actief zijn. Deze ideeën leiden uiteindelijk tot een tentatief 'Stage Model of Sequence Production'.

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1 INTRODUCTION

Behavior, and especially human behavior, has intrigued mankind for ages. Human behavior has been investigated at many levels of description. Disciplines such as neurobiology, neuroscience, and medical physics have predominantly approached the puzzle of human and animal behavior by addressing basic functions like how visual information is translated into neural signals and how neural signals are transformed into coordinated muscle contractions. Little is said about the flexibility of human beings let alone why behavior is as goal directed as it is.[2] As such this rather mechanistic, neurophysiological approach to human behavior constitutes one extreme level of behavior research. At the other extreme, psychologists, philosophers, sociologists, and anthropologists study the creative and intelligent aspects of human behavior. These researchers usually do not bother about how behavior is actually brought into play. Here, behavior research is concerned with beliefs, desires, and intentions (e.g., Fodor, 1975, 1981; Newell, 1980). This level of analysis has been termed the cognitive or symbolic-representational level of analysis (Looren de Jong and Sanders, 1990). A major assumption is that the neurophysiological and the symbolic-representational level of behavior analysis are basically independent and can be studied in isolation (Fodor, 1975). In terms of the computer metaphor, the 'software' can be studied irrespective of the underlying 'hardware'.

The present chapter is concerned with human behavior at a level between the neurophysiological and the symbolic-representational level: the functional level (Looren de Jong and Sanders, 1990). The functional analysis of behavior deals with human performance in perceptual-motor tasks and specifies *capacities* for actions. This often occurs in an artificial task environment. At the functional level of behavior, one wonders how humans perform certain tasks and what the limits of performance are. Or, in terms of the computer metaphor, what are the properties and capabilities of the 'Operating System'?

The present chapter centers on one particular aspect of functional behavior analysis, namely *skilled performance*. Skilled performance can be found in activities in which people perform the necessary movements in a practically automatic fashion, such as in typewriting, handwriting, speech, many kinds of sports, and in the control of man-made systems such as cars and computers. It seems obvious that practice improves the way we prepare, perceive, make decisions, and move in various situations. Yet, why is improvement associated with increasing flexibility? And why does skilled task performance require so little attention and effort while the human movement system has so many degrees-of-freedom to control? These issues are not only of theoretical interest. As technology develops and becomes more complicated to handle, modern systems are less constrained by technological possibilities and demand more from the human operator. So, performance of human-machine systems is more and more determined by the human user. There is a growing need to know more

[2] Some have argued that the responsible mechanisms can be studied directly at the level of the neural mechanism (e.g., Mountcastle, 1986). However, this approach has not been very fruitful yet.

about the human capacities and limitations to accurately accommodate technology to the human needs.

From the point of view that proficient execution of movement sequences is a major component of skilled task performance, the present chapter presents a review of influential models that are somehow related to the generation of sequences of movements and actions. It is recognized that there is a need for a generic model of skilled movement production and action since most available models have been developed in the context of a particular task. There are models for handwriting, typing, speech production, and musical performance. These models are necessarily limited in scope. Other models have addressed human information processing in artificial laboratory tasks which seem to have little resemblance to every day activities. It is as if these models describe behavior from distinctive beings. For example, models of motor behavior usually do not include the notion that processing capacity is limited and, hence, do not address capacity-related effects. On the other hand, information processing models have only addressed the production of very simple movements and do not relate to the proficient production of action sequences. Finally, it is not at all obvious how these models relate to contemporary notions that skilled action is controlled by several hierarchically ordered levels. The fact that all models aim at describing the same subject—human performance—justifies the present quest for a more generic model of human motor behavior.

The present chapter starts by introducing classic conceptions of movement production including Schmidt's (1975, 1976) Generalized Motor Program, Sternberg, Monsell, Knoll, and Wright's (1978) Subprogram Retrieval Model, and models on the hierarchical control of action (e.g., Gallistel, 1980; Miller, Galanter, and Pribram, 1960). In addition, notions on motor chunks (Van Galen, 1991; Verwey, 1994b, 1994c) and Sanders's (1990) recent empirical summary of the additive stage model will be treated. At the end of this chapter, this wide variety of notions will be summarized in the Stage Model of Sequence Production.

2 CLASSIC CONCEPTIONS OF MOVEMENT PRODUCTION

In the course of the century there has been a debate about the importance of information feedback in movement production. Three main streams of thinking about movement production can be distinguished which, eventually, culminated into a hybrid model. The first and oldest stream involved the idea that sequences of movements develop through chaining successive responses on basis of their feedback information (see e.g. Adams, 1984). Second, the insight emerged that feedback is not as important as originally conceived which led to open-loop models of movement claiming that movement is controlled by a central representation, that is, a motor program (Henry and Rogers, 1960; Keele, 1968). Third, a return can be observed to models stressing the importance of feedback information. Yet, these closed-loop models stressed the role of feedback in error-correction rather than in linking successive elements (Adams, 1971). In the mid-seventies, these basic notions of open- and closed-loop control were integrated into a hybrid model termed the Generalized Motor Program which was advanced by Schmidt (1975, 1976). It states that feedback is used at lower and unconscious levels of control but not, or not to any important extent, at higher and more conscious levels of control. A parallel line of thinking, dating back to the turn of the century, regards the notion that behavior is controlled hierarchically. Notions on hierarchical control appear to have developed more or less independently from those mentioned above. The fact that they turned out to be useful for explaining sequential behavior in certain types of tasks merits a brief discussion of these notions. Section 2 serves as an introduction to these basic concepts of motor control. As such it constitutes the basis of the remaining sections in this chapter.

2.1 Response chaining

The basic tenet of Pavlovian conditioning is that any source of stimulation just preceding a response will eventually come to elicit that response. Along these lines, Pavlov introduced the idea that successive response patterns could be linked together in that feedback caused by generating one response, triggers the next one. So, ultimately, an entire chain of responses can be produced without reference to the external environment which originally triggered the individual responses (Bain, 1868; Greenwald, 1970; James, 1890; for reviews see e.g., Adams, 1984; Gallistel, 1980; Lashley, 1951). Nonetheless, continuation of the sequence relies completely on triggering forthcoming responses by feedback information produced by the ongoing responses, a mechanism denoted as stimulus-response reflex chains or *response chains*. The major source of response-produced feedback would be proprioception, that is, information coming from receptors in the muscles, tendons, and joints indicating the posture of the body or of parts of the body.

Various problems with this response chaining notion have been raised. First, research on animals has shown that many skills can still be performed after surgical removal of kinesthetic feedback while other sources of feedback are also blocked (Bossom, 1974; Hinde, 1969; Keele, 1981; Keele and Summers, 1976; Taub and Berman, 1968). Neurobiologists investigating rhythmic movements in animals have indeed reported support for some central mechanism used for producing movements in the absence of feedback (Delcomyn, 1980; Grillner, 1985; Grillner and Wallen, 1985). With humans, research has shown that blocking kinesthetic sensation by a pressure cuff on the upper arm did not prevent people from tapping their fingers even with blindfolds and with auditory masking noise (Glencross, 1977; Laszlo, 1966, 1967). Moreover, people who had their dorsal roots cut as a result of injuries or operations to control pain were still able to perform various movements in the absence of feedback (Lashley, 1917).

A second problem for response chaining was that feedback processing was assumed to be too slow to account for the production of very rapid sequences (Glencross, 1977; Lashley, 1951). Many skills, such as piano playing (Lashley, 1951), typing (Shaffer, 1978), and speech production (Lenneberg, 1967), involve successive movements at intervals of less than 100 ms. Still, the time to react to kinesthetic stimulation appears to be 100 ms or more (Carlton, 1981; Glencross, 1977; Keele, 1968; Lashley, 1951; Schmidt, 1975).

Third, S-R chaining has problems to explain why a skill does not break down when different muscle groups are used for the same skill even though this has the effect that feedback changes drastically (Keele and Summers, 1976).

A fourth difficulty for chaining theory concerned the discovery of anticipatory effects involving overt behavior changes depending on forthcoming movements that are about to be carried out. Such effects can be observed in speech (i.e. coarticulation; Fowler, 1985; Kent and Minifie, 1977; Moll and Daniloff, 1971; Perkell, 1980; Perkell and Klatt, 1986), in effects of later on earlier keystrokes in typing and pianoplaying (Shaffer, 1976), in kinematic adjustments of the early phases of a manual reaching movement depending on how this movement will end (Hinton, 1984), and, of special interest to the current chapter, in the effect of the number of elements in a movement sequence on initiation time (Henry and Rogers, 1960; Sternberg et al., 1978). Such effects are difficult to explain by response chaining.

Finally, chaining assumes that each particular response chain should have its own distinct representation in memory. This was considered unlikely in view of the enormous number of movement representation to be stored (Adams, 1990; but see e.g., Logan, 1988). Together, these problems with response chaining as a necessary component of producing movement sequences led to the conclusion that "response chaining (...) is dead" (Adams, 1984, p.20). Only in lower species, which appear to have just a limited set of rigid movement patterns, chaining is still considered to be an important mechanism in governing sequential movements (e.g., Dean and Cruse, 1986).

2.2 Open-loop control

The arguments against response chaining led to the general view of a central program consisting of a sequence of commands that is "structured before the movement begins and allows the entire sequence to be carried out uninfluenced by peripheral feedback" (Keele, 1968, p.387). Precursors of this central program view date back as far as Von Helmholtz (1867), James (1890), Woodworth (1899), and Lashley (1917). The apparent insensitivity to the absence of feedback information led to the term *open-loop control*. The essential characteristic of open-loop motor programs concerns the possibility of controlling movements by a set of pre-planned centrally controlled efferent commands that are executed essentially without modification by afferent signals. It was formalized into a testable theory by Henry and Rogers (1960) and extended by Keele's (1968) formalization of the motor program as the vehicle for open-loop control. Keele's (1968) definition of the motor program entailed a pre-structured set of centrally stored specific efferent commands which, when executed, allow a desired movement pattern to be produced without reliance upon ongoing sensory information.

Open-loop control was considered consistent with evidence of movement corrections with latencies less than common reaction times (Pew, 1966), deafferentation studies (e.g., Cross and McCloskey, 1973; Laszlo and Bairstow, 1971; Smith, Roberts, and Atkins, 1972; Taub, 1976), the 'running off' of pre-planned command sequences when the movement is unexpectedly blocked (Wadman, Denier van der Gon, Geuze, and Mol, 1979), and dual-task studies demonstrating elevated attention demand prior to movement initiation (e.g., Posner and Keele, 1969). The existence of anticipatory effects, mentioned above, also supports the notion of a central motor program.

The memory drum model

One prominent open-loop model is Henry and Rogers's (1960) memory drum model which explicitly addresses sequences of movements. Its general impact and the fact that it describes how movement sequences are prepared—a central issue in this chapter—justifies a brief discussion. It started with the observation that simple reaction time (i.e. involving no choice element) for initiating a movement increased as a function of movement complexity. This had been earlier observed by Freeman (1907) but Henry and Rogers (1960) were the first to propose a more detailed model of the phenomenon. In a simple reaction time (RT) paradigm they used three levels of response complexity. Response A was a simple finger lift, response B was a ball-snatch task which required the subject to reach forward and upward to grasp a tennis ball suspended from a micro switch. Response C, although initiated from the same position as the A and B responses, included three components involving two changes in direction and successive contact with three targets.

The results indicated that simple RT to response B was 20 percent longer than to response A, while simple RT to response C was 7 percent longer than to response B. Although the empirical basis of this theory was the simple RT task environment, Henry (1980) extended his predictions to include the choice RT environment as well, albeit without further empirical support. These results were explained by a theory which relies heavily on the use of motor memory in voluntary acts involving motor coordination. Innate and learned neuromotor coordination patterns are conceived of as stored, becoming accessible for use in controlling the act by a memory drum mechanism that requires increasing time for its operation as the motor act becomes more complex.

This finding inspired a number of researchers to establish the conditions under which this complexity effect emerges. Although an operational definition of the term 'complex' was not explicitly stated in the 1960 article, Henry (1980) indicated that the intention had been to use the dictionary definition: "That is complex which is made up of a number of connected parts" (p.164). Thus, a more complex response would have a larger number of connected parts than a less complex response. After publication of the Henry and Rogers paper, the complexity effect was replicated many times in various types of tasks. It turned out that the increase in simple RT between Henry and Rogers's (1960) finger lift and their ball-grasp response can be attributed to the different inertia of the finger and the arm, that is the motor time, and not to the different number of prepared elements (Anson, 1982). However, the shorter time required to initiate Henry and Rogers's (1960) ball-grasp response as compared to their three-segment movement sequence appeared to have, indeed, been caused by the number of prepared sequence elements (Christina, Fischman, Vercruyssen, and Anson, 1982).

Problems with open-loop models

Open-loop models of sequence production had their problems as well. Keele's (1968) view that specific neural commands are stored in central motor programs seemed implausible because any slight change in sequence or effector would require a new representation. Also, the origin of the program was unclear (MacNeilage, 1970; Schmidt, 1982b). It appeared more likely that motor programs involve muscle-aspecific motor representations. An indication for this view concerned the observation that a person can write with various limbs while retaining ones distinctive handwriting style (Lashley, 1942; Katz, 1951; Merton, 1972; Thomassen and Teulings, 1983). Furthermore, Klapp (1977b) found indications that muscle selection need not be completed before programming begins and that preprogramming response duration is possible without knowing the limb with which the response is carried out. This is not expected when programming would involve muscle-specific commands.

In addition, the notion that feedback is not used was refuted by indications for feedback utilization in simple aiming movements (Abrams and Pratt, 1993; Cruse, Dean, Heuer, and Schmidt, 1990; Schmidt, 1975). The movements of deafferented humans and animals, which would corroborate the use of a motor program, appeared never quite 'normal'. The movements were clumsy and exhibited a reduction in fine control and precise movement (Bossom, 1974; Rothwell, Traub, Day et al., 1982). Distortion of proprioceptive input did have gross effects in animals and humans (Bässler, 1977; Dean and Wendler, 1983; Goodwin, McCloskey, and Matthews, 1972; Nielsen, 1963; MacKay, 1986).

Thus, the view that movements are unaffected by peripheral feedback was clearly incorrect. Feedback appeared essential for ensuring that performance is progressing as planned and that minor corrections can be made, as well as for updating or changing programs (Cruse et al., 1990; Summers, 1989).

2.3 Closed-loop control

As a reaction to the shortcomings of the open-loop tradition of motor learning, Adams (1967, 1971) proposed a *closed-loop* theory of motor control. Central to the closed-loop theory was the assertion that motor learning entails acquisition of the capability for detecting and correcting errors, as well as the growth of this capability. Even though the theory was primarily developed for generation of simple aiming movements and not for the production of movement sequences, it is essential to briefly discuss the theory as the concept of closed-loop control will emerge several times elsewhere in this chapter.

The closed-loop theory proposed that there are two states of motor memory, termed the memory trace and the perceptual trace. The memory trace is responsible for movement *initiation*, choosing its initial direction, and determining the earliest portions of the movement. Its strength develops as a function of knowledge of results and practice. The perceptual trace, on the other hand, *guides* the limb to the correct location. It is a representation of the feedback that the correct response should generate. During the movement, the subject compares the incoming feedback with the perceptual trace so as to determine whether the limb is approaching the correct final position: If it is, movement is stopped. If it is not, adjustments are made and the comparison is made again until the limb is in the correct position. The origin of the theory was servotheory in engineering (Adams, 1987). It is noteworthy that the comparison of feedback stimuli with a standard for error detection and correction differs essentially from the way in which feedback is used in response chaining.

By the time closed-loop theory had been developed, the earlier mentioned problem that feedback processing would be too slow for allowing 'normal' movement speed turned out to be less of a problem than originally assumed. Evidence had accumulated that earlier work had overestimated feedback processing times. For example rapid corrections (30-80 ms) of limb movements to unanticipated perturbations had been observed in animals (Evarts, 1973; Evarts and Tanji, 1974) and humans (Marsden, Merton, and Morton, 1972; Carlton, 1983). Even rapid saccadic eye movements, traditionally considered to be under open-loop control (e.g., Festinger and Canon, 1965), had been shown to be modulated by sensory feedback (Fuchs and Kornhuber, 1969; Morasso, Bizzi, and Dichgans, 1973). This left room for the possibility that even with rapid movements closed-loop control is used.

It became clear that feedback information can be utilized in various ways for the correction of ongoing movements. The type of movement appeared to play a dominant role here. Adams's theory dealt with the generation of slow linear positioning movements. However, in complex and rapid movements feedback seemed to be used in a different manner (Kelso and Stelmach, 1976). Moreover, the observation that movement is possible in the complete absence of feedback information remained troublesome (e.g., Lashley, 1917; Taub, 1976). Even with simple aiming movements, perceiving movement as being either open- or closed-loop was too simple (Abrams and Pratt, 1993; Cruse et al., 1990; Woodworth, 1899). Hence, Sternberg et al. (1978) and Klapp (1977a) argued that the programming concept does not necessarily exclude the possibility of using feedback: Even if a sequence is entirely preprogrammed, feedback might still be used at lower levels of processing with the aim of comparing the actual feedback with some 'response image' (e.g., Adams, 1984; Greenwald, 1970; Schmidt, 1975). So, there was a need for a theory acknowledging the merits of both open- and closed loop control. In the mid-seventies, Pew (1974) and Keele and Summers (1976) proposed their hybrid notions of closed-loop reflex states within the motor program. A more detailed hybrid theory was provided at the same time in Schmidt's (1976) Generalized Motor Program and in his parallel development of Schema theory (Schmidt, 1975).

2.4 The Generalized Motor Program: a hybrid model

Schmidt (1975) defined the Generalized Motor Program as a central structure capable of defining a movement pattern while incorporating possibilities for correction of errors in execution on the basis of feedback. The concept of the Generalized Motor Program hinges on two basic characteristics: it combines closed- and open-loop control and its generality prevents the need to store separate programs for each movement variation. Only when parameters have been specified, the 'Generalized Motor Program' turns into a 'motor program' controlling the intended movement. Representations in long- and short-term memory are assumed to be muscle-aspecific (Greenwald, 1970; Schmidt, 1975; Turvey, 1977). Muscle-specific commands are not specified until movements are being executed. This is indicated by, for example, the finding that muscle selection need not be completed before programming begins (Klapp, 1977b).

Two levels of control

Schmidt (1976) distinguished two levels at which movement is controlled. At the highest level are *voluntary decisions* based on a comparison between feedback from the actual movement and the expected feedback from the intended movement. This system is used to detect errors in response selection and gross errors in performance (Schmidt, 1976). Such errors arise when something in the environment informs the individual that the selected movement was inappropriate. At the same time, there is a lower level of control involving *spinal-level feedback mechanisms*. Fast-acting muscle spindle initiated feedback loops act to smooth out a movement by correcting small unexpected disturbances to the intended movement (Eccles, 1973; Evarts, 1975, 1981; see also Keele and Summers, 1976; Schmidt, 1982a). This lower level of control involves a very rapid (30-80 ms), subconscious and automatic process ensuring that the original program is executed as planned. These fast feedback processes operate to correct minor perturbations of the ongoing movement (i.e., execution errors), without changing the basic movement pattern that was initiated to achieve a particular goal (e.g., Abbs, Gracco, and Cole, 1984). Large errors in movements that may result from the selection of an inappropriate motor program or an unexpected event in the environment (i.e., selection errors), however, cannot be corrected until the program has run its course for at least one RT (say 200 ms). In that case central decision-making processes are required to select and specify a new motor program[3]. Hence, the open-loop motor program has an embedded closed-loop set of processes that serves to keep the limbs 'on track'.

Schmidt assumed that the reliance on feedback would diminish with practice: "Because of the lags in processing feedback, the subjects become less and less dependent upon feedback for performance, and the emphasis shifts from feedback-controlled, jerky performances to the smooth execution of almost completely open-loop movements" (Schmidt, 1975, p.233; for similar notions see Keele, 1968; Schmidt, 1987). If control is closed-loop this would be indicated by a radical departure from Schmidt's law (Schmidt, Zelaznik, Hawkins et al., 1979). This law assumes a direct relation between accuracy on the one hand, and movement duration and distance on the other hand and appears to hold for rapid movements only. However, recent research suggests that practice has a more subtle effect than a diminishing reliance on feedback. Instead, motor learning appears to involve an increasing reliance on feedback sources that are available (Adams, Gopher, and Lintern, 1977; Elliot and Jaeger, 1988; Proteau, Marteniuk, Girouard, and Dugas, 1987; Proteau, Marteniuk, and Lévesque, 1992). For instance, some tasks showed that fast low-level control involves visual feedback rather than proprioceptive feedback (Bootsma and Van Wieringen, 1990; Lee, Young, Reddish, Lough, and Clayton, 1983; Proteau et al., 1987). It seems that practice involves the development of a highly efficient low-level control mechanism which relies exclusively on the feedback information that is available rather then changing from closed- to open-loop control as originally assumed (Schmidt, 1975, 1976).

Parameter specification

Not each movement segment is assumed to have its own motor program because memory would not be able to store so many different programs. Therefore, Schmidt (1976, 1985) conceived of *invariant characteristics* and *parameters*. Invariant characteristics are constant aspects of a motor program irrespective of how the task is actually carried out. Hypothesized invariant characteristics are relative timing, relative force, sequencing of events, and the spatial configuration of the movement (Bernstein, 1967; Gentner, 1987; Heuer, 1988; Magill and Hall, 1990; Schmidt, 1988; Summers, 1989). Because the motor-program is abstract, parameters must be supplied to the program to govern a particular act. Variables such as overall force, overall duration, timing, direction, limb, and size

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[3] Later, Schmidt (1987) distinguished four types of responses to perturbations: the mono-synaptic stretch reflex (30-50 ms after perturbation), the transcortical stretch reflex (50-80 ms), triggered reactions (80-120 ms), and the voluntary response (120-160 ms). The existence of various levels of control, suggested by these responses, is in line with hierarchical conceptions of motor control but their role in movement control has yet to be established.

are thought to serve as parameters (see reviews by Adams, 1987; Marteniuk and MacKenzie, 1980; Schmidt, 1982a; Summers, 1989; Zelaznik and Franz, 1990)[4].

Schmidt (1975) argued that people can select parameters on the basis of rules (called *schemata*) between all past environmental outcomes and the values of the parameters used to produce those outcomes. This schema concept originated from a line of empirical evidence for central representations beginning with Lashley's (1917) idea of central motor programs and Bartlett's (1932) formulation of the schema notion. Four types of information are considered: (1) the initial conditions of the muscular system and the environment, (2) the specifications for the motor program, (3) the sensory consequences of the response, and (4) the outcome of the movement. These sources of information are stored together in the schema after a movement has been produced. The primary function of this schema is to specify parameter values for the Generalized Motor Program appropriate for performing the task at hand. When a number of movements has been carried out, the information about the relationship among these four sources of information is gradually abstracted. Given certain environmental conditions, the person can select optimal parameter values on the basis of the schema so as to reach the goal. Given that the schema is an abstraction of the information stored, it is possible to interpolate across parameters and, hence, to produce movements which have never been produced before. Rosenbaum (1985) made the interesting suggestion that parameters, such as the location to reach for, may be used for retrieving the appropriate motor program from memory. This might mean that parameters may be selected prior to the appropriate Generalized Motor Program.

Contextual interference

The contextual interference effect is a learning phenomenon demonstrating that interference during practice is detrimental to actual performance but beneficial to long-term motor learning. The typical way of introducing interference is by randomly varying some aspects of the task. The first report of an experiment on contextual interference as it relates to learning motor skills was published by Shea and Morgan (1979). In this experiment, subjects learned to move their arm as quickly as possible through three different three-segment patterns (picking up a tennis ball, knocking over a series of three barriers, and returning the ball to a final location) differing in the trajectories to be followed. Contextual interference was incorporated into the practice schedule by using a blocked practice schedule (low contextual interference) and a random practice schedule (high contextual interference). During the practice trials the blocked group performed better than the random schedule group. However, the random group performed better in a retention test 10 min after practice. After 10 days the random practice group performed better on a new three-segment movement pattern and a five-segment

[4] As will be discussed in Section 3, movements exceeding about 200 ms may be programmed during the actual movement. In large-scale movements this allows extent and duration programming to be postponed until after movement initiation (e.g., Heuer, 1986; Ivry, 1986).

movement pattern than the blocked group. It was concluded that a practice schedule with high levels of contextual interference leads to better retention of the practiced variations and increases adaptability to novel situations.

In a review of the contextual interference effect Magill and Hall (1990) delineated the conditions under which contextual interference is found. They proposed a two-stage hypothesis which relates to motor program theory. First, contextual interference effects are due to practice schedule manipulations in which skill variations require *different* motor programs. Second, if the skill variations involve parameter modifications of the *same* motor program, the contextual interference effect will either not be found, or a mixed schedule of blocked and random practice will lead to better learning than either a random only or a blocked only practice schedule. The underlying cause for the contextual interference effect would be the effort needed to construct or retrieve another motor program as opposed to the ease with which an already activated motor program can be used in which merely parameters are changed. Reconstruction requires more effort and, hence, better retention (Craik and Lockheart, 1972; Magill and Hall, 1990; Shea and Zimny, 1983, 1988). As such, the contextual interference effect underlines the notion of an invariant Generalized Motor Program which needs parametrization for actual movement generation.

A recent test of the schema theory

Influenced by the recent resurgence of the notion that *instances* of events are separately stored (e.g., Estes, 1986; Logan, 1988), rather than in the form of abstracted schemata, Chamberlin and Magill (1992a) suggested that the information related to each individual occurrence of a response may be stored separately in memory and that there is no such thing as a *Generalized* Motor Program. They argued that evidence for schema theory is limited to only three studies in which, in fact, movement patterns were passively experienced rather than actively practiced (Lee, 1985; Solso, Amant, Kuraishy, and Mearns, 1986; Solso and Raynis, 1979). To test the validity of schema theory, Chamberlin and Magill (1992b) had subjects first practice a task involving three sequential movement segments. The spatial configuration of the entire movement pattern and the relative segment sizes were the same in all conditions but there were three different absolute movement sizes. Next, the researchers assessed performance when the absolute size of the segments was new to the subjects while the spatial pattern was as practiced before. In contrast to their expectation, Chamberlin and Magill (1992b) found that timing performance for the new segment sizes was not affected by the degree of similarity between the practice and transfer exemplars, and that there was no advantage of a previously produced exemplar over a new one. These results were taken as support for the schema abstraction model of memory representations for motor skills, and as arguing against the storage of individual instances.

One may wonder, however, whether this study is a valid test of schema theory as there are three major flaws associated with this study.

1 Chamberlin and Magill (1992b) did not vary the spatial lay-out of their movement task, which would have involved a different motor program, but, rather the distance, which is more likely to be a single parameter. In line with Magill and Hall (1990), parameter specification is expected to adapt easily to a new task.
2 There was ample time for advance preparation, which has the effect that a next movement can be easily programmed in advance of sequence initiation. Recent research shows that effects of practice may be concealed under such conditions (Verwey, 1994c).
3 The subject's goal was to complete the movement in about 1200 ms allowing an average 400 ms for each segment. As will be discussed in Section 3 aiming movements of more than 200 ms may include on-line programming of the next segment. It may well be that the motor pattern used by Chamberlin and Magill (1992b) involved a sequence of three separate aiming movements rather than that the pattern was controlled by a single schema or motor program.

Together, these notions cast serious doubts on whether this study is an appropriate test of the Generalized Motor Program.

Shortcomings of the Generalized Motor Program

In fact, the discussion of the Chamberlin and Magill (1992b) study points to a general weakness of the motor program concept: There have been no explicit attempts to investigate how using different motor programs can be distinguished from using a single motor program. For instance, what are the boundaries of a motor program in handwriting or in sending morse code: the individual segment, the letter, or the word? In fact, it is not even clear what 'a movement' is. The notion that at a higher level motor programs involve open-loop control suggests that even slow movements, once initiated, are left to themselves. This contrasts with Adams's views that slow aiming movements are controlled closed-loop. This issue will be dealt with more thoroughly later in this chapter (Section 3.4).

Another weakness of the Generalized Motor Program concerns its lack of precision as to which are true parameters and which are merely derived from other, more basic parameters (Kerr, 1978; Marteniuk and MacKenzie, 1980). Furthermore, the distinction between invariant program characteristics and parameter variables remains unclear (Gentner, 1987, 1988; Heuer, 1988; Heuer and Schmidt, 1988; Summers, 1989; Zelaznik and Franz, 1990). It is not even obvious whether the same invariances occur across different tasks. There may be fundamental differences in the invariances observed when the same movement is performed in a closed (i.e., a stable) or an open (changing) environment (Poulton, 1957; Zelaznik, 1986), at different stages of learning (Marteniuk and Romanov, 1983; Moore and Marteniuk, 1986; Neumann, 1984; Zelaznik and Franz, 1990), or across different age groups (Burton, 1986). For instance, relative timing of the motor program was found to change at different speeds and in some circumstances switching to a new relative timing is quite easy (Burgess-

Limerick, Neal, and Abernety, 1992; Carnahan and Lee, 1989; Gentner, 1982; Heuer and Schmidt, 1988; Langley and Zelaznik, 1984; Vogt, 1988; Vogt, Stadler, and Kruse, 1988; Wann and Nimmo-Smith, 1990; Zelaznik, Schmidt, and Gielen, 1986). Advocates of the relative timing hypothesis, however, have ascribed deviations from a proportional duration model to variations in delay between central commands and resulting movements (Heuer, 1988). This might be due to limited processing capacity (Section 3; Verwey, 1993a, 1994b, 1994c), peripheral delays (Gentner, 1987), or to the possibility that in some tasks timing is triggered by external events (Cordo, Schieppati, Bevan, Carlton, and Carlton, 1993; Cruse et al., 1990; Lee et al., 1983).

Finally, as pointed out above, practice appears to have more subtle effects than simply abandoning closed-loop control. The rigid distinction between open- and closed-loop certainly underestimates the versatility of the (human) motor control system. In this sense one could better speak about the 'sensorimotor system' rather than about the 'motor system'.

2.5 Hierarchical control

In contrast to response chaining, which assumes that action sequences emerge from associations between succeeding elements in a sequence, there is the classic notion that fluently performed movement sequences are controlled *hierarchically* (e.g., Book, 1908; Miller et al., 1960; Selfridge, 1956). The concept of hierarchical control refers to the idea that fluently performed movement sequences are controlled at a number of levels—each unit at a higher level controlling more than one unit at a lower level. Whereas the higher levels deal with the longer term consequences, lower levels consider short-term details of actions and movements. Hierarchical control is often depicted in tree-like branching structures, consisting of a set of elements at different levels. Level of control has been associated with modifiability: "If the 'vital' centers of the lowest levels were not strongly organized at birth, life would not be possible; if the centers on the highest levels ('mental centers') were not little organized and therefore very modifiable we could only with difficulty and imperfectly adjust ourselves to the circumstances and should make few acquirements" (Taylor, 1932, p.437). So, hierarchical control would combine autonomous functions with the possibility of learning new operations.

Despite the intuitive appeal of hierarchical control, the functional analysis of behavior has provided evidence for only a limited number of control levels. Indications for hierarchical control at many levels seems to mainly come from analyses at the neurophysiological and the symbolic-representational levels of analysis (see Section 1).

A hierarchical model of behavior control largely stemming from *neurophysiological* analyses of behavior was proposed by Gallistel (1980). Despite its relatively recent publication, the theory has its roots in many classic ideas from various areas of research including behavioral neurobiology, psychology, physiology, ethology, and to some extent, philosophy. The theory describes a structural view of hierarchical organization of action and the way it is implemented in the central nervous system. Following Weiss (1941), six levels of action are outlined which range from the organism as a whole where all motor acts gain biological significance to the motor unit level where a motor neuron is attached to muscle fibers. These levels would involve processors operating independently. In view of the fact that the theory is largely based on neurophysiological notions it is not surprising that this theory is not able to make predictions with respect to the functional level of behavior.

Other notions on hierarchical control originated from the *symbolic-representational* level of analysis. An early model of this kind was forwarded by Miller et al. (1960). These researchers argued that the elements of behavior are feedback loops in which a test is performed whether an intended end situation is fulfilled. If not, an operation is performed and the situation is tested again. So, each of these feedback loops are Test-Operate-Test-Exit or TOTE units. Since the operational components of TOTE units may themselves be TOTE units a hierarchical structure develops which governs behavior. Miller et al. (1960) illustrate hierarchical control by the hammering of a nail. This would involve a higher level TOTE unit which controls nail hammering by way of two lower level TOTE units: one controlling hammer lifting and one controlling nail striking. These two units control behavior until the test at the higher order unit reveals that the head of the nail is flush with the surface of the work, at which point control can be transferred 'elsewhere'. Even though this approach can be considered a landmark in a period dominated by behaviorism, it has little to offer for the functional analysis of behavior as it is not capable of making detailed predictions of sequence performance either.

With respect to the *functional* level of analysis there seems to be also evidence for hierarchical control. A classic study which has frequently been referred to as showing evidence for hierarchical control of action is Bryan and Harter's (1899) study on morse code operators. They claimed that first letter and later word 'habits' are learned. As pointed out by Sternberg, Knoll, and Turock (1990), this claim concerned receiving rather than sending morse code. Other evidence does not exclude a perceptual locus of the hierarchical structure in receiving morse code (Leonard and Newman, 1964). Moreover, the often-cited conclusions of Book (1908) about multiple-stroke units in typewriting depend exclusively on introspection.

A line of research which was argued to corroborate the notion that performance is controlled hierarchically was initiated by Restle (1970) and had its largest impact in the seventies. It involved investigating the possibility that a relatively long complex keypressing sequence is controlled by a set of hierarchically ordered rules (e.g., Greeno and Simon, 1974; Jones, 1981; Povel and Collard, 1982; Restle and Brown, 1970). For example, Restle and Brown (1970) showed that subjects could learn sequences with lengths up to 32 elements more easily if hierarchical rules could be applied in the production of the sequences then when the sequences could not be described in terms of hierarchical rules. This is a clear example of control in the sense that some hierarchically structured plan is being traversed during action control. This contrasts with the notion that actions are controlled by hierarchically ordered processors as suggested by Gallistel (1980).

As will be argued in Section 5, most of the performance models have the problem that they do not specify the properties of the various levels and make no strong assumptions on how control is related to the information processing system. Furthermore, while some models assume that hierarchical models of control involve various information processors at each level, others assume that control of a single processor is transferred among levels within a hierarchical representation (Broadbent, 1977). Section 5 will discuss more recent research and will conclude that both types of hierarchical control—traversing a representation and simultaneously active processors at different levels—may play a role in highly practiced tasks.

In short, the concept of hierarchical control of action dates back to the turn of the century and is still used by many contemporary researchers. Evidence for the hierarchical control of actions appears to be derived especially from the neurophysiological and the symbolic-representational research domains. There is some evidence for hierarchical control at the functional level of behavior but there is a lack of conceptual clarity amongst the various models of hierarchical control.

2.6 Conclusions

This section serves the aim of introducing the basic concepts used in contemporary models of movement execution. (1) The contribution of response chaining is that it shows that links can develop between individual representations or codes in memory but its assumption that external feedback information would be responsible for the connection proved untenable. (2) Open-loop models stress the possibility that central programs guide movements while (3) closed-loop models emphasize the use of feedback for guiding the ongoing movement. (4) Both notions are included in the Generalized Motor Program which assumes that the use of feedback is not all or none but depends on the level of analysis. Thus, execution is closed-loop and minor perturbations are dealt with without the need for conscious awareness. At a central level, open-loop control is used suggesting that feedback need reach a conscious level. Some flaws of the concept are pointed out. Finally, (5) the notion of hierarchical control has been introduced. It is argued that evidence for hierarchical control mainly relies on research at the neurophysiological and the symbolic-representational level. There appears to be a considerable conceptual disagreement among the various performance models of hierarchical control. Section 5 will deal with this in more detail. First, Section 3 will focus on the issue how sequences of movements are programmed and executed and how one can determine whether movements are actually partitioned into separate segments.

3 PRODUCING SHORT MOVEMENT SEQUENCES

As indicated in the Introduction, a main aim of the present chapter is to discuss how movement sequences are produced. With respect to the distinction between individual movements and movement sequences, Cruse et al. (1990) distinguished between 'analog' and 'digital' descriptions of motor programs. Analog descriptions of motor programs emphasize the continuous use of control commands to the muscles, like in relatively simple rhythmic and aiming movements where feedback information can be used instantaneously. In the remainder of the present chapter these movements will be referred to as *single movements* or, with respect to movement sequences, as *sequence elements*. Digital motor program descriptions are characterized by the presentation of a *sequence* of commands to be executed at discrete intervals. This type of control primarily concerns sequences of movements (cf. Miller et al., 1960, p.91).

As pointed out in Section 2, the distinction between single movements and movement sequences is not always obvious. This is illustrated by the comparison of two definitions of the motor program. Schmidt (1975) proposed the motor program to deal with linear positioning movements and with rapid ballistic movements with short movement times whereas Van Galen and Teulings (1983) defined the motor program as "the central representation of an ordered sequence of movement elements" (p.10). This section will discuss hypothesized mechanisms for sequence production—i.e. digital motor programs—and will concentrate on the question how and when they play a predominant role. These mechanisms include programming a series of individual movements prior to the first movement, and programming one or more elements after execution of the first element has been initiated. Eventually, a taxonomy of movements will be proposed indicating the relation between analog and digital movements.

3.1 The effects of sequence length

It has been postulated that movement sequences are initially carried out under conscious control in an awkward poorly coordinated step-by-step manner. Once the task has been learned the sequence is carried out more skillfully under the unconscious control of a program so that separate elements need not to be selected one-by-one (e.g., Chamberlin and Magill, 1989; Henry and Rogers, 1960; Lashley, 1951; Pew, 1974; Rosenbaum, Hindorff, and Munro, 1986; Van Donkelaar and Franks, 1991a). The most notable phenomenon observed in the production of short movement sequences (i.e. up to four or six elements) concerns the observation that the time required to initiate a response increases with its complexity. In their proposal of the memory drum model, Henry and

Rogers (1960) called this the *complexity effect*. The complexity effect was assumed to be caused by the longer time required "for the more complicated pattern of circulation of neural impulses through the coordination centers before they are channeled to the motor nerves and start the actual movement" (Henry, 1980, p.164).

RT was shown to increase as a function of many manipulations including the number of movements required, the physical length of movements, and the duration of movements (for reviews see Kerr, 1978; Klapp, 1977a; Marteniuk and MacKenzie, 1980). Some studies also found an effect of sequence length on the time taken by individual elements in the sequence (Harrington and Haaland, 1987; Sternberg et al., 1978; Sternberg, Knoll, Monsell, and Wright, 1988; Verwey, 1994c). This section will primarily focus on the integrated production of movement sequences and, hence, the effect of number of movement elements in a sequence.

General explanation of the complexity effect

The complexity effect in movement sequences is commonly explained by the notion that individual response elements, or subprograms, are loaded into a short-term motor buffer prior to movement initiation. This process is referred to as *programming*.[5] Following the early formulation of the sequence preparation model by Henry and Rogers (1960, see Section 2) many versions of sequence preparation and control models have been formulated. The idea of advance loading a motor buffer can essentially be found in models of tasks as diverse as typing (Sternberg et al., 1978, 1990), writing words of different lengths (Hulstijn and Van Galen, 1983; Thomassen and Van Galen, 1992; Van Galen, 1991), making sequential hand postures (Harrington and Haaland, 1987), pronouncing word sequences (Eriksen, Pollack, and Montague, 1970; Klapp, 1971; Klapp, Anderson, and Berrian, 1973; Sternberg et al., 1978, 1988, 1990), and executing sequences of gross arm movements (Fischman and Lim, 1991; Norrie, 1967; Ulrich, Giray, and Schäffer, 1990). Even the requirement to rapidly deactivate force after activation in an isometric contraction is assumed to cause a complexity effect in that activation and deactivation are programmed in advance (Ivry, 1986; cf. Hulstijn and Van Galen, 1988; MacKay, 1983; Meulenbroek and Van Galen, 1988).

Given that the complexity effect is such an ubiquitous phenomenon, reasoning has often been reversed; the occurrence of a complexity effect is usually considered evidence for the integrated production of a sequence. As will be shown below in the discussion of simple vs. choice RT such an atheoretical reversal of reasoning may obscure that different mechanisms are operating.

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[5] Note the conceptual difference between programming in the sense of specifying kinematic parameters of individual sequence elements, and programming in the sense of loading sequence elements in a motor buffer which is related to the order in which the elements are produced.

The Subprogram Retrieval Model

The most influential model of sequence production is probably Sternberg et al.'s (1978) Subprogram Retrieval Model (see also Sternberg, Wright, Knoll, and Monsell, 1980; Sternberg et al., 1988). This does not surprise since it provides the most detailed account of sequence production and has served as a basis for most recent models. The subprogram-retrieval model was developed for the rapid production of typing and word pronunciation sequences in simple tasks and does not account for choice tasks. Programming the full sequence would occur prior to onset of the go-signal to initiate the sequence and would therefore not affect initiation time. The model accounts for the effects of sequence length found in initiation and in total execution time. In view of the observation that these effects are related, the execution of an element is assumed to be preceded by a set of three processes: (1) The *retrieval* process searches and retrieves the subprogram for the appropriate element by a sequential self-terminating search process, (2) the constituents of the element are *unpacked*, and (3) the *commands* for element execution are issued. This distinction of processes makes the Subprogram Retrieval Model an information processing account of sequence execution.

Retrieval can be distinguished from both other processes because it is indicated by the effect of sequence length on initiation and on interelement times, but it is not affected by the type of movement constituting a sequence element. In contrast, unpacking is affected by the type of element and not by the sequence length. So, the fact that sequence length and type of element have additive effects on the time to produce each sequence element shows that retrieval and unpacking are independent processes. The reason for distinguishing a separate stage for issuing commands comes from the observation that the effect of element type is considerably larger on interelement times than on initiation time. However, the empirical indications for this command stage appeared not very robust and the stage disappeared in a later version of the model (Sternberg et al., 1988).

Sternberg et al. (1978) noticed that the first element in a simple RT task shows a complexity effect even though the retrieval processes of the first element might just as well precede the go-signal. This was attributed to a difficulty in maintaining the result of the retrieval and unpacking processes for some time (Kornhuber, 1974; Eccles, 1969): these processes must follow onset of the go-signal. Recent work has supported this assumption (Canic and Franks, 1989).

Retrieval was assumed to involve search in a non-shrinking buffer. That is, once an element has been executed, it is not removed from the buffer and remains to affect search times for later elements. This notion is based on the observation of a quadratic sequence length effect on the duration of the entire sequence. It cannot be explained by a higher memory load associated with a longer sequence (Monsell, 1986; Sternberg et al., 1978; Sternberg et al., 1988). The time required for unpacking is determined by the size of each element. In speech, the element of programming is the stress group (a segment of speech associated with one primary stress) and the element size is affected by the number of syllables in a stress group. In typing the element of programming is the single key stroke (cf. Salthouse, 1984). With respect to the earlier distinction between analog and digital motor programs (Cruse et al., 1990), it should be noted that Sternberg et al. (1978, 1990) assumed that the control of single element execution and the control of the concatenation of individual elements are independent. This was termed the *element-invariance* assumption which suggests that separate processing stages are responsible for both tasks. This notion is elaborated in Sections 6 and 7.

Although the Subprogram Retrieval Model does a good job in explaining the main core of the data, some aspects are not accounted for (Sternberg et al., 1978): (1) the relatively small effect of sequence length on initiation time in one-handed typing, (2) the smaller complexity effect with longer sequences, and (3) the small but robust effects of sequential position on individual elements. In addition, Sternberg et al. (1988) mentioned that (4) variation of effects of sequence length and element size across experiments is very large, (5) there is still a sequence length effect on the duration of the final speech element even though no further element has to be selected, and (6) some unstressed words (*and*, *minus*) can be interpolated between words without an increase in the number of elements whereas interpolation of another (*by*) does affect this number. In the course of this section some of these anomalies will be explained in terms of biomechanical constraints on execution rate, on-line programming, and concurrent processing during execution.

3.2 **Programming in sequence production: simple or choice RT?**

The Subprogram Retrieval Model gives an account of sequence production in simple reactions and assumes that programming precedes stimulus onset. The notion that mechanisms of movement production should be examined in simple RT paradigms has not been undisputed however. One research group, led by Stuart T. Klapp, has contended that programming in choice RT would take place following the choice signal whereas in simple RT programming would precede the go-signal. The deduction was that motor programming can only be investigated in choice RT paradigms. This section will briefly outline this view and the reactions from other researchers so as to arrive at conclusions which may have an impact on contemporary research.

In arguing why simple RT motor tasks would be irrelevant to the study of motor programming, Klapp and his colleagues (e.g., Klapp, 1976, 1977a; Klapp, Wyatt, and Lingo, 1974; Klapp, Abbott, Coffman et al., 1979) point to observations that only choice RT—and not simple RT—depends on the complexity of the response. According to Klapp (1977a, 1981) this had been observed (1) when words vary in number of syllables (Eriksen et al., 1970; Klapp et al., 1973), (2) when short-amplitude aimed movements of the hand or the arm vary in required accuracy (Glencross and Gould, 1979; Klapp, 1975; Klapp and Greim, 1979; Semjen and Requin, 1976; Quinn, Schmidt, Zelaznik, Hawkins, and

McFarquhar, 1980), and (3) when keypress responses vary in duration (Klapp, 1977a; Klapp, McRae, and Long, 1978; Klapp et al., 1974; Jagacinski, Shulman, and Burke, 1980). Klapp et al. (1974) attributed failures to replicate the difference between simple RT and choice RT to a lack of motivation and to insufficient practice.

Besides the number of elements in a sequence—Henry and Rogers's (1960) original assertion (Henry, 1980)—complexity was assumed to increase with the physical size of a movement (e.g., Klapp and Erwin, 1976), keypress duration (Klapp et al., 1974; Klapp and Wyatt, 1976; Klapp and Rodriguez, 1982), and whether or not a concurrent task was carried out (Klapp and Erwin, 1976). In an attempt to reconcile the various operationalizations of complexity, Klapp and Rodriguez (1982) proposed that the underlying parameter of complexity is total response duration.

Objections against Klapp's contention that choice RT should be used in the study of motor programming were raised by Sternberg et al. (1978), by Henry (1980), and by Marteniuk and MacKenzie (1980, 1981). (1) In choice RT one can never be sure that the effect of sequence complexity on RT is not caused by other processes than programming such as Stimulus Identification and Response Selection (Sternberg et al., 1978). (2) It has been shown that choice RT may be affected by the nature of the alternative movement. This is unrelated to programming the executed movement and, hence, choice RT may be affected by factors that have an influence on other processes than programming (Marteniuk and MacKenzie, 1980, 1981; Sternberg et al., 1978). (3) Klapp et al. (1979) used the questionable procedure of eliminating subjects who did not fit expectations (Marteniuk and MacKenzie, 1981). (4) It is unclear what actually causes the difference between simple and choice RT because the studies differ in too many respects (Henry, 1980). (5) Finally, complexity has been manipulated in many different ways without actual understanding of the underlying mechanisms and, hence, whether the same phenomenon was actually addressed (Henry, 1980; for similar objections see Glencross, 1972; Ivry, 1986; Kerr, 1978; Van der Plaats and Van Galen, 1990).

The general outcome of the debate is that various researchers acknowledge the relative merits of both simple and choice RT (e.g., Canic and Franks, 1989). It is now believed that a large part of the programming process indeed precedes the go-signal in simple RT. So, simple RT yields information on factors that affect processes concerned with reading the program from the motor buffer whereas choice RT also shows factors affecting processes involved in loading the movement representations into the buffer (Ivry, 1986). Sternberg et al. (1978) and Klapp appear to have studied different aspects of the sequence production process, both of which happen to be affected by sequence length.

Up till now, no studies have systematically attempted to disentangle the processes involved in programming and in initiating movement sequences. This may, indeed, be a complex issue since the extent that movements are prepared in advance appears affected by many factors (see Sections 3.4 and 5). For instance, two alternative movements can be programmed in advance when executed by different limbs but when the same limb is used for executing the alternative responses, programming appears to occur during RT (Rosenbaum and Kornblum, 1982). In addition, it has been demonstrated that general movement characteristics, such as the rules required for producing a sequence (cf. Restle, 1970), can be programmed in advance despite the fact that many details of the movement are still unknown (Rosenbaum, Weber, Hazelett, and Hindorff, 1986; Ziessler, Hänel, and Sachse, 1990). In a similar vein, when alternative movements or responses start with the same elements these can be programmed in advance and different elements are programmed only upon presentation of the choice signal (Garcia-Colera and Semjen, 1988; Rosenbaum, Inhoff, and Gordon, 1984a; Rosenbaum, Hindorff, and Munro, 1987; Sanders, 1970). As will be argued in Section 3.4, large scale movements may also be considered as sequences and it remains unclear when the earlier elements of alternative movements are sufficiently equal to be programmed in advance. Furthermore, as movements take longer, programming need not involve the entire movement (Ivry, 1986). From a theoretical point of view, one may argue that choice RT in the case of selecting a parameter, such as force and duration of a movement, may be quite different from choice RT when another motor program is selected (e.g., Semjen, 1984).

It is probable that the control of action probably involves three levels (Section 5.2). This suggests that advance preparation may also involve three levels: In terms of a prepared action plan (Newell, 1978; e.g., Ziessler et al., 1990), in terms of a preloaded motor buffer (e.g., Gordon and Meyer, 1987; Rosenbaum et al., 1986), and in terms of an unpacked first movement element (Meyer, Yantis, Osman, and Smith, 1984, 1985). For example, one may have an active plan about what to do next, either with or without programming the individual elements in the motor buffer. It may be hard to distinguish the level of preparation empirically, especially because the level of advance preparation may differ across experimental tasks, trials and subjects (Meyer et al., 1984, 1985). In view of this finding, Klapp et al.'s (1979) procedure of eliminating subjects seems defendable as different subjects may have prepared actions up to different levels. It remains to be seen how these levels of preparation can be distinguished empirically and how they relate to simple and choice RT in various task domains.

Some of the issues that emerged from the simple vs. choice RT debate have been unraveled, however. There is ample evidence against Klapp's notion that total response duration underlies the complexity effect. Apart from the fact that manipulation of response duration does not always yield an effect on choice RT (Glencross, 1972; Kerr, 1979; Klapp and Erwin, 1976; Klapp and Greim, 1981), it has been found that the requirement to produce a specific response duration *per se* may increase RT. However, movements exceeding 200 ms need not be entirely programmed in advance (e.g., Hulstijn and Van Galen, 1988; Ivry, 1986; MacKay, 1983; see Section 3.4). Furthermore, the longer initiation time found with secondary tasks can hardly be attributed to increased programming load as is assumed with movements involving more than one element. In secondary task conditions, longer RTs are more likely to be caused by planning both tasks at a more abstract level and, possibly, by setting up an attention switching scheme (Broadbent, 1982; Wickens, 1989), rather than that programming takes more time.

The notion that lack of practice would underlie the complexity effect in simple RT has also proven untenable (Canic and Franks, 1989; Fischman and Lim, 1991; Henry and Harrison, 1961; Norrie, 1967; Verwey, 1994b; Williams, 1971). Recent research has confirmed the danger of confounding programming variables with variables affecting other levels of processing such as timing requirements of response alternatives and S-R and R-R compatibility (Bauer and Miller, 1982; Ivry, 1986; Kerr, 1978; Marteniuk and MacKenzie, 1980; Zelaznik and Franz, 1990).

In retrospect, one wonders why at the time of the debate the researchers did not attempt to resolve the issues empirically. By now, it can be concluded that the debate on simple vs. choice RT rested on the simple conception that movements can be prepared only in terms of programming. By now there is evidence that advance preparation involves at least three levels of increasing preparedness. In fact, it seems that the level of advance preparation is affected by more than just whether simple or choice RT is used. For a clear understanding of the processes involved in movement programming research should address these levels of advance preparation in detail.

3.3 The motor buffer

The concept of a motor buffer has already been alluded to on various occasions in this chapter and stands at the explanatory basis of skilled sequence production. Although experimental results have not always shown comparable results it appears possible to delineate some invariant properties of the motor buffer. A first property is that elements in a sequence probably have to be specified in the order in which they are executed (Rosenbaum et al., 1984a; Ulrich et al., 1990).

Second, it appears that once a sequence has been programmed, the content of the buffer remains active for some time, even after the sequence has been actually produced (cf. McLean and Shulman, 1978). Thus, a sequence is repeated more easily in the same than in a very different form (Rosenbaum and Saltzman, 1984). In the case a slightly changed version is required the buffer content can be used for generating the changed version (Gordon and Meyer, 1987; Rosenbaum et al., 1986). This closely relates to the current explanation of contextual interference which states that contextual interference is low when only parameters are changed (Magill and Hall, 1990; see Section 2).

A third property of the motor buffer is that the information is not stored in a muscle-specific way (Keele, 1968). Since many tasks involve concatenation of spatially different movements, spatial information dominates the motor buffer

(Bernstein, 1967). For example, choice RT is found to be shorter for mirror image sequences than for entirely different movements (Rosenbaum et al., 1984a) and in writing and drawing spatial characteristics appear more invariant than their temporal counterparts (Teulings, Thomassen, and Van Galen, 1986; Van der Plaats and Van Galen, 1990; Van Mier, Hulstijn, and Petersen, 1993). In a task in which subjects produced continuous keypressing sequences, Verwey and Dronkert (1994) and Verwey (1994c) found little evidence for a temporal basis of sequence production. It was argued that temporal aspects of movement sequences emerge from controlling individual parts of the sequence in isolation. The dominant role of spatial information in the motor buffer is consistent with the results of choice RT studies which involve single movements. These studies show that selection of responses occurs with respect to the spatial location of response keys (Cauraugh and Horrell, 1989; Pashler and Baylis, 1991; Proctor and Dutta, 1993) and that location information is more stable than distance information (Kelso and Holt, 1980; Laabs, 1973; Rosenbaum, 1991). However, this may only hold for tasks involving spatial characteristics. For example, in speech the stress group appears to be the basic element in the motor buffer (Sternberg et al., 1978).

Before introducing a next property of the motor buffer, a certain type of result deserves attention because it suggests that movement sequences are not always controlled by the contents of the motor buffer. Sequences involving repetition of a single movement, like tapping a single key (Garcia-Colera and Semjen, 1987, 1988), performing repetitive arm extension/flexion movements (Van Donkelaar and Franks, 1991a, 1991b), or executing repetitive hand postures (Harrington and Haaland, 1987), probably involve a rule representing the number of renditions (MacKay, 1983; Sternberg et al., 1990; Van Donkelaar and Franks, 1991b). It is doubtful whether this rule is part of the motor buffer. As usually no effects of sequence length are found on initiation and inter-element intervals beyond two elements, it is more likely that repetitions are controlled by a higher-level action plan. Indeed, when Harrington and Haaland (1987) compared their sequence of repeated hand postures with a sequence of *different* hand postures the size of the complexity effect increased, RT was influenced by the type of hand posture beyond the first, and interelement times started to show effects of sequence length. This suggests that with different elements the motor buffer was used but not with mere repetition (also see Section 5).

This leads to the fourth property of the motor buffer: Movement sequences can, but need not be controlled by using information in the motor buffer. Whether the motor buffer is used for producing movement sequences can be found by determining at which level of description the most straightforward relation is observed between number of alleged elements and the effects of sequence length. So, when sequences of words were described in the numbers of words, syllables, and stress groups, Sternberg et al. (1978) showed that sequence length in terms of stress group yielded the clearest relation between number of elements and the sequence length effect (see also Fowler, 1981, 1985; Sternberg et al., 1988, 1990). Similarly, in typing the individual keystroke appeared the unit of programming (see also Sternberg et al., 1990). In handwriting the unit of programming may be the letter (Pick and Teulings, 1983; Teulings, Thomassen, and Van Galen, 1983) but, probably due to the relatively low execution rates, people appear flexible in using lower-level units, such as line segments, as well (Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986; Van Galen, 1991; Van Mier and Hulstijn, 1993).

Another possibility of determining whether sequences are controlled by information in the motor buffer is related to the fifth property of the motor buffer; its limited capacity[6]. That is, the complexity effect levels-off as a sequence exceeds a certain number of elements (Logan, 1982; Monsell, 1986; Sternberg et al., 1988; Rosenbaum et al., 1987). In that case, later parts of the sequence appear programmed after the sequence has been initiated. It seems that the motor buffer may contain up to four to six elements. When the production of sequences is not affected by the number of elements, this may be a sign that the motor buffer has no, or only a limited, role in producing the sequence (cf. Harrington and Haaland, 1987). Another indication for the limited capacity of a motor buffer is that, when subjects prepare alternative sequences with common initial elements, they appear not to program both sequences separately but, instead, they program the initial elements up to the first difference and continue programming only after the choice signal has been identified (Rosenbaum et al., 1984a). The number of elements that can be programmed in advance seems to depend on two factors. First, leveling off occurs earlier as the individual elements are larger (e.g., one- vs. three-syllable words, Sternberg et al., 1988). Second, the size of the complexity effect reduces with practice (Hulstijn and Van Galen, 1983, 1988; Inhoff, Rosenbaum, Gordon, and Campbell, 1984; Sternberg et al., 1978; Van Mier and Hulstijn, 1993; Verwey, 1994b) and longer sequences can be programmed in advance (Schneider and Fisk, 1983; Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986; Verwey, 1994b, 1994c). So, advance programming involves more elements as the elements are larger or more complex—i.e. contain more constituents—and as the level of practice increases. The effect of practice on movement sequences will be addressed in more detail in Section 4.

In short, the discussion of the motor buffer as used in the production of movement sequences yields the following buffer properties: Elements of a sequence have to be specified in the order in which they are executed. Once a sequence has been prepared in the motor buffer the information remains active for some time. This allows easy repetition of the same or similar sequences. Spatial information appears dominant in the motor buffer although, at least in speech, other information may also be represented. Sequence production can be controlled by information stored in the motor buffer but this need not always be the case. Indications that movements sequences are carried out by utilizing

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[6] Note here the distinction between the concepts buffer capacity, implying the number of elements that can be stored in the motor buffer, and processing capacity, indicating that processes are slowed when they concur.

motor buffer information can be found in sequence length effects on initiation time, interelement intervals, and a leveling-off of these effects with sequences exceeding about four to six elements. When these effects are not found one should consider the possibility that sequences are controlled from a higher level. The level of the elements programmed in the motor buffer can be traced by relating the complexity effect to the number of elements at various levels of description. Finally, the buffer capacity is affected by the type and size of elements and the level of practice.

3.4 On-line programming

Indications for on-line programming

It is unlikely that very long sequences are programmed entirely in advance (Klapp, 1977a; Klapp and Wyatt, 1976; Rosenbaum et al., 1987; Sternberg et al., 1988). One of the dominant contemporary notions is that later parts of a long sequence are programmed after execution of the sequence has started. As stated above, this is indicated by a leveling off of the complexity effect when the sequence is longer (e.g., Klapp et al., 1979; Sternberg et al., 1978, 1988; Garcia-Colera and Semjen, 1988). In fact, Sternberg et al. (1978) also found indications for on-line programming in that the complexity effect in their third speech experiment leveled off quickly, but they considered it an anomaly.

More convincing evidence for varying amounts of on-line programming comes from observations that initiation time actually *decreased* with sequence length (Chamberlin and Magill, 1989; Garcia-Colera and Semjen, 1988; Ivry, 1986; Rosenbaum et al., 1987; Van der Plaats and Van Galen, 1990). It seems that the amount of on-line programming may increase disproportionally with sequence length.

The third type of evidence for on-line programming with respect to initiation time comes from studies in which a choice element follows a fixed set of stimulus-independent elements. The effect of the choice on the initiation time diminishes as the choice element is moved toward the end of the sequence (Garcia-Colera and Semjen, 1988; Rosenbaum et al., 1984a, 1987).

On-line programming may also be indicated by a slower execution rate of one or more individual elements in the sequence (Klapp and Wyatt, 1976). As many as seven types of execution rate effects can be distinguished. First, the first element may be executed more slowly (e.g., Chamberlin and Magill, 1992b; Christina, Fischman, Lambert, and Moore, 1985; Christina et al., 1982; Fischman, 1984; Fischman and Lim, 1991; Glencross, 1980; Portier, Van Galen, and Meulenbroek, 1990). This suggests that programming continues after onset of the first sequence element. Second, the interval prior to a specific element or the time taken to execute the preceding element may be lengthened (Garcia-Colera and Semjen, 1987; Semjen and Garcia-Colera, 1986; Van Galen, Meulenbroek, and Hylkema, 1986; Verwey, in press). This suggests that individual elements can be programmed, or respecified, immediately before their execution (Hulstijn and Van Galen, 1983; Piek, Glencross, Barrett, and Love, 1993). Third, relatively long sequences may show one or more relatively long interelement intervals (Brown and Carr, 1989; Schneider and Fisk, 1983; Sternberg et al., 1978; Verwey, 1994b, 1994c). These sequences are probably chopped into pieces, each of which is programmed before execution.

A fourth indication for on-line programming is that slower execution is sometimes observed at the end of a sequence. This was observed in repetitive key tapping (Garcia-Colera and Semjen, 1987; Piek et al., 1993), in pronunciation of word sequences (Sternberg et al., 1988), and in writing (Hulstijn and Van Galen, 1983; Van Galen et al., 1986). It suggests that in some tasks a process is required for stopping the sequence. Fifth, Verwey (in press, 1994b, 1994c) established that in the course of practice, the last element of a keypressing sequence was executed *faster* than earlier keypresses. This was taken to suggest that all but the last keypress had been slowed by some type of on-line programming process. A sixth indication for on-line programming is that entire groups of keypresses are carried out more slowly when followed by another group (Verwey, 1994c).

Finally, indications for on-line programming have been found in large-scale aiming movements of 150-200 ms and longer. On-line programming in these movements is suggested by the high sensitivity of performance to elimination of visual feedback in some phases of the movement (Carlton, 1981; Faust-Adams, 1975; Klapp, 1975; Young and Schmidt, 1992; for a review see Glencross and Barrett, 1992) and by the large variability in the decelerative portion of movement (Abrams and Pratt, 1993; Marteniuk, MacKenzie, Jeannerod et al., 1987; Soechting, 1984; Zelaznik et al., 1986). This is in line with the notion that aiming movements can be considered sequences of, at least, two movements (e.g., Woodworth, 1899). The first movement is a ballistic, open-loop movement, programmed before movement on-set, the second movement is a closed-loop movement the details of which are programmed on-line. The closed-loop segment may itself be considered a sequence of small segments, each of which is programmed on basis of feedback information. In other words, large-scale aiming movements may be considered sequences of movements which are programmed or parametrized during execution. The difference with the sequences regarded before in this section concerns the fact that the size and duration of the individual segments in aiming are not directly imposed by the task and the performer has some freedom in choosing their number and sizes (Zelaznik, Shapiro, and McColsky, 1981). That is, they are analog rather than digital (Cruse et al., 1990)

To sum up, on-line programming is suggested by smaller or even reversed effects of sequence length on the initiation interval, and by disappearance of the effect of a choice element on initiation time as this element is at a later position. Indications for on-line programming on sequence execution are often found in that one or more elements are delayed. Evidence for at least some amount of overlap been execution and programming has been reported by various investigators (e.g., Garcia-Colera and Semjen, 1988; Rosenbaum et al., 1984a; Verwey, in press). Finally, the notion that large-scale aiming movements involve an open- and a closed-loop part suggests that aiming movements may also be described as a sequence of movements the details of which are programmed on-line.

Converging evidence for on-line programming from dual task studies

Posner and Keele (1969) assessed the capacity demands of the processes involved in wrist-rotation to a target by requiring subjects to respond to a secondary probe stimulus presented at unpredictable moments of the primary wrist rotation task. The probe RT was lengthened most at the initiation of the movement suggesting that initiation was more demanding than execution. This was also found with respect to initiating speech sequences (Ladefoged, Silverstein, and Papçun, 1973) and high-precision aiming movements (Ells, 1973; Glencross and Gould, 1979; Zelaznik et al., 1981). Also, probe RT increased at the later stages of a movement as a function of the required precision of the movement (Ells, 1973; Posner and Keele, 1969) although only with relatively slow movements (Zelaznik et al., 1981). This corroborates the use of closed-loop control in high precision aiming movements which are slow enough to allow on-line error correction (Schmidt, 1976; Woodworth, 1899).

Glencross (1980) used sequences of rapid, low-accuracy arm sweeps but still found prolonged probe RTs during execution. Given that the movements were open-loop, the longer probe RTs were taken to suggest that programming more complex sequences proceeds when actual execution has commenced. The observation that probe RTs were affected by number of movement elements and not by the type of movement, led Glencross (1980) to the notion that programming demands were affected by sequence control and not by the demands of element execution (cf. Sternberg et al., 1978).

A few studies have addressed the effect of a secondary task on sequence production. Brown and Carr (1989) had subjects practice keypressing sequences of various lengths and added a memory load in some blocks of trials. Choice RT and rate of execution were affected by the secondary task but the effect was more pronounced for choice RT. Interestingly, the third response in the six-key sequence, which was already relatively slow in the single task condition, was delayed much more than the other responses in the secondary task condition. Given the observations that programming demands exceed execution demands (e.g., Posner and Keele, 1969) this corroborates that the sequences had been carried out in parts and, hence, relied on on-line programming.

Verwey (1993a) examined whether interference of a secondary task with a sequence of three keypresses diminishes with practice. This was not found and it was concluded that the reduced demands of keypressing with practice were used to increase production speed. An effect of expectancy on allocating processing capacity between tasks was suggested by the finding of similar interference levels when unexpectedly no secondary task stimulus was presented.

The possibility of advance allocation of processing capacity is supported by work of Zelaznik et al. (1981). They examined the effect of a secondary task on single aiming movements and observed that the mere possibility of an auditory probe made subjects decide to allocate less processing capacity to a slow aiming response (500 ms duration). This was not observed in the case of a rapid aiming movement (200 ms duration). They argued that the performer can decide to control the 500 ms movement in either a closed- or an open-loop fashion, whereas the 200 ms movement would always be controlled open-loop. This supports the idea that relatively slow aiming movements may be regarded as a sequence of movements, a number of which are programmed on-line. The results also show that subjects may change from closed- to open-loop control when the available processing capacity is expected to be too small for closed-loop control.

These secondary task results generally support the use of on-line programming in sequence production. Relatively slow, high-precision aiming movements may involve a closed-loop controlled final segment but one appears to be free in switching to a single open-loop movement. Again, programming a forthcoming sequence—either at its initiation or halfway a long sequence—interferes more with a secondary task than executing the elements of a sequence. This is consistent with the notion that on-line programming may have been concealed in some studies (e.g., Garcia-Colera and Semjen, 1988; Rosenbaum et al., 1984a). In view of the wide variety of effects it is unlikely that all are due to a single type of on-line programming. Direct evidence for independent types of on-line programming stems from additive effects of slowing of entire sequences and the usually fast last keypress of a sequence (Verwey, 1994c) and the finding of two or more levels of error correction in aiming (Cruse et al., 1990; Glencross and Barrett, 1992; Schmidt, 1987). Isolation of the various forms of on-line programming would greatly contribute to insight in the mechanisms of skilled sequence production.

Determinants of on-line programming

On-line programming appears to come in various guises. This section addresses the determinants of on-line programming in order to unveil underlying processes. In anticipation of the conclusions it can already be stated that the processing capacity required for executing individual sequence elements plays an important role. The idea that processing capacity is limited arose from secondary task research in which it is used as an explanatory construct for the finding that performing one task interferes with one that is performed simultaneously (Broadbent, 1958; Moray, 1967; Kahneman, 1973) or with one that follows rapidly (McCann and Johnston, 1992; Pashler, 1992; Telford, 1931). As regards movement sequences, limited capacity refers to the notion that processes engaged in executing some elements and programming other elements of the sequence concur and interfere because they draw on a common source of processing capacity (e.g., Brown, McDonald, Brown, and Carr, 1988; Brown, Carr, Brown, McDonald, Charalambous, and West, 1989; Van Galen, 1991;

Verwey, 1994b). This chapter will not treat underlying mechanisms but refer to limitations in processing capacity only as an explanatory concept.

The speed with which sequences are produced is a first determinant of on-line programming. When subjects are asked to produce sequences of discrete movements at a submaximal rate the complexity effect disappears (Canic and Franks, 1989; Van Donkelaar and Franks, 1990; Garcia-Colera and Semjen, 1987, 1988; Semjen and Garcia-Colera, 1986; Van Donkelaar and Franks, 1990). Longer interresponse intervals appear to facilitate on-line programming of individual elements. This seems to relate to the finding that closed-loop control in aiming movements is used with movements which take a relatively long time. Evidence for a larger degree of on-line programming at a lower speed in aiming is offered by studies demonstrating an increase in the number of times that acceleration crosses the zero line within a movement and the length of time that the muscles are active (as measured by EMG—Van Donkelaar and Franks, 1991a, 1991b). The idea that processing capacity is freed at submaximal production rates is consistent with findings that highly proficient pianists—who can be considered to play at a submaximal speed—can simultaneously sight-read music and perform an auditory shadowing task without interference (Allport, Antonis, and Reynolds, 1972; see also Shaffer, 1975). In terms of processing capacity it appears that when spare capacity is not used to increase the rate of execution (Verwey, 1993a) it can be used for programming forthcoming elements of the sequence.

The type of task is another determinant of on-line programming. This follows from the observation that there are considerable differences between tasks with respect to the size of the complexity effect and the number of sequence elements at which the complexity effect levels-off. For example, in handwriting and when producing sequences of large-scale aiming movements the complexity effect is primarily limited to sequences of one and two elements (Christina et al., 1985; Christina et al., 1982; Christina and Rose, 1985; Fischman, 1984; Van Donkelaar and Franks, 1990; Henry and Rogers, 1960; Hulstijn and Van Galen, 1983; Teulings, Mullins, and Stelmach, 1986). On the other hand, in typing and speech the complexity effect continues up to six elements (Sternberg et al., 1978, 1988). It seems as if sequences of more rapidly produced elements are associated with a later leveling-off of the complexity effect. One explanation for this is that tasks with more slowly performed elements have a greater potential for on-line programming (Hulstijn and Van Galen, 1983). That is, when the maximal rate at which elements in the sequence are executed is constrained by biomechanical factors, such as in writing and large-scale aiming, it is likely that there is enough capacity left for on-line programming without even affecting sequence execution rate. In that case subjects will tend to program only a few elements in advance. When execution rate is constrained by processing capacity, any on-line programming will affect execution rate and subjects are more likely to program as much in advance as possible. So, the underlying factor of the differences in complexity effects among tasks appears to be whether execution rate is constrained by capacity demands or by biomechanical limitations.

Some empirical support for this notion has been provided by Sternberg et al. (1978). They found a much smaller complexity effect in one-hand typing, which is relatively slow by nature, than in the much faster alternating hand typing (4 vs. 15 ms/letter). Further support comes from tasks in which the execution of the individual elements requires substantial processing capacity because of closed-loop control. From the capacity point of view it is expected that the high capacity demands of high accuracy aiming reduce the possibility for overlapping processing (Schmidt, 1987)[7]. A first indication for this possibility is provided by studies of sequential aiming movements in which an aiming movement was produced more slowly when it was followed by a second movement (Viviani and Terzuola, 1973; Williams and Sullivan, 1978; Williams, Sullivan, and Kerr, 1985).

More direct evidence for the interaction between the capacity required for producing a single element and on-line programming has recently been provided by Sidaway (1991). He demonstrated that the size of the complexity effect increases as the sequence elements require greater accuracy. Sidaway (1991) argued that programming time of the entire sequence is a function of the target that imposes the greatest accuracy constraint. In line with the proposed effect of single elements on sequence control it appears more likely that the complexity effect in sequences with higher accuracy constraints increased because more capacity was required for producing the individual elements and, hence, less on-line programming was possible. This notion is supported by Sidaway's (1991) findings that the first and second movement segments were slower when another segment followed and that total movement time increased with smaller target sizes. These effects are difficult to reconcile with the notion that the entire sequence is programmed in advance, as Sidaway (1991) suggests, but they are in perfect agreement with the notion that increased processing demands of the individual elements precluded on-line programming and, hence, required more advance programming.[8]

On-line programming may also be enforced by the number of elements in the sequence; as the sequence is too long to program in advance, on-line programming of forthcoming parts of the sequence is required. Indications for partitioning long sequences have been found by various researchers (Brown and Carr, 1989; Schneider and Fisk, 1983; Sternberg et al., 1978; Verwey, 1994b, 1994c). In line with the notion that demands of sequence execution reduce with practice so that longer sequences can be programmed in the motor buffer, on-line programming was found to disappear with extensive practice (Schneider

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[7] Consistent with Schmidt (1975, 1976, 1987) it is assumed that only fairly conscious and slow ways of feedback processing demand processing capacity and not low-level feedback processing (Bootsma and Van Wieringen, 1990; Blouin, Bard, Teasdale, and Fleury, 1993; Pelisson, Prablanc, Goodale, and Jeannerod, 1986; Prablanc, Pelisson, and Goodale, 1986).

[8] Increased accuracy demands may also slow down execution because of increased antagonist muscle involvement (Anson, 1982). This is a peripheral effect and on-line programming may still be possible here. So, research with rapid accurate aiming movements should discern between peripheral and central effects of high accuracy demand by electromyographic (EMG) recordings (e.g., Botwinick and Thompson, 1966).

and Fisk, 1983; Verwey, 1994b, 1994c). Furthermore, for shorter sequences the complexity effect reduced (Fischman and Lim, 1991; Hulstijn and Van Galen, 1983; Sternberg et al., 1978; Van Mier and Hulstijn, 1993; Verwey, 1994b) suggesting more on-line programming due to less demands of element execution[9]. Hence, the amount of on-line programming is also affected by practice.

To summarize, the occurrence of on-line programming appears to be determined by whether or not the capacity of the buffer is exceeded and whether processing capacity for on-line programming is expected to be available. Modifying variables are execution rate (instructed or imposed by biomechanical limitations) and processing demands of the individual elements (closed-loop processing and practice) in that on-line programming is more likely at lower rates and less likely as the individual sequence elements require more processing. This trade-off between demands of element execution and of sequence control signifies a violation of the element-invariance principle (Sternberg et al., 1978, 1990) for sequences of demanding movements; the demands of executing a single element in a sequence appears to affect the production of the entire sequence.

Variability in sequence organization

A number of researchers has suggested, more or less implicitly, that people may be relatively free in choosing whether or not to use on-line programming (e.g., Chamberlin and Magill, 1989; Zelaznik et al., 1981). It has been suggested, for example, that the amount of on-line programming is determined by a tendency of minimizing the mean and variance of interresponse times (Garcia-Colera and Semjen, 1988; Rosenbaum et al., 1987), by the type of feedback during practice (Young and Schmidt, 1990), the efficiency (Holt, Hamill, and Andres, 1990; Sparrow, 1983; see also Gentner, 1987), the trade-off between short-term memory and processing capacity load (Greeno and Simon, 1974), prior experience (Bartz, 1979), and the way instructions are presented (Geoffroy and Norman, 1982). So, the use of on-line programming is probably determined by a combination of task requirements and the capacity of the motor buffer. Changes in on-line programming usually involve the way in which sequences are broken up and whether closed- or open-loop control is applied (Zelaznik et al., 1981).

If one strategy has clear advantages over another, all subjects in the experiment are likely to end up using the same strategy (Crossman, 1959). However, if there is no clear relation between on-line programming strategy and performance, large individual differences may be expected (see e.g., Semjen, 1992; Rosenbaum et al., 1984a; Verwey, 1994c; Verwey and Dronkert, 1994). In that case the amount of on-line programming is likely to be affected by factors such as fatigue, motivation and cognitive style (e.g., Eysenck, 1967; Jelsma and Pieters, 1989; Jelsma and Van Merrienboer, 1989).

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[9] In Section 4 another explanation for a reducing complexity effect will be presented.

An important question concerns the flexibility people have after practicing some type of on-line programming. Can they easily switch to other on-line programming regimes or does a fixed scheduling mechanism develop which is hard to alter?

Conclusions on on-line programming and a taxonomy

There is ample evidence that movement sequences are not always programmed entirely in advance. Indications for on-line programming come from vanishing and reversed complexity effects with increasing sequence lengths and slowed execution of one or more individual elements. Various types of on-line programming can be distinguished. The need for on-line programming comes from a limited buffer capacity and from the need to correct execution errors in accurate aiming. The fact that on-line programming is often indicated by slowed execution of elements suggests a common limited processing capacity. Modifying variables of on-line programming are execution rate, either instructed or task related, and the capacity demands of executing individual elements which are affected by accuracy demands and practice. People seem to have some freedom in trading on-line programming for advance programming. Task requirements play a major role here. When task requirements are such that performance is not affected by the way movement sequences are produced, effects of personal and situational characteristics can be expected. In Section 6 of this chapter, a distinction will be made between three types of processes that may concur with movement execution.

Given the notion that movements exceeding 200 ms as well as sequences of discrete movement elements may involve on-line programming, a taxonomy is proposed in Table I.

Table I A taxonomy of movements including the open- and closed-loop control distinction and sequences of open- and closed-loop elements. Segments are imposed when their boundaries are specified by the task and segmentation cannot be changed.

		number of imposed segments	
		1 (analog)	> 1 (digital)
duration of a single segment/element	< 200 ms	ballistic/ open-loop	movement sequence
	> 200 ms	aiming/ closed-loop	aiming sequence

It assumes that there is no on-line programming in rapid aiming movements of limited accuracy (Schmidt et al., 1979). In accurate aiming movements and in relatively long sequences of discrete movements there is a need for on-line programming. This relates to the difference between analog and digital movement control (Cruse et al., 1990) in that in analog movements (aiming) the number of segments is not imposed directly by the task whereas it is in digital movements (sequences).

A special category in the taxonomy concerns sequences of aiming movements. Since on-line programming may be used for on-line correction of each individual aiming movement as well as for preparing forthcoming movements, it is unclear whether forthcoming aiming segments are programmed during execution of the earlier ones, or whether the need for on-line programming of the ongoing aiming segment prevents this. The general finding in this type of task is that complexity effects are usually quite small (e.g., Christina et al., 1982; Fischman and Lim, 1991; Sidaway, 1991). If individual segments are relatively slow or require little accuracy, this might allow on-line programming of forthcoming aiming movements. However, if there are greater accuracy demands for the individual elements, this may change due to the need for on-line correction. With sequences of elements which take very little time to produce, as in typing and speech, sequence length effects may also occur at the individual elements because searching the buffer is not possible during execution of the preceding element. So, in sequences of aiming movements the balance between on-line programming in terms of correcting on-going movement and on-line programming in terms of programming a forthcoming movement during the preceding one seems highly dependent on the task requirements and may even differ across subjects.

3.5 Conclusions

The rapid production of relatively short movement sequences is characterized by programming the individual elements in a short-term motor buffer in advance of sequence production. This is indicated by an effect of the number of elements on the time to initiate the sequence. Sometimes, a sequence length effect can be found on execution of individual elements. This is ascribed to the need to search the motor buffer for the appropriate element. A discussion on the merits of simple and choice RT tasks suggests that different process occur during simple and choice RT and that advance preparation may differ considerably over tasks and subjects. The motor buffer is characterized by a largely spatial content and a limited storage capacity. The latter property necessitates long sequences to be programmed on-line. Various indications for on-line programming in initiation and interresponse times have been discussed along with some converging evidence from secondary task research. The use of on-line programming appears determined by the buffer capacity and the limited availability of processing capacity. Modifying variables are execution rate (either instructed or imposed by biomechanical task properties) and processing demands of the individual elements (affected by the use of closed-loop processing and practice). The fact that one can program forthcoming movements while executing earlier ones suggests at least two levels of control; one for executing the programmed movement and one for programming the next. In many speeded tasks, these levels interfere in that processing at either level is slowed in case on-line programming is used. Only in relatively slow tasks no interference need to be found. People appear to have some freedom in the extent they use on-line programming. Large individual differences can be expected when sequences can be performed in various ways without large performance deficits. Finally, a taxonomy is proposed of various types of movements. It reflects a functional similarity between aiming movements of over approximately 200 ms and sequences of discrete movements. In sequences of relatively long lasting elements, on-line programming in the sense of preparing forthcoming elements may be used. However, as the accuracy of the individual elements increases, the amount of on-line programming may decrease due to the need for feedback processing.

4 HIGHLY PRACTICED MOVEMENT SEQUENCES: MOTOR CHUNKS

4.1 The motor chunk concept

A contemporary view is that skilled sequence execution relies on the availability of a library, or 'thesaurus', of representations of fixed movement patterns which is distinct from the mechanism responsible for actual execution (Adams, 1984; Allport, 1980; Cruse et al., 1990; Semjen and Garcia-Colera, 1986; Greeno and Simon, 1974; Keele, Cohen, and Ivry, 1990; MacKay, 1982; Schmidt, 1975; Semjen, 1992; Shaffer, 1976; Summers, 1989; Vallacher and Wegner, 1987; Van Galen, 1991; Verwey, 1994c; Whiting, Vogt, and Vereijken, 1992). This section discusses indications for this contention and how the representations of such motor patterns develops. The notion is advanced that consistent practice with the same movement sequence yields an integrated sequence control structure, or *motor chunk*, which allows rapid sequence initiation because the chunk can be selected and loaded in the motor buffer as a whole rather than element by element (e.g., Gallistel, 1980; Portier and Van Galen, 1992).

4.2 Indications for the existence of motor chunks in task performance

The notion of motor chunks is at least as old as Book's (1908) suggestion that with practice the units of motor organization for typing change from individual letters to words and phrases. Another indication that highly practiced movement sequences may be controlled by an integrated sequence representation was advanced almost forty years later by Craik (1947). Craik noted that certain hand movements were more difficult to interrupt than others because they were, in his words, "triggered off as a whole" (p.61). These examples relate to an old conception in the psychology of motor control that complex motor skills are built from an alphabet of more elementary motor patterns. Some of these motor elements are thought to be reflexes innate to the organism which can be incorporated into newly acquired skills (e.g., Fukuda, 1961; Keele, 1986; Zanone and Hauert, 1987). So, a motor chunk is defined as *an integrated representation of one or a series of elementary movements which can be selected and retrieved from long-term memory as a whole and which is subsequently loaded in the motor buffer.* The notion of relatively fixed and integrated motor chunks can be found in various areas of research including ethology, neurophysiology, and behaviorism (for reviews see Adams, 1984; Gallistel, 1980; Keele et al., 1990). For instance, research with humans has shown that under stress and after lesions of the frontal lobes inappropriate but stereotyped movement sequences are made (Fentress, 1983; Luria, 1973; Schwartz, 1982). In the next section indications for the use of motor chunks in real-world and in laboratory tasks will be considered.

Motor chunks in natural tasks

In behavioral research there is ample evidence for a large repertoire of movement representations which are linked in order to construct new movement sequences. One indication stems from two contrasting patterns of results found in studies of *single* movements. In line with the motor programming notion, Rosenbaum (1980) found a different specification time for arm, direction, and extent of rapid aiming movements as well as indications that decisions about extent were made after movement initiation. In contrast, under conditions designed to reflect a natural task environment, Goodman and Kelso (1980) did not only find better performance than Rosenbaum (1980) but also found no differences between the times needed to specify the various parameters. They concluded that if the S-R mapping is 'natural', aiming movements are organized as 'wholes', rather than constructed in a series of steps. This has been explained by the possibility of retrieving from memory a fully fledged motor chunk representing the entire movement (Ivry, 1986; Logan, 1988, 1990; Neumann, 1987; Rosenbaum, Vaughan, Barnes, and Jorgensen, 1992; Zelaznik and Franz, 1990).

Evidence for the use of motor chunks in movements that are clearly made up of a sequence comes from various areas of research. In handwriting, evidence has been found that the complete letter, or even a name or a signature, may be controlled as a single unit which relies primarily on spatial coding (e.g., Hulstijn, 1987; Pick and Teulings, 1983; Teulings et al., 1983; for reviews see Thomassen and Van Galen, 1992; Van Galen, 1991). So, there is evidence that RT increases with the number of strokes when producing novel symbols but not, or hardly, in the case of familiar letters (Hulstijn, 1987; Hulstijn and Van Galen, 1983, 1988). Precuing facilitates production of letters rather than strokes (Teulings et al., 1983). Moreover, drawing each line segment in an unfamiliar writing pattern twice, increases initiation time as a function of number of segments which is not observed in familiar letters (Van Mier and Hulstijn, 1993). Further evidence for motor chunks in writing concerns the fact that writing style, which differs clearly amongst people, does not differ much across limbs of individuals (Lashley, 1942; Katz, 1951; Merton, 1972; Thomassen and Teulings, 1983).

Evidence that motor chunks underlie the production of speech and typing comes from the fact that the elements of programming—the stress group and the single keystroke (Salthouse, 1984; Sternberg et al., 1978, 1988; see Section 3.1)—are actually short movement sequences themselves (Sternberg et al., 1990). With respect to typing Grudin (1983) argued that multi-character units are used for programming (cf. Book, 1908). Furthermore, the fact that secondary task interference delays all segments of a reaching and grasping movement corroborates its reliance on a single motor chunk (Haggard, 1991). These findings suggest that motor chunks, which were once controlled as a sequence of elements, may themselves serve as individual elements in the motor buffer. The persistence of a small sequence length effects suggests that these 'mega' elements remain more loading than their individual constituents (Eriksen et al., 1970; Sternberg et al., 1990).

Another source of evidence for the existence of motor chunks in natural tasks comes from various types of anticipatory effects. These are effects which appear to serve the aim of facilitating performance of later elements (Section 2). In typing, for example, the effect shows as preparatory finger movements occurring before the preceding finger has actually reached the key it aimed for (Shaffer, 1976). Similar effects have been observed in speech (coarticulation, e.g., Fowler, 1985; Kent and Minifie, 1977; Moll and Daniloff, 1971; Perkell, 1980; Perkell and Klatt, 1986), saccadic and blink suppression (Volkmann, Schick, and Riggs, 1969; Volkmann, Riggs, and Moore, 1980), and manual reaching (Hinton, 1984; Rosenbaum et al., 1992). These anticipatory effects cannot be explained by on-line programming which merely slows execution of individual elements.

Finally, Logan and Cowan (1984) noted that the time required to stop ongoing action in typing and speaking does not show the typical refractoriness effect (i.e., the second of two responses given to two successive stimuli is relatively slow—Kantowitz, 1974; Pashler and Johnston, 1989; Welford, 1952). In a similar vein, signals to modify parameters of an ongoing movement, such as extent, appear to have privileged access (see e.g., Brebner, 1968; Megaw, 1972a, 1972b, 1974; Semjen, 1984; Rosenbaum, 1980). These findings can be easily justified in a theory stating that movement sequences are produced by an autonomous motor chunk which leaves enough processing capacity for deciding about and execution of on-line movement modification.

Developing motor chunks in laboratory tasks

As the development of motor chunks in everyday tasks is usually hard to pursue and allows little experimental control, various studies have focussed on the development of motor chunks in artificial laboratory tasks.

An indication for the development of motor chunks in relatively gross aiming movements has been reported by Fischman and Lim (1991). Subjects practiced one-target and two-targets aiming tasks and showed considerable performance improvement while at the same time the complexity effect reduced. In comparison to control subjects, experimental subjects showed poor performance in a three-targets transfer task. Therefore, the improvements found with practice could not be attributed to more efficient task performance in terms of improved on-line programming. The explanation was advanced that a specialized representation had developed for controlling two-targets aiming which interfered with three-targets aiming. The finding that this effect also occurred when subjects produced the three-targets task with the unpracticed hand suggests that this representation was effector-aspecific. This is in-line with the notion that the motor chunk is at the level of the—also effector-aspecific—motor buffer (Section 3). This study suggests that *motor chunks develop from consistently executing a sequence of movements which is programmed entirely in advance*.

As discussed in Section 3 reduction of the complexity effect may indicate the development of on-line programming. Yet, there are reasons to believe that it may also indicate chunk development. As mentioned above, Fischman and Lim's (1991) indications for chunk development were accompanied by a reduction of the complexity effect. And in handwriting, for instance, the development of motor chunks is usually accompanied by a sharp reduction of the complexity effect; The number of line segments and letters have much smaller complexity effects in familiar than in unfamiliar figures, patterns, and words (Hulstijn and Van Galen, 1983, 1988; Van Mier and Hulstijn, 1993). The relative contribution of on-line programming and chunk development to the reduction of the complexity effect appears task-dependent as some tasks allow more on-line programming than others (Section 3).

To cast some light on the issue of when and how motor chunks develop, Verwey and Dronkert (1994) had subjects practice a sequence of nine different keypresses with nine fingers which was repeatedly performed in rapid succession. Each sequence was structured by inserting a relatively long response-stimulus interval at two or three fixed positions whereas at the remaining positions each response was followed immediately by the next stimulus. It was reasoned that the long response-stimulus intervals would allow advance programming of the group of forthcoming key presses and that practice would induce the formation of motor chunks for each of the individual groups of keypresses. The alternative hypothesis was that practice produces a rhythmic structure involving a binary tree hierarchical structure (Keele and Summers, 1976; Summers, 1975). Predictions of both hypotheses were tested in unstructured blocks which had only zero stimulus-response intervals and which were intertwined with the structured practice blocks. Motor chunking would be indicated in the unstructured condition by a gradual increase of the ratio between intervals at the start of a group and the intervals within a group which would exceed the 2:1 ratio predicted by the rhythm hypothesis. This would occur irrespective of whether the groups could be represented by a binary hierarchy or not. The results confirmed both predictions and favored the motor chunking explanation over the rhythm explanation.

Other indications for motor chunk development in laboratory tasks come from various studies on the effect of practice with relatively long keypressing sequences. Initially, these sequences are characterized by the presence of a relatively long interelement interval which suggests that the sequence cannot be entirely programmed in advance (Brown and Carr, 1989; Schneider and Fisk, 1983; Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986; Verwey, 1994b). But with practice, this relatively long interval disappears (Schneider and Fisk, 1983; Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986; Verwey, 1994b). This has led to the notion that practiced sequences load the buffer less and can be produced as a whole (Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986).

Converging evidence for chunk development was reported recently by Verwey (1994c). This study replicated the results obtained by Verwey and Dronkert (1994) for a different partitioning of the sequence which did not obey the binary tree either. In this study the development of motor chunks was indicated by the pattern of results in a transfer phase as well; performance of entirely or partly different response groups was very poor. This corroborates the idea that motor chunks are sequence-specific (e.g., Sternberg et al., 1990). An important methodological result was the finding that when there is time for advance programming of the sequence, this may conceal the existence of motor chunks with shorter sequences. That is, there was little difference between performance at new and practiced sequences when both were short *and* there was ample time for preparation. The existence of chunks emerged only with longer sequences that could not be entirely programmed in advance and in the absence of preparation time. This result relates to findings with rapid pronunciation and typing of words and nonwords in that nonwords are usually produced slower than words (Fendrick, 1937; Shaffer, 1973; Rosenbaum, 1991) unless there is ample time for preparation (Sternberg et al., 1978). Finally, consistent with the notion that motor chunks are highly content specific, Verwey (1994c) found that the occurrence of parts of the practiced sequences in otherwise new sequences did not contribute much to performance. The notion that the processing load of selecting a motor chunk is independent of the size of the sequence it represents, was confirmed in Verwey's (1994c) study by the finding that a response group was slowed when followed by another group and that this slowing was not affected by the number of elements in the next group.

In conclusion, the notion that highly practiced movements and movement sequences involve retrieval of an integrated motor chunk, rather than time consuming sequence construction, is corroborated by the study of natural as well as artificial tasks. Evidence for the use of motor chunks in speech, handwriting and typing stems from the observed difficulty to change learned movement patterns, from the possibility of describing initiation and interresponse times of a sequence of chunks parsimoniously as a function of sequence length, from anticipatory effects such as coarticulation, and from the ease of stopping and modifying parameters of ongoing movement sequences. Laboratory tasks corroborated these findings and suggest that a reduction of the complexity effect in the course of practice may indicate chunk development. Motor chunks develop when movement sequences are practiced in a consistent order.

4.3 Determinants of chunk development

There might be various ways to bring about the development of specific chunks in movement sequences. The major principle is that a sequence of movements is repeatedly and consistently executed in rapid succession (Verwey and Dronkert, 1994; Verwey, 1994c). With long sequences, the boundaries of chunks are determined by any aspect of the task that causes the sequence to be executed in temporally separated parts. This may occur by including some long inter-movement intervals during practice (Gordon and Meyer, 1987; Lashley, 1951; Newell, 1981; Summers, 1975; Verwey, 1994c; Verwey and Dronkert, 1994), by explicit or implicit instruction (Geoffroy and Norman, 1982), or by having subjects practice parts in isolation (Schmidt, 1982a; Wightman and Lintern, 1985). In fact, these options have all in common that the sequence is carried out by chopping it into a pieces, each of which is repeatedly and consistently programmed in advance.

An important question at this point concerns whether with additional practice, motor chunks merge into a bigger chunk in which all elements are still individually represented, or whether the motor chunks remain to be controlled as separate chunks. Indications for the first notion have been reported by Zimmer and Körndle (1988) in that transfer to the basic skills of riding a so-called pedalo decreased at higher skill levels, but further research under more controlled conditions is required to investigate this issue more thoroughly.

4.4 Some theoretical notions

Although motor chunks are considered to be fairly specific with respect to the temporal and spatial characteristics of the sequences they control, they still appear to allow parametrization. For example, the study by Fischman and Lim (1991) showed transfer of practice to the other limb and a tracking study by Pew (1974) showed transfer to a mirror image tracking trace. The status of parameter specification in motor chunks is unsettled but seems related to parameter setting in motor programs (Schmidt, 1976).

Neumann (1984, 1987) asserted that parameter specification in highly practiced tasks need not rely on explicit specification. Instead, parameters may be specified by a process which directly translates information from the outside world into the appropriate parameter format (e.g., Cordo et al., 1993; Cruse et al., 1990; Proteau and Girouard, 1984; McLeod, McLaughlin, and Nimmo-Smith, 1985) and default parameters may be integrated into the motor chunk (Rosenbaum et al., 1992; Zelaznik and Franz, 1990). In addition, default parameters may be changed beforehand (Neumann, 1984) or modified on-line. On-line modification need not affect performance of highly trained movement sequences as long as the modification process exceeds processing capacity (cf. Logan and Cowan, 1984). This view is consistent with the notion that, in the end, only the intent to achieve a goal is sufficient for producing the desired action while all lower level details are left to automatic parameter specification (James, 1890; Stelmach and Hughes, 1983). For now it seems plausible that only those parameters require on-line specification that are repeatedly changed during practice. Other parameters become encapsulated in the motor chunk as defaults or are specified automatically by external information.

It should be recognized that evidence for motor chunks is usually also considered evidence for a Generalized Motor Program (Schmidt, 1976). In fact, both concepts have common characteristics like spatial coding and parameter specification. However, while the Generalized Motor Program does not explicitly assume that movement patterns include sequences of more or less elementary movement patterns, the motor chunk notion asserts that most highly practiced movement patterns are controlled by a representation at the motor buffer level which governs the sequential execution of a set of elementary movements. Whereas little has been said about the origin of the motor program, the relation between motor chunks and the motor buffer shows that motor chunks develop by consistently programming the same elements in advance. Approaching the issue of skilled motor control from a motor buffer and motor chunking point of view can be considered an update of the Generalized Motor Program concept in that it covers a broader range of tasks and indicates how motor chunks develop.

The mechanism underlying motor chunk development has been discussed by MacKay (1982) and Wickelgren (1969). They assume that executing a single element facilitates or primes execution of the next element in the motor chunk (see also Keele et al., 1990; Lashley, 1951). In this respect it relates to the classic response chaining notion. The difference with response chaining is that motor chunks concern 'internal' associations—i.e., within the representation—rather than associations that operate through the feedback that results from executing movement elements. The associations within motor chunks causes activation of individual movement elements, that is, response priming, and is assumed to be an obligatory consequence of practice (Hebb, 1949; Schneider and Fisk, 1984; cf. Logan, 1988). Response priming has been assumed to underlie sequence production in speech (MacKay, 1982), sequential keypressing (Brown and Carr, 1989), sequential key striking (Fischman and Lim, 1991), and hand writing (Hulstijn and Van Galen, 1988; Teulings, Thomassen, and Van Galen, 1986). An indication for response priming in speech is suggested by findings that components of longer words are produced faster than otherwise identical components of shorter words (Lehiste, 1970). Note that this contradicts Sternberg et al.'s (1978) observation that interelement intervals *increased* with sequence length. Perhaps this effect disappears with extensive practice. Verwey (1994c) did find that the mean effect of sequence length on individual elements decreased with practice, but he did not observe a reversal in that elements in shorter sequences took longer. Possibly, enormous amounts of practice are required for replacing Sternberg et al.'s (1978) buffer search by response priming (Verwey, 1994a, 1994b).

With respect to the notion of motor chunks as consisting of encapsulated chunks of information that are retrieved as a whole from memory, a fascinating parallel is found in a recent model by Pashler and Baylis (1991). They showed that practice with choice tasks in which artificial categories of stimuli are consistently used, each of which requiring a separate response, induces the development of integrated stimulus representations which can be prepared as a whole and which are linked to—again—spatial response locations. Like the motor chunk, practice seems to also have the potential for developing integrated stimulus categories. Furthermore, it was shown that abstract stimulus and abstract response representations may be associated (see also Proctor and Dutta, 1993). This is in line with Verwey's (1992) finding that sequence initiation times increased when, after extensive practice, the stimulus-sequence mapping was reversed. Moreover, just like the buffer can be loaded with individual elements when no motor chunk is available, Pashler and Baylis (1991) showed that ad hoc categories of stimulus groups can be constructed in the absence of an appropriate category in long-term memory (Duncan, 1977, 1978). It would be interesting to investigate further the similarities between stimulus and motor chunks and how they interact.

If the indications for the development of integrated stimulus categories, motor chunks, and their associations are valid it follows that complex human behavior can, indeed, be described in terms of production rules which specify the actions that should be carried out on basis of certain environmental conditions (Anderson, 1983, 1987; Card, Moran, and Newell, 1983; Newell and Simon, 1972). Yet, these models do not show how these integrated chunks and categories develop. Nor do they assume interactions between the execution of individual elements and the control of sequences due to capacity limitations.

4.5 Conclusions

The study of real world and artificial laboratory tasks confirms the notion that well-practiced movements and movement sequences rely on the retrieval of integrated motor chunks, rather than that the motor buffer is loaded in a time-consuming construction process. Motor chunks develop when a sequence of elementary movements is repeatedly executed in rapid succession. In line with the Generalized Motor Program it is assumed that after motor chunks have been loaded, they allow specification of parameters such as limb and general movement amplitude. In many tasks, motor chunks are dominated by a spatial representation of the movement pattern. In contrast to the Generalized Motor Program, the motor chunk notion places emphasis on a motor buffer in which the elements of a sequence are individually programmed in early practice while they are loaded in a single step when a chunk has been established. The fact that letters and stress groups can be programmed as single elements suggests that motor chunks load the motor buffer only to the a limited extent so that they function as single elements. The finding that the complexity effect does not change when each element in a familiar pattern is repeated (Van Mier and Hulstijn, 1993), suggests separable levels of control for individually programmed elements and for motor chunks. Processes responsible for the execution of individual elements are probably able to alter all elements in a uniform way such as repeating twice each individual element in the buffer. It is unclear to what extent consistent practice with a series of chunks leads to a new merged chunk and it is also not clear whether the constituents of a more elaborate chunk remain distinct entities. Finally, indications for the development of associations between representations of single stimuli and groups of stimuli as well as motor chunks support the attempts to describe complex human behavior in terms of production rules.

In sum, current notions on the motor buffer and content-specific motor chunks appear to provide an update of the concept of a Generalized Motor Program and merge the results of studies on relatively simple movements and movement sequences while also accounting for the effects of practice. This notion suggests that the production of movement patterns involves at least two levels of control which only interfere to the extent that they exceed the available processing capacity. The first level involves searching a non-shrinking motor buffer and retrieving the individual elements in proper order; at the second level the individual elements are translated into a muscular language in which force and timing are dominant. Section 5 will address how the motor buffer may be loaded and, as such, will present a third level of control.

5 ACTION PLANS AND HIERARCHICAL CONTROL

When writing words, the letter may be the unit of programming (Teulings et al., 1983; Hulstijn, 1987). Yet, these units are performed in a particular order: letters are usually written in a particular order so as to form words and sentences. And when driving a car, one produces a series of movements which have not all been programmed in advance. Still, the processing capacity required for driving a car in more complex traffic situations is very low for experienced drivers while it is markedly higher for inexperienced drivers (Verwey, 1993b). It is unlikely that this is caused by the greater difficulty inexperienced drivers have in performing the actions to control the car. There appear to be plans for placing elementary movements and motor chunks into a correct order. This section will address this issue in a critical evaluation of models of action control. It will be argued that movement in complex tasks is controlled at three levels (i.e. executing an elementary movement, producing a sequence of movements, and putting sequences in a specific order). This type of *hierarchical control*, which is inherently rigid—it is concerned with the hardware of the system—should be distinguished from the use of a *hierarchical representation* at the highest, most abstract of the three control levels, which is highly task-dependent but allows no concurrent processing.

5.1 Concatenating motor chunks: action plans

Various authors have made a distinction between movements and actions (e.g., Newell, 1978; Marteniuk and MacKenzie, 1980). While movements are characterized by a fixed spatial and temporal pattern, these factors are considered unimportant for actions. According to Newell (1978) action plans are identified by the *goal* at which they are directed (e.g., open the door, lift the weight, kill the dog). As a consequence, a variety of potential movements may be invoked to carry out an act (Bernstein, 1967) and, by the same token, a variety of movements may be identified as a particular act (Mischel, 1969).

What do goals or intentions, look like? Section 3.3 has already referred to action plans to account for the fact that tasks involving repetitive movements show no complexity effect as the sequence exceeds two elements (Garcia-Colera and Semjen, 1987, 1988; Harrington and Haaland, 1987; Van Donkelaar and Franks, 1991a, 1991b). In these tasks the action plan is likely to involve a rule representing the number of renditions (MacKay, 1983; Sternberg et al., 1990; Van Donkelaar and Franks, 1991b) rather than that the motor buffer is programmed in advance.[10]

Other indications for the existence of action plans come from analyses of complex and real-world tasks. The general idea is that intentions in these tasks are translated into more and more concrete action descriptions until, eventually, actual movements are carried out (Broadbent, 1977; Heckhausen and Beckmann, 1990; Miller et al., 1960; Norman, 1981; Powers, 1973; Reason, 1977, 1979; Simon, 1969; Vallacher and Wegner, 1987). This suggests that complex behavior is governed hierarchically, a view which relates to studies in which the use of hierarchically ordered rules facilitates the memorization and production of artificial keypressing sequences (e.g., Povel and Collard, 1982; Restle, 1970). At first sight, these studies suggest that there may be many hierarchical levels of control (see also Section 2.5). So, action plans may involve intentions and goals in more or less hierarchical structures as well as a structure counting the number of movement repetitions. Given the fact that action plans seem to take different forms, entirely depending on the task at hand, the properties of action plans are hard to define. Another problem with the notion of hierarchical control is that it is unclear how it relates to the processes assumed to make up the information processing system (Section 2.5). This issue will be discussed next.

[10] This assumption can be tested by examining the pattern of interference with a secondary task which also involves some type of counting task. Programming the motor buffer and executing a sequence should be affected much less than repeating a certain movement (e.g., Miller and Navon, 1987).

5.2 Hierarchical control

Two concepts of hierarchical control

What does hierarchical control precisely mean? There appear to be two types of hierarchical control (e.g., Broadbent, 1977). The first type assumes that there are various *independent processors*, each one receiving information from a higher level, translating it, and passing it on to a lower level. In this way, each level controls the input to the lower level (e.g., Keele et al., 1990). This type of hierarchical control can be seen in large organizations where employees at higher levels determine the general course of action and those at lower levels fill in the details. One characteristic of this type of hierarchy is that the moments of decision-making at the various levels are unrelated. The only limitation is that, since a piece of information is processed in stages, lower-order stages necessarily have to await information from higher levels. With respect to the production of movement patterns, it is postulated that this type of hierarchical control relates to and is limited by the structure of the information processing system, that is the 'hardware'.

The second notion regarding hierarchical control is that of *transfer of control*, which denotes that there is *a single processor* which carries out operations regarding various levels of a hierarchical representation, in succession. So, the tasks of this processor are represented in a plan which may have hierarchical properties. Whether or not this is the case depends on the task at hand. The important characteristic is that there is only one processor which interprets a plan or, in case of a hierarchical representation, traverses a hierarchically tree. An example of a hierarchical tree of goals and intentions is the act of driving to a destination. In that situation, the highest level intention is to drive to a specific destination (strategical level—Michon, 1985; Rasmussen, 1983), at a lower level this intention is translated into subgoals such as interacting with other traffic (tactical level). At the lowest level, individual movements are selected and executed (control level). This type of hierarchical control is based on the 'software' of the system and is highly flexible. In that case, hierarchical control "lies in an abstract description of the state of the 'production system' in Long Term Store, not in the existence of processors at different levels or anything of that sort" (Broadbent, 1977, p.189). With respect to the structure of the information processing system this type of task control is less interesting in that its characteristics are largely task-dependent and not, or to a much lesser degree, system-dependent.

Three levels of control

With respect to the production of movement sequences it is imperative to separate these two concepts of hierarchical control (Broadbent, 1977; Fodor, Bever, and Garrett, 1974). With respect to the control of movement sequences by more or less independent processors—which may operate at the same time—there appear to be three levels of control (Sections 3 and 4): the level of the action plan, the motor buffer level, and more peripheral levels, responsible for executing elementary movements. This notion clearly relates to a multi-processor view in which decisions are being made at three levels. The notion that there should be a third level relies on the logical deduction that motor chunks and movements should be concatenated by some plan. But is there any empirical evidence for such a plan?

In line with Broadbent (1977), Sternberg et al. (1990) argued that truly hierarchical control implies that elements at one level of the hierarchy should not be affected by changes at another level. They tested this hypothesis in speech and typing and found evidence for two levels: a level comparable to the motor buffer and one at the level of executing single elements. Evidence for further levels of control were not found since changes at one level affected performance at the higher or lower-level.

However, there are indications that Sternberg et al.'s (1990) element-invariance requirement is too strict. Section 3 showed that in rapidly performed sequences, executing individual movements and programming forthcoming ones interfere in that execution and programming are carried out more slowly (see Verwey, in press). Only at lower rates these levels may be entirely independent.

One strong indication for independence between executing movements from the motor buffer and control exerted by a higher level comes from the observation that, given that individual elements in a response group were slowed when followed by a next element (Verwey, 1994b) and that a response group was slowed when a next response group followed it, these effects were *additive* (Verwey, 1994c). This finding suggests that, in contrast to what Sternberg et al. (1990) claimed, *control at different levels need not be entirely independent since it may draw on a shared limited processing capacity*. Still, independence is indicated by the fact that different factors affect different stages and, hence, have additive effects on the interval times.

Further evidence against Sternberg et al.'s (1990) assertion that control at different levels should be independent comes from the observation that the last elements in repetitive movement sequences and in writing were slower at the end of the sequence. This was attributed to on-line activation of a stopping mechanism (Garcia-Colera and Semjen, 1987; Hulstijn and Van Galen, 1983; Van Galen et al., 1986). Together, this section suggests that complex movement patterns are controlled by more or less independent processes at three levels. These levels are not entirely independent in the sense that activity at one level may slow activity at another level. Only at submaximal rates they may be entirely independent. The attractiveness of this view is that there is some evidence that the processes at these three levels can be identified as additive processing stages and, hence, have their own characteristics. This notion will be elaborated in Sections 6 and 7.

Traversing hierarchical representations

At first sight many studies seem to favor the idea that there are more than these three levels of control. On second sight, these studies are concerned with behavior that is controlled by a single processor which traverses a hierarchical description of the task; they are not consistent with the idea of control exerted by independent processors at several levels.

One type of study providing support for this type of hierarchical control investigated the production of artificial sequences. These sequences appear more easily retained when they are constructed by applying hierarchically ordered rules (e.g., Povel and Collard, 1982; Restle, 1970; see also Section 2.2). These studies suggested control by a hierarchical representation in that more errors occurred at some than at other positions in the sequence. In more recent research, the use of hierarchical control was suggested by timing data as well (Gordon and Meyer, 1987; Rosenbaum, Kenny, and Derr, 1983; Kornbrot, 1989). Rosenbaum et al. (1983) proposed that once the hierarchical structure has been prepared, the sequence is executed by a single control process traversing the tree. They stated that "a complex decision-making process occurs before the execution of each response" (p.100). This is not expected when individual elements in a programmed sequence are executed.

In daily life, some types of errors are characterized by the fact that they tend to occur when one is performing familiar actions without paying much attention to them. In addition, they tend to continue for some time without being noticed (Freud, 1941; Heckhausen and Beckmann, 1990; Mannell and Duthie, 1975; Miller et al., 1960; Norman, 1981; Reason, 1977, 1979). Performance of the actions per se appears to be normal but they are simply out of context. These findings have been interpreted in terms of hierarchical control. They are consistent with the notion that the errors resulted from the fact that the relevance of the action was not matched against the higher order intention. An explanation in terms of an error made by a high level processor in a multi-processor system is less likely in that a higher level processor, which would remain active all the time, should have noted a deviation from the intended goal and should have corrected the error rapidly. So, these types of errors are in line with the second type of hierarchical control proposed above: A hierarchical representation is used for controlling the behavioral pattern rather than that independent processors simultaneously control behavior.

Given the sequential nature of traversing the hierarchical tree—elements are not processed simultaneously—it seems fair to assume that these hierarchical representations control behavior at a single level in the information processing system. That is, only one processor deals with the representation. Most likely, this level is the action planning level as action plans are flexible and accessible to consciousness as are hierarchical goal representations. The notion that control is hierarchical in the sense that there are three more or less independent processing stages and one of them may use hierarchical representations to control its action, resolves the apparent contradiction between control at many different levels which is highly flexible but works in a purely serial fashion, and models of information processing which assume only a few processing stages but which may operate at the same time.

The Hierarchical Editor Model

Rosenbaum et al.'s (1984a, 1987) Hierarchical Editor Model (HED) probably belongs to the most cited models of hierarchical control. For this reason, this model deserves explicit attention. The HED assumes that both planning and execution of a movement sequence involve a process of traversing a hierarchical tree representation. Rosenbaum et al. (1984a) found convincing evidence in choice RT tasks for the use of a hierarchical representation when sequences were programmed. The suggestion that short sequences are *programmed* by traversing a hierarchical representation is not inconsistent with the notions in this chapter; there is nothing against a hierarchical plan at the action planning level which is used for selecting and loading elements into the motor buffer. Given the nature of the sequences the authors used—similar to those used by Restle (1970)—the use of a hierarchical representation for determining which movements to program is not surprising.

However, the claim that *execution* involves hierarchical control receives limited support from the data. In fact, Rosenbaum et al. (1984a) appear to have found evidence for only two levels of control in that stimulus-dependent elements were preceded by a longer interval than elements that did not depend on the stimulus (see, e.g., Figure 4 in Rosenbaum et al., 1984a). This is consistent with on-line programming and, hence, with control at two levels (Verwey, in press). In fact, Rosenbaum et al. (1984a) admitted that they obtained indications that subjects need not determine the identities of all responses in a forthcoming response sequence before the first response in the sequence is carried out. Apart from these two levels, Rosenbaum et al.'s (1984a) data do not show that there were more hierarchical levels as is claimed by the HED.[11]

So, detailed examination of the data that gave rise to the HED are in line with the notion that programming involves a hierarchical representation whereas execution relies on only two levels of control: executing a preprogrammed part of the sequence by reading the motor buffer and on-line programming of stimulus-dependent elements by loading the motor buffer.

[11] Recently, Semjen (1992) could not replicate all aspects of Rosenbaum et al.'s (1983) results. He argued that sequence production involved segments rather than elements—his subjects were trained musicians—and that segment preparation concurred with executing the preceding segment. He also pointed to the fact that his skilled subjects had a large flexibility in timing and could change strategies. This study exemplifies how control by a hierarchical plan and by a multi-process information system may have effects at the same time.

5.3 Conclusions

Besides the notion that movement can be controlled by executing single and largely ballistic elements and by a sequential search and retrieval process at the level of the motor buffer, this chapter proposes a third level of control, the action plan, which incorporates a more or less conscious level of control. The content of the action plan is largely task-specific. In repetitive movements, action plans involve a rule indicating the number of times a movement is to be repeated. Action plans may also involve intentions which are used for programming the motor buffer. In unfamiliar tasks, action plans may be dominated by verbal descriptions (Adams, 1969, 1984; Anderson, 1983, 1987; Fitts, 1964; Neumann and Ammons, 1957) while with practice action plans may include more abstract information which can be used directly to select the appropriate motor chunks.

Action plans may be structured hierarchically. However, it is imperative to distinguish control by sequentially traversing a hierarchical action plan from control in terms of processes at different levels that are active at the same time. Whether sequential movements are controlled by an action plan or by the motor buffer can be determined by examining sequence length effects on initiation and interval durations, and by examining whether there are additive effects of the presence of a next element in a response group and the presence of a next response group in a sequence of response groups.

The effect of action plans on the timing of the individual elements of sequences is limited when the motor buffer is used for on-line programming of parts of the sequence. In that case, programming and execution may concur (e.g., Semjen, 1992). Action plans may also be used for programming the buffer in advance. In that case, properties of the action plan may be determined from error patterns without affecting interval data. The fact that planning and execution may diverge is demonstrated by the fact that the typical word frequency effect (Shaffer, 1973; Rosenbaum, 1991) disappears when there is ample time for preparation (Sternberg et al., 1978; see also Verwey, 1994c).

With respect to well practiced tasks the level of control may vary across and within experiments and, probably, even within a single subject in that sequence production may sometimes depend on the programming and execution of motor chunks—in that case action plans play no role during execution—and sometimes on the programming and execution of individual elements in the motor buffer—and the motor buffer plays no role. Only when a detailed action plan is no longer available and there are only motor chunks, the execution of an overlearned behavioral pattern cannot be controlled by an action plan. This is seen in overlearned tasks which deteriorate when one tries to execute them more 'consciously', like in sports. Control by an action plan probably misses the low-level smoothening as found with the various types of anticipatory effects that are possible with motor chunks (Section 4). Sometimes, the order of elements may not even be available at the level of action planning.

Note that there is an interesting parallel between the notions of three levels of control in this chapter and the two levels of control suggested in implicit sequence learning (Cohen, Ivry, and Keele, 1990; Curran and Keele, 1993). Possibly, the implicitly learned sequences rely on the presence of motor chunks whereas action planning is required to decide on the course of action in ambiguous situations where different elements may follow another. The relation between implicit sequence learning and the notions expressed in the present chapter certainly needs empirical pursuit.

6 INFORMATION PROCESSING AND SEQUENCE PRODUCTION

In the previous sections the conclusion was drawn that the production of sequences of movements involves simultaneous activity at at least three levels of processing. This section will pursue the possibility that the processes at these levels are related to the processes that have been postulated in the various information processing models developed in the domain of single movements in simple and choice RT tasks. In addition, Sternberg et al.'s (1978, 1980, 1988) Subprogram Retrieval Model will be taken into account as this model aims directly at the processes responsible for executing sequence elements.

6.1 Discrete processing stages in various information processing models

One important assumption of cognitive psychology is that reactions are carried out by way of information flow through a series of distinct and contingent mental processes or *stages* related to perception, decision, and response execution (Broadbent, 1958; Donders, 1868/1969). Various models have been proposed in more or less recent years.

A comprehensive line of research addressing processing stages was started by Sternberg (1969). The rationale of Sternberg's (1969) method is that processing stages can be derived from the effect of simultaneous manipulation of two task variables. Additive effects of the variables suggest that the variables affect different stages, interactive effects indicate that the variables influence a single stage (for a detailed discussion of the assumptions see Miller, 1988; Sanders, 1980, 1990). The method is commonly known as the Additive Factor Method (AFM). This section will discuss the most recent empirical summary of the model which was advanced by Sanders (1990). With respect to motor stages, Sanders (1990) referred to two lines of research. One line, mainly carried out by Spijkers and colleagues, regards aiming movements (e.g., Spijkers and Sanders, 1984; Spijkers and Steyvers, 1984; Spijkers and Walter, 1985; Spijkers, 1987). The other line of research involved handwriting and was carried out by Van Galen and co-workers (Van Galen and Teulings, 1983; Meulenbroek and Van Galen, 1988). Given the different nature of both types of studies it is not always clear whether the stages found in either line of research are comparable so the resulting stage structures are separately presented in the overview displayed in Table II.

Table II Overview of processing stages observed in movement preparation and execution. Numbers denote analogous processing stages. Underlined stages are assumed to be carried out after identification of the imperative stimulus or, in simple RT, after detection of the go-signal.

process or stage	affecting variables	general process label
Spijkers (1989); Sanders (1990): AFM, single keypress and aiming movements, simple/choice RT in aiming		
1 Response Selection	S-R compatibility relative S-R frequency	
2 Motor Programming	speed, direction force, distance	
6 Motor Adjustment	instructed muscle tension, response specificity	specific preparatory processes
Van Galen and Teulings (1983); Meulenbroek and Van Galen (1988): AFM, choice RT writing letters/lines		
1 Program Retrieval/ Motor Programming	seq. length (n=1, 2), novelty	load program from LTM
2 Parametrization	symbol size, accuracy, writing speed	specify force and time, motor activation
6 Initiation	muscle group (wrist vs. finger), direction	recruiting appropriate muscle motor units
Allen and Tsukahar (1974); Requin et al. (1984); neurophysiological correlates in animals and humans, choice RT in aiming		
1 Goal Planning	relative S-R frequency	constructing a nonmotoric code
2 Motor Programming	spatial characteristic, direction	specifying spatial and temporal characteristics
5 Movement Execution	force	specifying movement extent or force
Ivry (1986): simple and choice RT in timed isometric contractions		
1,2 Program Construction	during choice RT or foreperiod in simple RT	load timing, force activate and, with shorter contractions, force deactivate commands into buffer
3-6 Program Implementation	during simple RT and choice RT	implement commands
Sternberg et al. (1978, 1988): AFM, simple RT in speech and typing sequences		
1,2 Programming		(not explicitly addressed)
4 Search/Retrieval	sequence length (n=1..5)	self-terminating sequential search through a nonshrinking buffer (or tag?)
5 Unpacking	number of stress groups per word	

Converging evidence is provided by neurophysiological studies by Allen and Tsukahar (1974) and Requin, Lecas, and Bonnet (1984). Furthermore, Ivry (1986) studied the timed production of isometric force pulses of different durations and found evidence for the notion that force and timing are separate components and that programming involves force activation and deactivation for short pulse durations and only of force activation at longer durations; with longer durations force deactivation is programmed on-line. Ivry's (1986) model shows that simple RT involves a larger amount of advance programming than choice RT. Finally, Sternberg et al.'s (1978, 1988) Subprogram Retrieval Model of typing and speech sequences, discussed in Section 3, was also developed by applying the Additive Factors Method and describes the processes involved in producing individual sequence elements. Table II gives an overview of the processing stages inferred by these models.

Given the assumption of *stage robustness* the same processing stages should be involved in the various tasks (Sanders, 1990). However, in some tasks not every stage need to play a significant or even a distinguishable role. This suggests that at least some of the stages proposed in the various models should, in fact, involve the same functional stage. On this assumption, the numbers in Table II proposed which processing stages in the different models may in fact involve the same stage. Of course, comparison of the stages of the various models is complicated by the variety of variables and terms used and can only be tentative.

Given that Ivry's (1986) and Allen and Tsukahar's (1974) models are largely in support of the other models but are based upon different types of research, a tentative model should be derived from integrating the three AFM structures of Spijkers et al., Van Galen et al., and Sternberg et al. This task is simplified when considering some additional studies in which sequence length was factorially manipulated with another variable. So, additive effects have been observed between sequence length and: the effect of lexical decisions on words and nonwords (Osman, Kornblum, and Meyer, 1990), S-R compatibility (Inhoff et al., 1984), reversal of stimulus-sequence mapping after practice (Verwey, 1992), number of repetitions of each individual element in the sequence (Neumann and Koch, 1986; Van Mier and Hulstijn, 1993), and foreperiod duration (Hulstijn and Van Galen, 1983). In terms of Sanders's (1990) version of the stage model, these findings preclude Identification, Response Selection, and Motor Adjustment—i.e. motor preparation—as the locus of sequence programming. The observation that single vs. repeated execution of individual elements in a familiar sequence had an additive effect with sequence length on RT (Sternberg et al., 1990; Van Mier and Hulstijn, 1993) indicates that sequences are not constructed in Sternberg et al.'s (1978) Unpacking stage either. The logical need for distinguishing the retrieval of a motor chunk and the construction of a sequence from assigning kinematic parameters (e.g., Rosenbaum, 1985; Sternberg et al., 1978, 1990) suggests that what is often referred to as 'programming', includes two separate processing stages. This distinction is also found in the motor programming literature where a distinction is made between selecting a motor program—assumed to be similar to a motor chunk—and specifying parameters (Schmidt, 1976).

On basis of these considerations a *Sequence Construction* stage is postulated. The stage is responsible for loading the motor buffer. The duration of this stage is solely determined by the number of elements that is programmed in the buffer or the time needed to load a motor chunk into the motor buffer. Postulation of the Sequence Construction stage implies that, according to the AFM, additive effects are expected between sequence length and kinematic parameters such as speed, direction, and force of the first element. Future work should test these predictions. Section 7 will address this issue in more detail.

6.2 **Concurrent processing in sequence production**

Indications for on-line programming have been discussed in Section 3. It was shown there that indications for on-line processing in initiation time are not always accompanied by similar indications in execution rate (e.g., Garcia-Colera and Semjen, 1988; Rosenbaum et al., 1984a). The observation that on-line programming sometimes slows execution suggests that processes involved in sequence execution and on-line programming draw on a common source of processing capacity (Brown et al., 1988, 1989; Van Galen, 1991; Verwey, 1994b). So, in contrast to the element-invariance principle, elements in a sequence are assumed to interact (Schappe, 1965). This is consistent with the classic Gestalt principle that the whole is more than (i.e. different from) the sum of its parts, which has also been applied to the production of movement sequences (Zimmer and Körndle, 1988). Because on-line programming is still a rather ill-defined concept there is a need for distinguishing exactly which processes may concur in sequence production and what 'on-line' denotes. For one thing, there are various indications that 'on-line' does not only denote that processes that usually occur before sequence initiation, now occur later. There are indications that postponed processes may overlap with those involved in execution (Rosenbaum et al., 1984a; Garcia-Colera and Semjen, 1988; Verwey, in press). As this is usually indicated by slowing of sequence execution the term *concurrent processing* will be used rather than, for example, *parallel processing* which suggests overlap without interference (Verwey, 1994c). This section will present evidence that with practice different processes may concur during execution of a movement sequence.

Concurrent Response Selection

When the production of long movement sequences is required, or when the nature of some elements can be only identified after earlier elements have been executed, there is a need for selecting and programming forthcoming elements on-line. Research has shown various indications that selection of later elements in the sequence may concur with the execution of earlier ones. Inhoff et al. (1984) found that the effect of S-R compatibility of the first and last two responses in a four-key sequence was to slow down the execution of the second response of a four-key sequence. Given the general notion that S-R compatibility primarily affects Response Selection (Sanders, 1990; Sternberg, 1969), the third and fourth response appear to have been selected during execution of the first and second response. In another study, subjects chose between pairs of three-key sequences, with the first uncertain response in serial position one, two, or three (Rosenbaum et al., 1984a, exp.3). Choice RT decreased with distance of the uncertain response from the beginning of the sequence (see also Rosenbaum et al., 1987). Again, this supported the notion that selection and programming of the uncertain response could concur with sequence execution. Another example is that reaching was slower when more response alternatives of the ensuing grasping movement were available (Rosenbaum et al., 1992). All these studies suggest that what has been referred to as on-line programming in Section 3 includes, at least, selection of a forthcoming sequence element or in terms of the stage model, Response Selection.

Rosenbaum (1987; Rosenbaum et al., 1984a) noticed that the effect of selecting a later response was only partly reflected in the form of lengthened interelement intervals. He suggested that at least some of the processes involved in selecting and programming the uncertain response occurred *in parallel* with execution of the earlier elements, that is without delaying the execution of the earlier elements. Preliminary indications for Response Selection and Programming without interference were reported by Garcia-Colera and Semjen (1987, 1988). When the position of a stressed key tap was shifted to the end of a tapping sequence, the effect of the stressed tap was no longer reflected in RT and did also not affect tapping rate. Verwey (in press) noted that the rate of key tapping was submaximal and suggested that Response Selection effects might reappear at high execution rates. So, Verwey (in press) varied the demands on selecting the last element in a sequence of three- and five-element keypresses which were executed at maximal rate. Response Selection demand was varied by way of the compatibility of the imperative stimulus and the last key in a keypressing sequence. Earlier key presses were stimulus independent. In the five-key sequence the effect of S-R compatibility was entirely absent suggesting Response Selection without interference. In the three-key sequence the compatibility effect was found in RT as well as in the interval directly preceding the last key. With practice, however, this effect disappeared too. Since S-R compatibility is assumed to affect only Response Selection this is a clear demonstration of the possibility that next elements in a sequence may be selected on-line without slowing ongoing movements.

Concurrent Motor Programming and Sequence Construction

There are no studies in the literature that make an explicit distinction between Motor Programming and Sequence Construction. However, there are indications that both Sequence Construction and Motor Programming may occur after initiation of a sequence. With respect to Sequence Construction these indications include the observation that long sequences are not entirely programmed in advance and may be partitioned (Section 3). Indications that Motor Programming may occur after sequence initiation come from the deduction that it follows Response Selection, which was also found to concur with sequence execution (Verwey, in press), and from the observation that changing the force of a single tap in a tapping sequence was accompanied by longer intervals before and after the stressed tap (Piek et al., 1993). The extent that Sequence Construction and Motor Programming can overlap with sequence execution is unclear. This issue can be investigated by examining whether changes in kinematic parameters of a single element will, possibly only with extensive practice, disappear from interelement intervals (cf. Piek et al., 1993).

Concurrent Retrieval

As mentioned before, Sternberg et al. (1978) noticed that the interval between executing successive elements in a sequence increases with its length. This result was confirmed in other studies (Harrington and Haaland, 1987; Sternberg et al., 1988; Verwey, 1994c). This was attributed to search and retrieval from the buffer preceding each sequence element. However, this effect was not found in many other sequence production tasks (e.g., Fowler, 1981; Hulstijn and Van Galen, 1983; Huggins, 1978; Lehiste, 1980). Hulstijn and Van Galen (1983) and Sternberg et al. (1988) suggested that this difference might have been due to the fact that searching the motor buffer may have concurred with executing the earlier element, that is to concurrent Retrieval. Meulenbroek and Van Galen (1988) observed a complexity effect in line drawing and, at the same time, they found that a line was drawn more slowly when it was followed by a second one. This replicated earlier findings (Van Galen and Teulings, 1982, 1983; Van Galen et al., 1986) and was also attributed to concurrent Retrieval. Finally, there have been occasional findings of a relatively fast last element in various sequences (e.g., Brown and Carr, 1989; Rosenbaum, Saltzman, and Kingman, 1984; Sternberg et al., 1978). This was not explained in these publications but Verwey (1994b, 1994c, in press) demonstrated that the last keypress of a sequence gains more from practice than earlier ones and argued that the slower earlier keypresses reflect the development of concurrent Retrieval. This notion can be tested more directly by showing that nonfinal elements in longer sequences are slower than in shorter sequences whereas this should not hold for the last element in the sequences.

An indication that concurrent Sequence Construction and concurrent Retrieval are independent is found in the pattern of results reported by Verwey (1994b) in that the last keypress in his four-key sequence reduced more with practice than in his two-key sequence. This was attributed to the need in the two-key sequence for Retrieval to wait until the last keypress had been loaded into the motor buffer by concurrent Sequence Construction. In addition, Verwey (1994c) found that groups of keypresses, assumed to be controlled by separate motor chunks, were slowed when performed in succession but that this did not affect the fact that the last keypress was faster than the others. This suggests independence between processes involved in preparing forthcoming chunks, such as Response Selection, Motor Programming, and Sequence Construction, and those involved in Retrieving and Unpacking elements from the buffer. No studies have explicitly addressed whether Retrieval alone or Retrieval as well as Unpacking concur with executing the preceding sequence element.

Interactions between concurrent processes

With the exception of the studies by Garcia-Colera and Semjen (1988) and Verwey (in press), concurrent processing is usually indicated by slowed sequence execution. This shows that processes may interact when simultaneously active due to a limited processing capacity (Section 3). Note that this need not violate stage independencies. Processes may concur without violating the assumption of independent stages (Miller, 1988). Hence, future research may test whether processes at different stages overlap by examining whether the effect of stage variables disappears with practice. If so, this demonstrates increasing overlap with practice and Sternberg et al.'s (1990) element invariance principle, which assumes independence between levels of control in sequence production, may apply again because processing demands have reduced.

6.3 Conclusions

This brief review indicates that the major additive stage models share similarities. A Sequence Construction stage is postulated which is responsible for loading the motor buffer and which is independent from Motor Programming. Motor Programming is assumed to be associated with translating the abstract information in the motor buffer to actual movements by way of specifying kinematic variables. Whether Motor Programming follows or precedes Sequence Construction is as yet unclear. The literature shows that skilled sequence production is characterized by increasing concurrence between processes involved in selecting and retrieving elements from the motor buffer. This is typically indicated by slowed sequence execution although in the case of Response Selection, it was indicated by the absence of an effect of varying selection demands on initiation and interelement intervals. Slowed sequence execution is attributed to interactions between processes due to limited processing capacity. Computational interactions are not assumed. Little research has addressed the possibility of distinguishing concurrent processing in detail but the fact that the various processing stages may be active at the same time supports the notion in Section 5 that hierarchical control, in terms of processes that are simultaneously active, may rely on the possibility that Response Selection, Sequence Construction, Motor Programming, Search and Unpacking concur.

7 THE STAGE MODEL OF SEQUENCE PRODUCTION

7.1 Characteristics of the model

The results and theoretical views discussed in the present chapter lead to the tentative *Stage Model of Sequence Production.* This model presents hypothetical processing stages responsible for preparing and executing sequences of different movements. As with any 'new' model, there is not much new since most of the ideas derive from earlier points of view. The major ideas can be traced back to Schmidt's (1975, 1976) Generalized Motor Program, Sternberg et al.'s (1978, 1988) Additive Factors Model of sequence production, and Sanders's (1980, 1990) recent version of the Additive Factors Model of information processing in choice reaction tasks. It links to the notion that processing capacity is scarce as proposed by various capacity and resource models (e.g., Kahneman, 1973; Moray, 1967; Wickens, 1984, 1989). Finally, the model shows where the Generalized Motor Programs, postulated by Schmidt (1976), come from—i.e. from associating single movement representations into motor chunks. The Stage Model of Sequence Production is consistent with contextual interference in that it explicitly assumes that high contextual interference requires constructing unfamiliar sequences each time anew in the motor buffer.

7.2 The Stage Model of Sequence Production

Section 6 introduced stage models of information processing. For the preparation and execution of movement sequences, the various processing stages proposed in Table II can be summarized in the Stage Model of Sequence Production. This model is presented in Fig. 1. It is based on the *stage robustness* assumption: relations between experimental variables—and hence the stage structure inferred by applying the AFM—should not change as a function of the levels of the variables (Sanders, 1990). In other words, the Stage Model of Sequence Production rests on the notion that the production of a single response and the production of a movement sequence basically involve the same processing stages; the stage structure may only differ in that one or more processing stages that are active in one type of task do not affect another task. In short, the Stage Model of Sequence Production postulates that after analysis and identification of the imperative stimulus (see Sanders, 1980, 1990), an abstract response code is chosen in Response Selection, the motor buffer is loaded in Sequence Construction and movement parameters are specified in Motor Programming. Then execution starts which includes searching each next element in the motor buffer which is subsequently Retrieved and Unpacked so that the appropriate motor units are activated in Motor Adjustment. Thus, Sanders's recent version of the stage model is extended with Sternberg et al.'s (1978) Retrieval and Unpacking stages, and with the above postulated Sequence Construction stage.

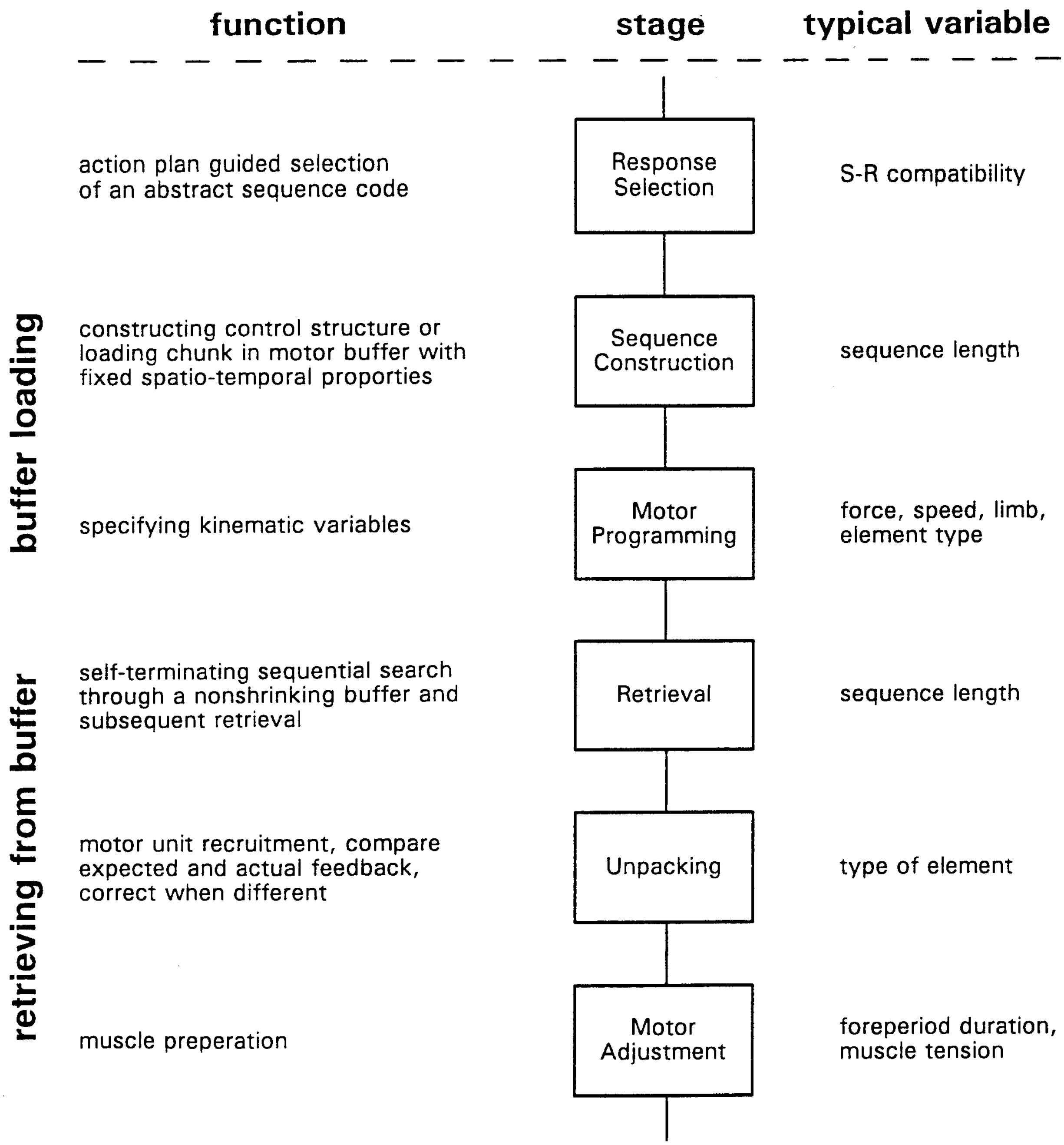

Fig. 1 The Stage Model of Sequence Production: a tentative model of the processing stages involved in the preparation and execution of relatively short sequences.

Response Selection is responsible for determining or computing the next movement. In simple reaction tasks Response Selection is assumed to occur prior to the arrival of the go-signal. In choice RT it refers to selection of the appropriate response representation from a predefined set of responses (e.g., Duncan, 1977; Pashler and Baylis, 1991). In more complex tasks, information about forthcoming movement patterns are retrieved from an action plan. So, it is in Response Selection that a hierarchically structured action plan is traversed. During this process, abstract representations for individual movements or for motor chunks are read and transferred to the next stage. The size of these codes is independent of the number of elements in the sequence it denotes (Verwey, 1994c).

With respect to practiced movement sequences, *Sequence Construction* translates the selected movement representation into a more elaborate sequence representation in the motor buffer. This representation controls the order of the sequence elements. The separate elements are still represented in an abstract code. In well-practiced tasks motor chunks can be loaded as a single unit in the motor buffer. In less well practiced tasks, Sequence Construction might involve a step-by-step process in which the individual elements are selected and stored in the buffer. In both cases, constructing the sequence takes longer as there are more constituents. That loading larger chunks still requires somewhat more time follows from the finding that the time to initiate words with more syllables is longer than with words with less syllables (Eriksen et al., 1970; Klapp et al., 1973) and that the number of line segments and letters have much smaller complexity effects in familiar than in unfamiliar figures, patterns, and words (Hulstijn and Van Galen, 1983, 1988; Van Mier and Hulstijn, 1993). However, as pointed out above, the complexity effect associated with familiar sequences, which is assumed to rely on motor chunk loading, is much smaller than that associated with constructing a new sequence in the motor buffer.

The representation in the buffer is assumed to have the same invariant characteristics as the Generalized Motor Program: sequencing of events and spatial configuration of the movement (Bernstein, 1967; Gentner, 1987; Heuer, 1988; Magill and Hall, 1990; Schmidt, 1988). Relative timing is considered an emergent feature of executing the spatial movement pattern (e.g., Terzuolo and Viviani, 1980; Van der Plaats and Van Galen, 1990; Verwey, 1994c). Motor chunks are assumed to include default parameter settings for the kinematic movement characteristics that had been fixed during practice, and subskills for translating changing aspects of the task directly into parameters (Cordo et al., 1993; Cruse et al., 1990; Neumann, 1984, 1987; Rosenbaum et al., 1992; Zelaznik and Franz, 1990). So, the use of motor chunks may make parametrization in the next stage—Motor Programming—unnecessary. This solves the problem that the distinction between invariant characteristics and parametrization is ambiguous (see Section 2): The parameters are the aspects of the movement which were variable during practice. With respect to entirely new tasks in which the selection of each next movement requires much processing, there may be little gain in saving the individual elements in the motor buffer. Hence, Sequence Construction may be bypassed in that each selected movement is executed immediately. Only when a new sequence involves few elements and subjects are required to execute the sequence rapidly, it is still useful to load the buffer in advance.

Parameters are explicitly specified during *Motor Programming* if parameter values are not included in the motor chunk as default values or if they are different from the default values. It is assumed that parameter values which are added to the content of the motor buffer are similar to those which have been discussed in relation to the Generalized Motor Program—force, general speed, direction, limb, and size. In line with the parameter remapping notion (Rosenbaum et al., 1986) Motor Programming is assumed to be concerned with parameters that hold for the entire sequence in the motor buffer. So, Motor Programming specifies the kinematic parameters only once. This is assumed to occur after Sequence Construction has loaded the buffer and before the first element of the sequence has been initiated.

Motor Programming is followed by the two processes proposed by Sternberg et al. (1978) which precede execution of each sequence element. *Retrieval* searches the motor buffer for the appropriate element and retrieves it (Sternberg et al., 1978, 1988, for related models see Lashley, 1951; Rosenbaum, 1985). In line with the Subprogram Retrieval Model a sequential self-terminating search process is assumed. So, as a sequence contains more elements the time to retrieve each element increases. This effect of sequence length should be distinguished from the effect of sequence length caused by constructing the sequence in the motor buffer. The rationale for suggesting two loci for the effect of sequence length concerns the finding of an effect of sequence length on simple RT, which is attributed to processes involved in producing individual elements (Sternberg et al., 1978, 1988), as opposed to the sequence length effect in choice RT, related to setting up a motor program. The assumption that two stages are responsible for the sequence length effect may be tested by showing that the complexity effect is larger in choice than in simple RT (cf. Sternberg et al., 1978, 1988).

After the appropriate element has been located and retrieved, the relevant motor units are recruited in *Unpacking*. Unpacking takes care that the movement is carried out as intended and, in line with the Generalized Motor Program (Schmidt, 1976), minor deviations are automatically corrected on the basis of differences between actual and expected feedback. This suggests that the motor buffer also contains information on the expected feedback for each element in the sequence. Consistent with Sternberg et al. (1978, 1988), this stage is assumed to be affected by the type of element.

Finally, *Motor Adjustment* is assumed to follow Unpacking because its existence has been postulated from the observation that variables involved in preactivating muscle groups interact (Spijkers, 1987, 1990). Hence, it is probably the last processing stage that can be distinguished. Empirical separability of Unpacking and Motor Adjustment follows from additivity of single vs. repeated execution of individual elements in a familiar sequence and foreperiod duration (Sternberg et al., 1978). The existence of Motor Adjustment was postulated from findings with relatively simple movements such as aiming.[12] In sequence production tasks this stage may not play a significant role except for the first sequence element but the stage robustness assumption warrants inclusion in the model.

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[12] Perhaps Meyer et al.'s (1984, 1985) observations of high states of advance preparation are related to those of the variables associated with Motor Adjustment.

In the Stage Model of Sequence Production timing is controlled at the Response Selection level by a clock determining the moments that subsequent response representations are being selected (Keele, 1981; Shaffer, 1982, 1984a; Rosenbaum, 1985). In sequences involving motor chunks, timing is also controlled by setting a rate parameter which determines at which rate the motor chunk is carried out. This approach to timing is consistent with the notion that timing is controlled at two levels (Shaffer, 1984b; Vorberg and Hambuch, 1978, 1984) and that timing is independent of the effector (Keele, 1987; Keele and Ivry, 1987; Keele, Pokorny, Corcos, and Ivry, 1985).

The Stage Model of Sequence Production is consistent with the notion expressed earlier that there are at least three hierarchical levels of control, each with a more or less independent processor while processors at lower levels are responsible for more fine-grained details of the movement pattern. So, Response Selection involves the selection of a movement representation (sequence or individual movement) from the action plan. In the case of a sequence these representations are used for loading the individual elements in the motor buffer during Sequence Construction, and for parametrization of the buffer content during Motor Programming. Control in the sense that the motor buffer is being read out occurs by searching and retrieving the elements from the buffer in Retrieval. These two processes may concur: retrieving movement representations from an action plan and elaborating it in the motor buffer may overlap with searching and retrieving element information from the motor buffer. At the third level, the retrieved movement elements are actually executed in Unpacking which, again, may overlap with processes responsible for both other levels of control. As stated before, these processes are subject to mutual interference in that they may be slowed by a limited processing capacity. Note that the number of processing levels decreases by one when the motor buffer is not used.

An important characteristic of motor chunks is that people are free in choosing whether to use chunks or whether to select and execute individual elements (given that their is an appropriate action plan). So, when the appropriate chunks exist, people can easily switch between loading entire sequences in the motor buffer or loading individual elements which are immediately executed. With relatively slow tasks, such as handwriting and drawing, these two modes of performing movement sequences may yield similar performance and, hence, may be used both (Hulstijn and Van Galen, 1983, 1988; Teulings, Mullins, and Stelmach, 1986; Van Galen, 1991; Van Mier and Hulstijn, 1993). Similarly, in a cycling keypressing task, Verwey and Dronkert (1994) and Verwey (1994c) observed large individual differences and suggested that people are free in using motor chunks or individual elements for loading the buffer. In their task, where the duration of both preparation and execution processes affected performance, there may have been little gain in using chunks as retrieving and loading motor chunks requires more time than when retrieving and loading single elements. In the end, the net result may be comparable. Only when a detailed action plan is absent this is not possible and movement sequences can be produced only by using motor chunks. This may occur when performing highly practiced skills, such as in sports, when the individual sequence elements are long forgotten.

7.3 Some supporting evidence

The model is consistent with many findings in motor research. For example, it is in line with the notion that force and timing are separately controlled (Freund and Budingen, 1978; Ivry, 1986; Smith, Hepp-Reymond, and Wyss, 1975; Tanji and Kato, 1973; Zelaznik and Hahn, 1985): Assuming that the relative timing of a movement sequence is determined by the motor chunk chosen at the Response Selection level, general force can be programmed separately for both hands (Heuer, 1986) in Motor Programming. The Stage Model is also in line with evidence that specification of spatial configuration is independent of specification of kinematic information (Smyth and Pendleton, 1989), and that the sequence representation does not specify the limb to perform the movement with (Fischman and Lim, 1991; Heuer, 1980; Inhoff et al., 1984; Rosenbaum, 1977, 1991; Merton, 1972; Proctor and Dutta, 1993; Zelaznik and Franz, 1990). That Response Selection and Sequence Construction are and remain separate processes, even with extensive practice, is suggested by additivity of the complexity effect and the effect of reversal of stimulus-sequence mapping after extensive practice (Verwey, 1992).

The fact that highly practiced people are usually well able of performing a second task together with producing the sequence is attributed to the fact that biomechanical limitations usually restrain production rate so that practice has the effect of freeing processing capacity for performing other tasks as well. Obviously, these tasks should not rely on the same sense and effector organs (e.g. Allport et al., 1972; Shaffer, 1975) or on the same codes in short-term memory (Navon and Miller, 1987). Only when there are virtually no biomechanical rate limitations, interference with a secondary task may not reduce with practice (Verwey, 1993a).

7.4 Closed-loop movements

The notion that sequences may involve movement elements that require closed-loop control (e.g., Adams, 1971; Schmidt, 1975) has received little explicit attention in the area of sequence production research. The Stage Model of Sequence Production assumes that high-precision aiming movements comprise at least two segments, a ballistically launched initial movement followed by a closed-loop final segment. The closed-loop segment, in turn, can be considered a movement of which the force parameter is continuously adapted on basis of feedback information. The details of the final segment can obviously not be specified in advance but it appears plausible that a single movement is programmed in advance and that the force or extent parameter is respecified repeatedly in Motor Programming on basis of feedback information (cf. Bootsma and Van Wieringen, 1990; Lee et al., 1983; McLeod et al., 1985; Neumann, 1987; Proteau et al., 1987). So, in terms of the Stage Model of Sequence Production, closed-loop aiming movements involve cycling through Motor Programming, Retrieval, Unpacking and Motor Adjustment. Feedback information is used intermittently for specifying or altering force or extent parameters. This may be performed relatively fast (Semjen, 1984; Zelaznik and Franz, 1990) but as suggested in Section 3 the capacity demands associated with this process may prevent concurrent preparation for a next element, especially with relatively unfamiliar movements. Only when required aiming accuracy is limited, cycling time may decrease—i.e. a smaller number of corrections—and processing capacity may be available for advance programming of the next aiming movement.

7.5 Effects of practice

One major problem of human movement is how the information processing system deals with the large number of degrees of freedom while processing capacity is limited (Bernstein, 1967; Turvey, 1977). In the Stage Model of Sequence Production this is solved by the inclusion of default parameters in motor chunks and the development of subskills which directly specify parameters depending on external information (Neumann, 1987). The absence of motor chunks with their default parameters and automatic parameter specification mechanisms in novices explains why they have difficulty in performing complex tasks. In contrast, experts are able to perform tasks easily by loading the appropriate action plans—facilitating Response Selection—and motor chunks—facilitating Sequence Construction. When they can execute the task so rapidly that the biomechanical properties become the main delimiter of execution rate, processing capacity is freed and indications for capacity limitations disappear from performance (e.g., Allport et al., 1972; Shaffer, 1975).

It has been stressed repeatedly that practice probably affects all stages of processing (e.g., Gallistel, 1980; MacKay, 1982; Newell and Rosenbloom, 1981). The level at which the main effect of practice occurs depends on the task requirements and on the existing repertoire of motor chunks and action plans. For reaction tasks with simple movements, the predominant effect of practice may occur at Response Selection as processing at this stage is usually least practiced in artificial laboratory tasks (Pashler and Baylis, 1991; Proctor and Dutta, 1993). With movement sequences, practice should affect initiation times and interresponse times differently as distinct stages are involved in initiating a sequence (involving Response Selection, Sequence Construction, and Motor Programming) and in executing individual elements (Retrieval and Unpacking). Different learning rates of initiation and interelement times have indeed been observed when movement sequences were practiced (Brown and Carr, 1989; Verwey, 1994b).

7.6 The Stage Model of Sequence Production and the Generalized Motor Program

In discussing the Stage Model Of Sequence Production a picture has emerged which has various commonalities with Schmidt's (1976) Generalized Motor Program. Both conceptions share the assumptions that the main structure (GMP or chunk) can be retrieved as a whole, that spatial coding is dominant, and that parametrization is required for execution. Both stress the reliance on memory and practice. Their differences originate from the fact that they were developed for different types of task. The motor chunk concept has been developed in motor sequence learning where control of sequences of relatively simple movements is stressed (Verwey, 1994c; Verwey and Dronkert, 1994). Motor programs have emerged in a field mainly interested in single movements with a stress on aiming or timing accuracy (e.g. Rosenbaum, 1980; Young and Schmidt, 1990). In terms of Cruse et al. (1990), the Generalized Motor Program concept was mainly applied in the study of analog movement control and the motor chunk in digital movement control. However, the distinction has rarely been stated explicitly and some researchers have considered the Generalized Motor Program to govern movement sequences as well (e.g., Chamberlin and Magill, 1992a,b).

The advantage of the Stage Model of Sequence Production over the Generalized Motor Program is that the Stage Model makes an explicit differentiation between processes acting at three levels of control and assumes different properties of control at these levels. This allows a more detailed process model which can account for the various types of concurrent processing discussed before. The assumption that the motor buffer can be loaded in a laborious construction process as well as by retrieving an 'off-the-shelf' motor chunk explains why highly prepared sequences do not show effects of familiarity and experience. This is shown in that digraphs are only typed more slowly as they are more unfamiliar when they could not be prepared (Larochelle, 1982; Sternberg et al., 1978) and that new, short keypressing sequences can be executed almost as rapidly as practiced ones after ample preparation time (Verwey, 1994c).

7.7 Testing the model

The Stage Model of Sequence Production rests on the notion that movement control involves three levels of control which are largely independent. The model can be tested by application of the AFM. This has its limitations in that the AFM breaks down with longer sequences of movements because longer sequences need not be programmed entirely in advance. So, additive effects of sequence length with Response Selection and Motor Programming variables may not appear when the sequence exceeds motor buffer capacity.

A further difficulty is the possibility that concurrent processes may be concealed when processing capacity limitations have not been reached. As suggested in Section 3, this may be the reason that sequences of slow movements may not show sequence length effects in their interelement intervals. In view of the notion that aiming movements may be partitioned in sequential parts, the higher level processes (Response Selection, Sequence Construction, and Motor Programming) should be tested with simple individual sequence elements, such as keypresses, which typically involve ballistic movements. This will yield little chance on interactions between levels of control due to capacity limitations. One aspect of the model which certainly requires investigation is the order of Sequence Construction and Motor Programming. It is assumed that Motor Programming follows Sequence Construction in that parameter specification would follow setting up the abstract program. Rosenbaum (1985) suggested that parameters may be used for selecting the appropriate motor program and, hence, are selected prior to the motor program or motor chunk. Future research should investigate this. On the other hand, research of the lower processes (Retrieval, Unpacking, Motor Adjustment) should involve short sequences of movements so as to prevent capacity interactions with higher level processes.

7.8 **Conclusions**

On the basis of various well-known models of (1) motor behavior, (2) the production of relatively short movement sequences, and (3) information processing, the Stage Model of Sequence Production is proposed. The model is characterized by a series of six information processing stages which only interact to the extent that there is a limited processing capacity. The model distinguishes Response Selection, Sequence Construction, Motor Programming, Retrieval, Unpacking, and Motor Adjustment. Although initially developed for the production of movement sequences, it seems to cover aiming movements as well. The Stage Model of Sequence Production extends the Generalized Motor Program in that it shows which processing stages are involved in movement production and how the processes at these stages interact.

8 GENERAL CONCLUSIONS

The present report addresses the issue of how people can become so remarkably proficient in complex tasks. It is argued that this relies on the capacity of the information processing system to process information simultaneously at at least three levels and on the use of fixed, task-dependent representations describing the elements in a rapid sequence of sequential movements. These structures have been called *motor chunks*. Furthermore, there seem to be representations at a more abstract level controlling the order of individual movements and motor chunks. These representations are termed *action plans*.

The review of the major classic notions of motor behavior introduced the basic concepts of movement production: response chaining, open- and closed-loop movement control, the Generalized Motor Program and schema theory, and hierarchically ordered levels of control in movement production. Sequences of up to about five elementary movements are produced by advance programming of the individual elements in a short-term motor buffer. This is indicated by the longer sequence initiation time as the sequence contains more elements. Longer sequences are programmed on-line: They are broken up in smaller parts or the elements are even executed immediately upon their selection. Processes involved in preparing and executing individual elements may overlap and delay each other. This suggests that they share a *single processing capacity*. Sequences consisting of elements which are produced relatively slowly due to biomechanical constraints have more possibility for overlapping or parallel processing due to the limited rate of execution. In these sequences on-line programming need not affect sequence execution.

Consistent production of the same sequence of movements yields motor chunks. Motor chunks are memory representations which can be loaded into the motor buffer in a single step. As all information in the motor buffer, motor chunks are relatively abstract, dominated by spatial codes, and require further specification by selecting the appropriate parameters. Consistent use of the same parameters during practice leads to integration of the parameters in the motor chunk. This has the effect that they need not be selected when the chunk is loaded. Also, subskills may develop which directly translate external information into the appropriate parameters. Complex action patterns are controlled by action plans stating which movements and motor chunks are to be selected next. These action plans are highly task-specific and may involve hierarchically ordered rules which are used for performing complex tasks. It is imperative to distinguish control of action by traversing a hierarchically structured action plan from hierarchical control in the sense that processes at various stages are active at the same time. Evidence has been found that processes at at least three stages may operate simultaneously. These processes are computationally independent but interference may result from sharing the limited processing capacity.

Together, the notions on the Generalized Motor Program, information processing in a series of processing stages, the development of motor chunks, and hierarchical control of movement patterns led to the proposal of the Stage Model of Sequence production. This model assumes that complex behavior involves six stages of processing: Response Selection, Sequence Construction, Motor Programming, Retrieval, and Unpacking. These processing stages are involved in the three levels that control complex behavior patterns. Proficient task performance relies on the possibility that these processes are simultaneously active and on the availability of action plans (guiding Response Selection) and motor chunks (facilitating Sequence Construction). Motor chunks can be retrieved as a whole and default parameter values eliminate the need to make explicit decisions on all degrees-of-freedom of the human movement system. This allows movement sequences to be based on sequences of motor chunks, each involving a series of more basic movements, as well as on action series involving step-by-step execution of the individual movements indicated by the action plan. As processing speed increases and required processing capacity decreases with practice, processing capacity may be freed which can be used for other tasks (i.e., diminishing secondary task interference) or for improving task performance (e.g., parameter selection is adapted better to task demands). This analysis of skilled task performance shows that the production of skilled movement is not activating 'some' motor program but involves simultaneous activity at various levels of information processing.

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11. AUTHOR(S)

W.B. Verwey

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

TNO Defence Research
Schoemakerstraat 97
2628 VK Delft

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

This report presents a review of the literature on the rapid production of sequences of movements in general and the effects of practice on sequence production in particular. A basic notion in this chapter is that a sequence of up to five movement elements can be programmed in advance by loading information on each element into a short-term motor buffer in a step-by-step manner. Subsequently, the content of this motor buffer is used for rapidly executing the entire sequence. Evidence is discussed that the programming of individual sequence elements may also occur while earlier sequence elements are executed. Due to a limited processing capacity this shows as a reduction in sequence production rate unless the individual elements are already executed slowly because of biomechanical limitations. When a particular movement sequence is practiced extensively an integrated representation of the sequence develops. This representation is termed a motor chunk. Motor chunks facilitate sequence programming in that they allow the motor buffer to be loaded in a single processing step. Individual movements and movement sequences which are controlled by motor chunks are concatenated by action plans. A distinction is made between hierarchical action plans and hierarchical control in terms of processes at different stages that are simultaneously active. Together, these notions lead to the tentative Stage Model of Sequence Production.

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