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Tracy L. Brown

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DEFINING THE ROLE OF AUTOMATICITY IN SKILL ACQUISITION: INTERACTIONS BETWEEN WORKING MEMORY AND PRACTICE IN TASK PERFORMANCE

By

Tracy Lewis Brown

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ABSTRACT

DEFINING THE ROLE OF AUTOMATICITY IN SKILL ACQUISITION: INTERACTIONS BETWEEN WORKING MEMORY AND PRACTICE IN TASK PERFORMANCE

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The existence and nature of automaticity is a hotly debated topic, representing on one hand a central component in contemporary views of skill acquisition, criticized on the other through its association with a perspective on attention and processing resources that is falling into disfavor. A review of the literature indicates that the problems confronting the concept of automaticity result from the general incoherence of current attentional theory and the failure to identify the specific changes in underlying information processing operations which correlate with the emergence of automatic performance. This paper advances a formulation of automatic processes in skill acquisition based on the assumption that task performance can be viewed as the ordered execution of a number of task components linked together in the service of an overall task goal. In this view, automaticity develops over practice when task components become directly interassociated, eliminating the need for their storage in working memory. The formation of direct interassociations (unitization) is distinguished from another logically possible class of mechanisms which may also mediate working memory demands as a function of practice (optimization). To test this framework, an experiment was conducted in which changes over practice in a speeded sequential keypressing task were studied as a function of concurrent task demands on working memory capacity, sequence length, and

frequency of sequence repetition. The results indicated that changes in working memory demand over practice could plausibly be interpreted in terms of unitization, which was manifested in the emergence of integrated motor programs for frequently practiced sequences. There was no evidence for the efficacy of optimization mechanisms in the task studied. Whether such factors play an important role in tasks with less determinate temporal structure remains an open question. It is concluded that the concept of automaticity, if conceptually linked to specific operational changes in the information processing system as practice increases, should play a useful and important role in contemporary accounts of skill acquisition.

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INTRODUCTION

The concept of automaticity corresponds to a process that is widely recognized in the phenomenology of everyday life. It refers to the gradual emergence, with practice at a task, of performance that seems effortless, fluent, and relatively free of concentration and conscious attention. It connotes the liberation of attention during performance, enabling one to concentrate on other aspects of the task at hand or to attend to something else at the same time. It implies as well that some form of change has occurred in how the task is handled; that some type of learning mechanism has come into play which fuels the transition from performance that requires effort and concentration to something that seems easy, unconscious, and sometimes unintentional.

Despite the intuitive appeal of this sort of account as a component of skill acquisition, the concept of automaticity has not been very well developed in modern psychological formulations (Navon, 1985; Schneider, 1984). Although automaticity is mentioned a great deal, and in a variety of different contexts, attempts to specify the underlying structural or information processing changes associated with automaticity have been rare (but include LaBerge, 1975; Logan, 1979; Anderson, 1982; Schneider, 1984). More often than not, treatments of automaticity have tended to enumerate the features of automatic processes rather than to explain how they got that way or why those features seem interrelated.

The purpose of the present research is to address the nature of the transition from attended to automatic performance and the task variables which make such a transition possible. In the first chapter I will

examine the strengths and shortcomings of existing conceptualizations of automaticity with respect to their coherence, systematicity, and completeness. The second chapter will build on the strengths identified previously toward a general conceptual framework in which one form of automaticity, called unitization, can be carefully defined. The third and fourth chapters delineate, respectively, the rationale and method for an experiment to test and refine the conceptualization. In chapters five and six the results of the experiment are reviewed and discussed with particular reference to the evidence for unitization and its implications for the areas of attention and skill acquisition.

CHAPTER 1

On the Status of Automaticity

While the concept of automaticity occupies a central position in many contemporary views on skill acquisition, its status as a useful and viable theoretical construct remains controversial. In this chapter I review the empirical and theoretical background in which the issues concerning automaticity are defined, concluding that the incoherence of current attentional theorizing and the relative lack of explicit formulation of the concept of automaticity lie at the heart of the current ambivalence regarding its utility and viability. In addition, some ideas are developed which may help to integrate, to some extent, the diversity of views regarding attention as it concerns the concept of automaticity.

Coherence.

The problem of coherence can be addressed by reference to the diversity of views regarding attention and to the linkage between attention and automaticity. Different views of attention have a tendency to spawn different views of automaticity. For the so-called "intraperceptual" theories of attention (Johnston & Dark, 1982; Kahneman & Treisman, 1984; Broadbent, 1982), automaticity is seen as operating in the perceptual domain and plays an important role in the early vs. late selection issue (Deutsch & Deutsch, 1963; Treisman, 1964; Norman, 1968; Treisman & Riley, 1969; Duncan, 1980; Johnston & Dark, 1982). In this

area, evidence concerning the automaticity or nonautomaticity of various perceptual processes, including word and letter perception (Posner & Snyder, 1975; Paap & Ogden, 1981; Kahneman & Treisman, 1984; Regan, 1981), perceptual selectivity (Treisman, 1964; Treisman & Geffen, 1967; Treisman, Kahneman & Burkell, 1983), and visual search (Graboi, 1971; Shiffrin & Schneider, 1977; Jonides & Gleitman, 1976), is taken as informing the viability of the concept of automaticity in general. Attention and automaticity interact somewhat differently in the area of executive control (Carr, 1979), in which capacity demands are associated with the coordination and execution of information processing operations in task performance (Anderson, 1982; Logan, 1978, 1979, 1980; Shallice, 1972). In addition, the observation of capacity limitations in working or short-term memory tasks (Miller, 1956; Waugh & Norman, 1965) has in turn stimulated an association between attention and memory processes (Atkinson & Shiffrin, 1968; Hasher & Zacks, 1979; Anderson, 1982). To the extent that these domains differ in their conceptualization of attention, so do they present diverse implications for the definition and description of automaticity. A coherent approach toward the concept of automaticity must address this multiplicity of contexts in which automaticity is discussed, with the intention of establishing some conceptual linkages between them.

Nevertheless, these varying perspectives on the problems of attention, though they give central capacity limitations a different locus in the information processing system and assign them different functions, do allow the same general approach to automatic processes--specifically, that processes that constitute "attention" are not involved in automatic performance. A more serious problem in terms of coherence stems from the increasing popularity of multiple resource views of attention (Allport, Antonis, & Reynolds, 1972; Navon & Gopher, 1979; Allport, 1980; Navon, 1984). Multiple resource models replace a unitary concept of attention with the notion of an array of more specialized resources. Thus, different tasks may require different combinations of various resources, none of which is any more central, or any more associated with the phenomenology of attention and consciousness, than any other. This type of orientation has been motivated by the finding that decrements in performance associated with simultaneous performance of a secondary task (referred to as "task concurrence costs" in dual-task performance) vary as a function of the modality of two or more secondary tasks, or that two tasks equated for difficulty produce different amounts of task concurrence costs when paired with a third task (Allport, Antonis, & Reynolds, 1972; Kantowitz & Knight, 1974, 1976). Findings of this sort indicate that at least part of the interference effect arises from non-central processes specific to modalities or "channels". Proponents of a more unitary concept of attention have adopted the notion of structural interference (Kahneman, 1973) in response to these findings. Structural interference refers to task concurrence costs arising from structural limitations of the information processing architecture which are held to be conceptually separate from interference caused by overloading a unitary pool of central resources. As Allport (1980) has noted, the concept of structural interference handles these findings nicely but fails to provide a principled means for distinguishing structural interference from capacity overload.

A major problem in evaluating multiple resource models has been that none of the advocates of this view have attempted to specify the nature, number, or organization of potential resource pools (Navon & Gopher, 1979; Allport, 1980; Hirst, 1982). Arguments for the view have tended to take one of two forms, either aggressively criticizing more unitary conceptualizations of attentional resources (e.g., Allport, 1980), or in emphasizing the explanatory power of their own view (Navon & Gopher, 1979).

In the absence of information about the nature, number, and organization of resource pools, the multiple resources orientation serves rather dismally as a backdrop for thinking about automaticity. One problem is that the multiple resources concept strips attentional theory of its traditional linkage with phenomenology and consciousness (Navon & Gopher, 1979; Posner & Snyder, 1975; Carr, 1979). If one wants to establish a scientific explanation for the feeling that performing a task requires less "effort" or "concentration" than at some earlier point in practice, then one needs some means for relating attentional resources with consciousness. In a view with innumerable, unidentified, and unorganized resources (what might be called the "chronic undifferentiated multiple resources" view) this phenomenon cannot be addressed.

A second problem stems from the indeterminance of the function and organization of resource pools. If attention is viewed as an assembly of resource pools whose function and organization is unknown, then how is automaticity to be represented? Assuming that each resource pool is itself limited in capacity (as Navon & Gopher do) one might be led to conclude that automaticity involves nothing more than non-overlapping resource requirements. Tasks performed simultaneously may interfere initially because they tap the same resource at the same point in time; interference could decrease with practice by changing the resources needed for the tasks or by adjusting their temporal coordination. From this point of view, multiple resource theories have room for notions of "restructuring" or strategy change (Cheng, 1985) and for notions of attention switching or time sharing (Broadbent, 1982; Damos & Wickens, 1980), but not for automaticity as typically conceived.

The only other option--in the absence of an explicit organizational scheme for resource pools--is the position that automatic processes utilize no resources at all. The emergence of automaticity in skill acquisition then reduces to the transition from resource-invested to resource-free performance. The evaluation of this idea hinges importantly on the definition of "resources". When "resources" are broadly conceived, in the sense that any mechanism with an identifiable function qualifies in principle as a resource, then the idea of resource-free performance translates into a strange form of dualism--automatic information processing becomes magical. This is because resources as broadly conceived would include any part of the information processing system. When resources are more exclusively defined as mechanisms with identifiable functions that are themselves limited in capacity, then to advance a formulation of automaticity necessarily entails the postulation of information processing mechanisms that are _not_ limited in capacity. This conceptualizaton has two noteworthy implications. One is that it presupposes the same type of distinction that is inherent in the more unitary views of attention that the multiple resources view is intended to replace, namely that there is some type of general or central capacity (or capacities). Second, it implies the existence of information processing systems that are unlimited in capacity, a claim which seems inconsistent with the apparent limitations of the human nervous system.

The diversity of theoretical possibilities for conceptualizing the structure and organization of attentional resources can be mind-boggling, even in the domain of unitary views of attention, and it becomes especially confusing given the added complications of multiple resource views (see Navon, 1984). Moreover, some of the options coming from multiple resource theory appear to be functionally equivalent to the more traditional notions of central capacity limitations and structural interference (Kahneman, 1973). Regardless of how one may construe these possibilities, it is clear that the conceptual background for automaticity provided by attention theory seems far from coherent; confronted on the one hand by a lack of consensus regarding the domain of phenomena to be addressed by the terms "attention" and "automaticity", complicated on the other by fundamental reconceptualizations of the nature and organization of attentional resources.

Were this picture as grim as it seems, one tempting response would be to discard the concept of automaticity as typically formulated in lieu of more analytic constructs from multiple resource theory involving interactions and tradeoffs among resource pools (see Navon & Gopher, 1979). Unfortunately, multiple resource theorists have been among the first to point out that the conceivable patterns of trade-offs and interactions between resources in a multiple resource framework are woefully underdetermined by the experimental manipulations available in dual-task methodology (Navon & Gopher, 1979; Navon, 1984). Navon (1984) has recently argued that it is impossible to prove the necessity of a concept of resources in accounting for dual-task performance and apparent capacity limitations, and has gone so far as to take the initial steps toward a model of "attention" that has no limited capacity resources (Navon, 1985).

One can understand Navon's pessimism when endeavoring to disambiguate the findings of research on dual-task performance equipped with a multiple resources framework that makes no assumptions about the nature, number, or organization of the resources mediating performance. There are indications, however, of a path leading out of this theoretical morass (see Posner, 1982), which may not only clarify a conceptual framework for automaticity but also provide a bridge between the "chronic undifferentiated" multiple resources view and the more traditional unitary, centrally-limited capacity model.

The first indication lies in the observation that the experimental data motivating the multiple resources view provides evidence only for specific resources, not against the existence of general or central resources existing in addition to specific resources (Allport, 1971; Allport, Antonis, & Reynolds, 1972; Kantowitz & Knight, 1974, 1976; Gopher, Brickner, & Navon, 1982). For example, in the investigation of Allport et al (1972) variations in task concurrence costs as a function of secondary task modality are taken as evidence for specific resources, which is presented as evidence against the notion of a general purpose central capacity. What the authors fail to consider is that there were significant amounts of task concurrence costs for all primary-secondary task combinations, which provides equally direct evidence for the existence of general resources, in addition to modality-specific ones (see Carr, 1979; and Posner, 1982; for similar arguments). The case is further strengthened by the ubiquitiousness of dual-task interference between tasks that are almost totally different in terms of their input and output modalities (e.g., Keele, 1967; Johnston, Greenberg, Fisher, & Martin, 1970; Trumbo & Noble, 1970; Kahneman & Wright, 1971; Kahneman, 1973; Logan, 1976, 1979; among others).

What is suggested by these considerations is a sort of hybrid model of attention (Posner, 1982) consisting of both general and specific resources. This seems a convenient formulation in a number of respects. First, it serves as a bridge between the multiple resources view and the central capacity limitation view, integrating the empirical findings which have motivated the multiple resource notion with the phenomenological and experimental basis for central capacity limitations. In addition, it establishes a more coherent framework for thinking about the transition from attended to automatic performance, to the effect that the emergence of automaticity corresponds to a reduction of demands made on central resources through the operation of learning mechanisms enabled by increasing familiarity with the task. Thus, automaticity may be viewed as a sort of task-specific learning which produces a dedicated performance structure where central, general purpose resources are not needed (Anderson, 1982; Fitts & Posner, 1964; Keele, 1967).

As may be apparent, serious questions accompany this formulation of automaticity. What is a "central resource"? What type of mechanism can produce a decrease in the central resource commitment required for a task? First, a "central resource" may be thought of as a general purpose capacity--any limited capacity functional entity in the information processing system that is likely to be required during initial practice in a wide variety of tasks. Formulating central resources in this way entails only the proposition that some resources are more general than others; general in terms of their applicability to tasks of varying nature. It does not necessarily imply that some resources are intrinsically "central" because of their function (though this may be the case), or that "central resources" are a well-defined set whose members can be enumerated or described (though that would seem a worthwhile enterprise). Interestingly, some good candidates for "central resources" are suggested by the domains of attention described above: perceptual processing and recognition (Broadbent, 1958, 1984; Posner & Snyder, 1975; Johnston & Dark, 1982; Kahneman & Treisman, 1984;), memory processes including memory retrieval, working memory and short-term memory (Waugh & Norman, 1965; Baddeley & Hitch, 1974; Baddeley, 1976; Atkinson & Shiffrin, 1968), and executive control or response planning and preparation (Logan, 1978, 1979, 1980; Carr, 1979). The second question, involving the type of mechanisms which may mediate demands on central resources as a function of practice, will be held for a later section.

In summary, I have attempted to establish the claim that formulations of automaticity are faced with the problem of incoherence resulting from varying orientations toward "attention", including both the domain of phenomena to be addressed by the term and the more fundamental issue of its nature and function. Building on suggestions from Posner (1982) and others, I have developed a basis for dealing with the problem of incoherence, as regards the formulation of automaticity, involving the notion of a "hybrid" model of attention which integrates the features of the general purpose central limited capacity view with the multiple resources view. It should be noted that a more specific elaboration of the hybrid model is not required at this point given the scope of the present research. The strategy is to identify a particular function (or "resource") which for both logical and empirical considerations can be confidently described as central, general-purpose, limited in capacity, and linked to consciousness. Armed with a description of this resource's function, it is possible to explain how a task may engage the resource and how, with practice, the commitment required for the resource may be reduced. Whether this resource is the only central resource, or if other central resources can be identified independently, or if other functions can be shown to depend on this resource independently of whether other resources exist, are questions which can be pursued at a later time without compromising the basic thrust of the present research. Thus, I am trying to establish a conceptual framework and a concomitant experimental strategy for identifying and eventually taxonomizing these functional resources that qualify as central or general, and for explicating the mechanisms by which performance that is initially limited by reliance on these resources comes to rely less on them--and hence becomes more "automatic"--through practice.

Sytematicity and Completeness.

The problem of systematicity may be an indirect manifestation of a predominant interest in the characteristics or features of automatic processes rather than in how and why automatic processes become automatic to begin with. In part, this may be because empirical investigations involving automaticity have tended to be concerned with whether a given process is or is not automatic (e.g., word perception), rather than with a more fundamental description of the mechanisms which underly the emergence of automaticity. This has led to a relative abundance of what might be called "criterial" definitions of automaticity, in which a list of characteristics, features, or criteria is enumerated in the service of providing a decision algorithim for the automaticity or non-automaticity of a given process (LaBerge, 1981; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977; Kahneman & Treisman, 1984; Jonides, 1981; Hasher & Zacks, 1979).

Criterial definitions have their uses. Perhaps most importantly, they have generated an impressive set of characteristics or features with which a more complete treatment of automaticity must be concerned (see Table 1). While serving adequately as a decision algorithim, criterial definitions convey the impression that automaticity consists of a variety of covarying, interassociated features whose underlying dynamics are worthy of exploration. However, if one´s objective is to focus on automaticity itself, rather than to use the concept of automaticity as a supplementary feature in the description of some other process, then something more is needed.

The problem of systematicity relates to this failing of criterial definitions. In short, current formulations of automaticity are strong in identifying the characteristics of automaticity, but weak in explaining why those characteristics are interassociated and how they develop. What is needed might be called a "conceptual" definition--a description of the underlying dynamics of automaticity which takes the features identified by criterial defintions and integrates them into a

TABLE 1

Commonly Cited Features of Automatic Processes

Features/Definition	Comments/Associated Work
Cheap or free in terms of processing resources, "effort", or drain on general-purpose, limited capacity central processing mechanism.	Most frequently mentioned defining feature. See Shiffrin & Schneider, 1977; LaBerge, 1981; Hasher & Zacks, 1979; Jonides, 1981; Shiffrin, Dumais & Schneider, 1981.
Absence of task concurrence costs; automatic processes will not interfere with simultaneously performed tasks.	Exact claims depends on what is meant by a "simultaneously performed task". A corollary of above. See Posner & Snyder, 1975; Logan, 1979; Griffith & Johnston, 1977; Bahrick & Shelley, 1958.
Obligatory but capacity demanding; A fixed, predetermined, uninhibitable allocation of resources in the service of an obligatory process triggered by specific stimuli.	Typically identified in connection with Stroop and Stroop-like phenomena. See also Shiffrin, Dumais & Schneider, 1977; Navon & Gopher, 1979; Paap & Ogden, 1981; Regan, 1978, 1981.
Difficult to inhibit once started.	Shiffrin & Schneider, 1977; LaBerge, 1981; Jonides, 1981.
Difficult to inhibit <u>before</u> starting.	A stronger version of above, also conneced with Stroop-like effects. See LaBerge, 1981, and alternative interpretations of Stroop phenomena, Francolina & Egeth, 1981; Kahneman & Treisman, 1984.
Increasing stimulus control.	A derivative formulation of two preceeding.
Without intention.	See Hasher & Zacks, 1979; Posner & Snyder, 1975; Navon & Gopher, 1979, LaBerge, 1981.
Without awareness.	See same references as one preceeding.
Cannot be improved upon by practice or feedback.	See Hasher & Zacks, 1979.

TABLE 1 (continued)

Commonly Cited Features of Automatic Processes

Features/Definition	Comments/Associated Work
Resistance to modifications, inflexible.	See LaBerge, 1981.
Insensitive to changes in expectancy.	Relates to two-process formulation in work and letter perception. See Posner & Snyder, 1975; Stanovich & West, 1981; Neely, 1977. See also Jonides, 1981.
Invariant across arousal level.	In connection with the Yerkes-Dodson law. See Hasher & Zacks, 1979.
Characterized by (or limited to) simplicity.	See Hirst, Spelke, Reaves, Caharack & Neisser, 1980; Neissar, Hirst & Spelke, 1981; Lucas & Bub, 1981.
Resistant to introspective access.	Reference to "fingertip memory" and difficulty in articulating skilled performance. See Anderson, 1976, 1982.
Characterized by parallel processing.	Connected mainly to visual search task. See Shiffrin & Schneider, 1977; Neissar, 1967; Graboi, 1971.
Automatic processes are unlimited in capacity themselves.	See Kahneman & Treisman, 1984; Navon, 1975. There seems to be some confusion over whether "automatic" is taken as the absence of capacity demand on a central resource or if "automatic" is interpreted as unlimited in capacity. These are very different claims. See also Logan, 1979.

conceptual framework in which the interrelationships and underlying dynamics of these features can be explained and predicted.

The problem of completeness is closely related to the issue of systematicity. It refers to the fact that, with rare exceptions (identified below), contemporary treatments of automaticity have not attempted to describe the underlying dynamics which mediate the emergence of automaticity. While there are numerous descriptions of "attended" performance (Norman, 1968; Shallice, 1972; Kahneman, 1973; Posner, 1982), and numerous criterial descriptions of automatic performance (e.g., LaBerge, 1981), the precise nature of the transisition from attended to automatic performance seems to have been avoided.

The rationale for the present research builds on the exceptions to this description, most notably Anderson (1982) and Logan (1978, 1979, 1980). The objective is to merge these contributions with the perspective on attention developed in the preceeding section in order to develop a conceptual framework in which the issues concerning the existence and nature of automaticity can be carefully framed and investigated.

CHAPTER 2

Automaticity, Working Memory, and Skill.

The overall form of the following discussion involves the development of two general points. One is the identification of primary memory (James, 1890; Waugh & Norman, 1965) or working memory (Baddeley & Hitch, 1974; Baddeley, 1976) as a unitary central resource that is limited in capacity. The second is the adoption of what might be called a "skills assembly" view of task performance (Miller, Galanter, & Pribram, 1960; Shallice, 1972; Logan, 1978, 1979, 1980; Reason, 1979; Carr, 1979; Anderson, 1982; MacKay, 1982). Subsequent discussion will focus on the interaction between working memory and task performance and how the concept of automaticity can be addressed in this framework.

Working Memory.

In the preceeding section on the problem of coherence and the challenges of the multiple resource views, a "hybrid" model of the structure of attentional resources was outlined. The essential claim of a hybrid model is that some limited capacity resources are more "central" than others, where "central" reduces to the sense of a "general purpose" function likely to be required across a wide spectrum of conceivable tasks. The proposal I would like to advance is that a temporary storage function, related to the existing concepts of primary memory (James, 1890; Waugh & Norman, 1965), working memory (Baddeley & Hitch, 1974; Baddeley, 1976), and short-term memory (Atkinson &

Shiffrin, 1968), can be identified as a "central", general purpose limited capacity resource. (For convenience, I will refer to this hypothetical resource as working memory.) This is not to say that working memory is the only central resource, or that working memory performs only the functions ascribed to it below, or that working memory is not simply one manifestation of a more abstractly conceived central resource. The logic of this development entails only that working memory, as a temporary storage mechanism, is a limited capacity resource that is engaged by the need to retain information for a period of time during the performance of a task, and that this need is common to a wide range of tasks.

Naturally, working memory can be (and has been) conceptualized in a number of ways, as the plurality of labels with varying implications and metaphors listed above indicates. These conceptualizations include working memory as a sort of hard-wired assortment of "slots" into which information is written for short-term storage (Atkinson & Shiffrin, 1968; Norman & Rumelhart, 1975), working memory as the temporary activation of regions of long-term memory (Atkinson & Juola, 1974; Shiffrin & Schneider, 1977), and working memory as a sort of "mental blackboard" where processes write their output and read their input (Allport, 1979). At a more fundamental level, working memory might be described as a limited capacity process which establishes relational properties or associations between concepts or items in long-term memory that are not already established and stored there, and whose identity and relationship is in some sense necessary for the successful completion of a task.

With respect to the concept of automaticity being developed here, the exact dynamics of working memory are not critical so long as it can be agreed that working memory is a limited capacity entity which represents information for temporary or short-term storage. There is considerable evidence that working memory corresponds to a limited capacity resource (see Lachman, Lachman, and Butterfield, 1979). There are also good grounds for supposing that working memory is a central resource, in the sense that it ought to be required across a wide variety of tasks that might otherwise seem to have complementary distributions of resource demands (see e.g., Keele, 1967; Kahneman, 1973; Logan, 1976, 1979). Finally, if granted the view that working memory serves to represent relational information not already stored in long-term memory, then it is easy to formulate some hypotheses about what types of learning mechanisms may bring about a reduction in the working memory commitment required for a task as practice increases.

Working Memory and Task Performance.

This view of the role of working memory in task performance builds on work in the areas of skill acquisition (Anderson, 1982; MacKay, 1982; Miller, Galanter, & Pribram, 1960), attention and consciousness (Shallice, 1972; Carr, 1979), and on the role of attention in task performance (Logan, 1978, 1979, 1980; Reason, 1979). As will be evident, what these views amount to is a description of how different tasks engage working memory resources during performance. This is taken to be a prerequisite to proposing how working memory resources may not be engaged by a task that has had more practice, which is the starting point for defining automaticity.

We begin by assuming the view that any task performance situation consists of a goal (Anderson, 1982), formulated in the mind of the performer, that must be met in order for the task to be successfully completed. The route to achieving that goal will probably depend on the completion of a set of smaller goals, what might be called "sub-goals", which lead from the initial state to the desired main goal state. Each sub-goal may in turn entail more subordinate sub-goals, so that any task can be described in terms of a hierarchy of goals ranging from the overall or main goal at the top of the hierarchy to an assortment of subordinate goals which must be assembled and met in order for the main goal to be achieved. This description is highly similar to the TOTE unit (Test - Operate - Test - Exit) formulation developed by Miller et al (1960). Each goal in the hierarchy might be viewed as a TOTE unit. This type of framework is also inherent in recent treatments of skill acquisition (Anderson, 1982; MacKay, 1982).

A key assumption in the view being developed here is that, in some form or another, the information contained in this "goal-hierarchy" task description must be represented in the mind of the performer in order for the task to be successfully completed. Thus, in a novel task situation, the performer is faced with the job of figuring out how the task is done, which, in terms of this description, refers to formulating and organizing the required goals and "sub-goals". This process of assembling the "goal structure" of the task corresponds to "interpretative" (Fitts, 1964) or "declarative" (Anderson, 1982) performance, in which slow and hesitant performance is attributed to uncertainty and errors in figuring out how to accomplish the task at hand.

The second major assumption is that the goals in a goal structure, when repeatedly assembled in the service of a particular task, become directly and permanently interassociated with one another. This could be formulated, for example, in terms of a network representation where task goals are represented by nodes and their interassociations are links between the nodes that increase in strength as a function of practice at the task. The same principle can be expressed in terms of Anderson's (1982) production system approach, in which a process called composition combines two or more subordinate productions into a sort of "macroproduction". At bottom, there appears to be a number of ways that this process can be described (see also MacKay, 1982), each of which carries along slightly different constraints and implications. For present purposes, the terminology of the network representation will be used with the implicit presupposition that this basic point can be mapped into a more specialized framework when experimental evidence gives us reasons for preferring one framework over another. For convenience, the formation and strengthening of direct interassociations among goals in a goal structure will be referred to as "unitization" of the goal structure.

The concept of unitization, when combined with the preceeding discussion of working memory, enables the generation of some hypotheses about automaticity. These can be derived from the central assumption that an important function of working memory is to assemble and maintain the goal structure of a task during initial performance. After practice, the process of unitization effectively reduces the amount of information that needs to be represented in working memory during performance through having established permanent associations between the relevant goals. The process is analogous to the phenomenon of "chunking" as identified in memory for chess positions (Chase & Simon, 1973) and in digit span performance (Miller, 1956). The concept of working memory as a limited capacity mechanism which represents new relational properties between old ideas or concepts is consistent with this idea.

With regard to skill acquisition, the basic idea is that a novel task situation is likely to require a new goal structure that is not already unitized. On the other hand, many of the sub-goals for the task, which could be described as more molecular components at lower levels in the hierarchy of the goal structure, may be commonly performed entities that are already strongly unitized. Thus, the involvement of working memory may be restricted in general to the higher levels of the goal structure required by the novel nature of the overall or main goal. This suggests that novice performance involves selecting and organizing more molecular, lower-level, unitized goals and assembling them into a form that will satisfy the task's main goal, while expert performance--at least in routine skills (Hatano & Inagaki, 1983)--may involve retrieving or activating a specialized, task-specific goal structure that is already assembled, and for which the working memory requirements are minimal. In this framework, the emergence of skill in a task can be discussed in terms of the level of the goal hierarchy at which unitization has occurred--having fewer pre-unitized goals in the goal structure means greater working memory demands during performance. Unitization at higher levels reduces working memory demands and speeds performance through avoiding the need to represent or compute task goals.

The process of unitization may be illustrated with a sequential keypressing task. In this task, each of four different command labels specifies a sequence of five keypressing responses represented as digits. For example, command "set" is executed by pushing buttons 3, 2, 1, 5, and 4, in that order, where the buttons are labelled on a keyboard in front of the subject. The instructions are to punch out the keypressing sequence corresponding to the command label presented.

The goal structure for a keypressing trial in this task consists of a main goal, "complete sequence X", which consists of sub-goals designated by each digit in the sequence. Each subgoal consists of the sensory and motor processes needed to locate and press the corresponding key. In the present framework, the claim is that during initial practice at this task the associations between the command label and the other sub-goals in the goal structure must be represented in working memory because those associations are not permanently learned. After unitization, the established associations can be used to drive keypressing performance without having to be represented in working memory. The resulting savings in working memory commitment is meant to correspond to the subjective feeling that less conscious attention is required for the task, and that daydreaming or some other concurrent activity which did not seem possible before seems possible now.

It should be noted that the development of unitization requires what might be called "operational constancy". Specifically, the sub-goals subsumed under any common dominating goal must be constant in terms of their identity and sequence in order for stable associations to form. This description of operational constancy corresponds to what has been called "consistent mapping" in experiments on visual search (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977; Graboi, 1971; Kristofferson, 1972, 1977; Neisser, Novick, & Lazar, 1963; Schneider &

Fisk, 1982) and on symbol-to-keypress mapping tasks (Logan, 1979). In this research, the criteria for automaticity were met relatively quickly when the correspondence between specific stimuli (i.e., letters or digits) and specific responses was held constant. Where stimulus-response correspondence varied, however, no amount of practice was sufficient to produce what could be considered as automatic peformance.

This principle of operational constancy is taken to be the major limitation on the development of unitization in task performance. If the goal structure of a task varies continuously without repetition or patterning, then the present framework claims that the task cannot in principle be unitized. Variations in goal structure which follow a systematic pattern translates into a more complex, though constant, structure with context-dependent branching. More complex goal structures are viewed here as requiring more practice for unitization, because more associations must be formed and strengthened, but not as being impossible to unitize in principle.

Optimization.

Having defined the concept of unitization in terms of the formation of interassociations between components in task performance, it is important to consider that there are other logically possible ways in which a task's goal structure may change over practice--ways which may also be capable of producing increases in speed and accuracy and decreases in temporary storage requirements. These mechanisms, which I will refer to collectively as optimization factors, correspond to changes in the temporal and structural organization of the task other than the formation and strengthening of interassociations among task components that defines unitization. For example, one might learn after practice that some elements of the task as performed initially are actually irrelevant to the task's goal, and can be dropped out without harm. It is also possible that the task may be temporally reorganized, changing the order in which task components are executed to maximize efficiency. A third possibility is that the algorithm underlying performance is fundamentally reorganized, as in Cheng's (1985) analogy contrasting addition and multiplication. If one learns to use a multiplication algorithm instead of a serial addition strategy in mental arithmetic, the resultant savings in temporary storage requirements come from an algorithmic change rather than from the build-up of associations in an otherwise unchanged task structure. In this example, the contributions of unitization are limited to the working memory representation of the sub-goals of the addition or multiplication procedures themselves.

Another logically possible type of optimization could involve changes in the ability to discriminate between task-relevant and task-irrelevant information. During initial practice the performer might take in and store information that, with practice, is learned to be irrelevant and unnecessary to performance. As an example, consider a sorting task where forms are separated into different stacks according to a three-digit number. With practice, the performer may learn that some numbers are uniquely identified by just the first digit, and that the rest of the number need not be processed or stored. This would reduce the working memory demands of the task by minimizing the amount of information that needs to be handled during performance, a process which capitalizes on learning about regularities in the structure of task-relevant information. Such learning would seem to accrue gradually as a result of experience in the task situation, but seems conceptually quite different from the type of learning involved in unitization.

It is interesting to note that changes in the task algorithm associated with optimization may interact with the process of unitization. Dropping out, adding, or reorganizing task components may produce discontinuities in performance efficiency over practice. The speed of performance may dip downward, reflecting the transient demand on working memory before unitization of the modified goal structure is complete, and then increase towards a new and higher asymptote enabled by increased efficiency. Such irregularities in performance gain over practice could be related to the observation of plateaus in skill acquisition (see Bryan & Harter, 1899; Logan, 1985). The probability of errors might increase because of interference from old associations in the goal structure, giving rise to branching errors (Reason, 1979; Norman, 1981).

A third type of optimization relates to the temporal organization of the task. This type of optimization stems from the observation that many tasks may entail unavoidable working memory demands for information that is constantly changing (and thus cannot be unitized). Examples could include visual search under varied mapping conditions (Shiffrin & Schneider, 1977; Graboi, 1971), or the working memory representation of words or meanings in reading connected text. The point is that the amount of demand on working memory for representing this sort of information may vary during performance, being larger or smaller at one time in performance than at another. Given this temporal profile of working memory demands during performance, it is possible that these demands may be spread out or redistributed in time enabling the elimination of periods of excessive demand or the simultaneous processing of other information at a particular point in time.

In the literature on dual-task performance (Bahrick & Shelley, 1958; Damos & Wickens, 1980; Gopher & North, 1977; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; among many others) this temporal adjustment process is called "attention switching" or "time sharing". In some cases, it is offered as a theoretical alternative to automaticity (Broadbent, 1982; Damos & Wickens, 1980), though in the present framework both unitization and attention switching as described above are considered as viable possibilities, the task being to isolate the contributions of each in a particular task.

For present purposes, the most important point about attention switching is that it does not require operational constancy. To illustrate this, consider a dual-task variant of the sequential keypressing task described earlier. In this version, a sequence of digits is presented and the subject is instructed to press the corresponding keys as labelled on a keyboard. The subject must retain the digits in memory in order to complete the keypressing sequence after the digits are removed from view. On dual-task trials, a separate series of digits is presented before the keypressing sequence. The subject is asked to recall these digits after completing the keypressing. Thus, the digits to be recalled and the digits for the keypressing task must be simultaneously represented in working memory. Because the recall digits are constantly changing in identity from trial to trial they cannot be chunked, and because the keypress sequences are also constantly changing, they cannot be unitized.

Attention switching in this task would involve rapid alternation between the recall digits and the keypressing digits. In a condition where the keypressing digits were constantly changing and could not be unitized, attention switching could develop because the overall temporal organization of the task remains constant. Note, however, that unitization could not develop if the keypressing digits changed from trial to trial. This differential dependence on information constancy is the principle basis for distinguishing between attentional switching and unitization. It is worthwhile to note in addition that the development of an attention switching strategy depends on practice under dual-task conditions. If the subject is not given a chance to observe and exploit the temporal organization of concurrent performance, then attention switching would not have a chance to develop. Unitization, on the other hand, can develop without the opportunity to practice both tasks concurrently (see Logan, 1979). Thus, manipulating the amount of dual-task practice in a task provides a means for distinguishing between the contributions of attention switching (which is at heart a process that operates on between-task temporal relationships) and unitization (which is at heart a process that operates upon within-task sequential relationships).

To summarize thus far, I have developed the concept of unitization, based on previous work in skill acquisition (Bryan & Harter, 1897, 1899; Miller, Galanter, & Pribram, 1960; Keele, 1967; Anderson, 1982; MacKay, 1982), and suggested how unitization may mediate the working memory demands of a task as a function of practice. Unitization is viewed as one of potentially many mechanisms which may influence working memory demands. Several examples illustrating the additional mechanisms, classed together for present purposes as optimization factors, have been presented and discussed. While the present research focuses on the mechanisms and conditions associated with unitization, this is viewed as only the first step in distinguishing the potential variety of mechanisms which may underlie contemporary use of the term "automaticity".

One implication of this conceptual framework is that the phenomena traditionally associated with automaticity may result from a variety of interacting processes, variously potentiated by the nature of the task and the conditions of practice. "Time sharing" and "automaticity", typically viewed as competing theoretical options, may actually be closely related processes working hand in hand to reduce capacity demands in performance.

Summary.

This completes the sketch of the conceptual framework for automaticity. The research described in the next chapter is designed to determine whether automaticity occurs as defined here in reference to the concepts of unitization and working memory. It seems important to clarify, however, that this framework has some noteworthy limitations. As noted above, the current view does not address the existence or nature of "hard-wired" automatic processes (Hasher & Zacks, 1979). In addition, the focus on working memory as a passive storage mechanism has tended to obscure the potential role for automaticity in perceptual processing—an area which relates directly to a significant portion of existing work on automaticity (e.g., visual search and Stroop-like phenomena). Whether automaticity in perceptual processing is amenable to the goal structure analysis developed in this framework is a question for further development.

A more fundamental limitation is that the present formulation serves only as a sort of minimal test case for automaticity, in the sense that only one potential underlying mechanism associated with automaticity--unitization--is conceptualized with respect to a relatively narrowly defined central resource with a carefully prescribed function. Good arguments could be made for other types of automaticity that are defined with respect to other central resources or functions, the development of which would complement the present framework. How one construes these possibilities awaits a more refined and detailed model of processing resources.

Despite this narrowness, the present framework seems to serve several important purposes. One is that it may establish a more detailed understanding of the relationship between attention and skill, providing an important component in modern accounts of skill acquisition. In addition, the distinction between unitization and optimization highlights the possibility that there may be a number of ways that attention demands may be reduced with practice. The current view provides a basis for distinguishing between these possibilities. Finally, if the framework developed here is supported in the data, it may point the way toward a more fruitful conceptualization of the nature of attention.

CHAPTER 3

Overview of Research Design and Rationale

The experiment described in the next two sections was designed to lay the groundwork for a series of experiments focusing on the questions and predictions of the preceeding formulation of automaticity. In the present experiment, the principle objective was to document the occurrence of unitization as it has been described and defined above. Having established this, additional manipulations in the experiment were used to provide further details about the nature of the mechanisms underlying unitization and the conditions in which they may operate.

A sequential keypressing task, which was developed in the course of a pilot study, was used in the experiment. In this task, subjects were first asked to memorize several different digit strings (e.g., 6 - 5 - 1 - 4 - 2 - 3), and to associate each digit string with a sequence label, consisting of a single letter. The subject was drilled to a criterion on repeating the digit string when prompted with its corresponding sequence label. After the sequences were memorized, the subject was presented with a keyboard containing labelled pushbutton switches which corresponded to the digits in the sequences. Subjects were instructed to press the keys corresponding to the digit sequence when its sequence label was visually presented on a computer monitor. The task can be described as having two general components, accessing the digits in the appropriate sequence and mapping the digits into the appropriate keypressing sequence. Three dependent measures were taken from each keypressing trial: the latency from the presentation of the sequence label to the first keypress (called Time To Respond or TTR), the average latency from one keypress to the next in the series (called Fluency), and whether the sequence was completed correctly.

Two main variables in the experiment were practice and task concurrence. The practice effect concerned changes in speed and accuracy at two points in performance, one early (T1) and one late (T2) in the experiment. These points were separated by about two and a half hours of practice. Task concurrence involved the contrast between single-task trials and dual-task trials. Single-task trials were exactly the same as described above--responding to the sequence label with the appropriate keypressing pattern was the subjects' only concern. Dual-task trials could be described as single-task trials carried out in the retention interval of a digit span task. Eight digits were presented for about four seconds, followed by the presentation of the sequence label. After keypressing was completed, the subject was instructed to recall the digits. Thus, the subject had to retain the digits in working memory while processing the sequence label and completing the keypressing sequence.

The key finding in the experiment was the interaction between practice and task concurrence. Assuming that both tasks made initial demands on working memory, the finding that task concurrence costs are smaller later in practice (at T2) than earlier in practice (at T1) indicates that the working memory demands of one or both tasks have decreased. As such, the experiment was designed to isolate changes in working memory demands relative to the keypressing task, with changes attributable to practice at the digit span task being minor or, preferably, nonexistent. For this reason, all of the practice intervening between T1 and T2 consisted of single-task trials. In addition, subjects were coached in the use of a verbal rehearsal strategy to prevent the emergence of spontaneous rehearsal strategies which could have produced discontinuities in digit span performance. However, if practice related changes in digit span performance did occur, the use of a control group which did not perform dual-task trials until T2 would detect and isolate the effect. This control condition will be described in greater detail below.

There are two noteworthy points about using this task as a way of tracking the working memory demands of the keypressing task. First, since the inference is based on observing changes in task concurrence, alternative explanations involving initially non-overlapping resources, or any other "static" formulations, can be ruled out. Second, the nature of the digit span task allows a fair degree of confidence that initial interference between the tasks is occurring in working memory and not in some other resource, capacity, or function. This is because the digit span task requires no input, output, or mental computation other than that required to retain the digits during the interval in which the keypressing task is performed. This makes the idea of more "peripheral" interference between the tasks seem implausible. The logic of this approach is described in more detail by Logan (1979).

It should also be noted that the use of two chronometric dependent variables (TTR and fluency), could permit a further specification of where the two tasks interfere. The TTR variable, which is the latency from the presentation of the sequence label to the execution of the first keypressing response, would include the time required for the perceptual processing of the sequence label, the recall of the associated digit sequence, and the preparatory or activational processes needed to initiate keypressing. The fluency variable, which indicates the rapidity of keypressing once started, would include the processes by which motor control is transferred from one keypressing target to the next and the processes driving the overt execution of motor responses. Observing whether the practice by task concurrence interaction held for TTR, fluency, or both, would provide additional information about the aspects of the keypressing task which engage working memory and the mechanisms which may mediate the changes in working memory requirements.

Having established that the working memory demands of the keypressing task were reduced as a function of practice, the remaining conditions in the experiment were designed to provide further information about the nature of the mechanisms which mediated the effect. The principle goal of these additional manipulations was to determine if unitization, as formulated in the preceeding section, played a role in the reduction of working memory demands. The alternative to unitization is the class of factors referred to above as optimization. The general strategy for distinguishing these possibilities lies in the manipulation of operational constancy, which would affect these mechanisms differently. Since unitization requires operational constancy, the removal of operational constancy would wipe out the working memory savings attributable to unitization. Since optimization factors are in principle independent of operational constancy, these mechanisms would not necessarily be disrupted.

<u>Shift Conditions</u>.

The contrast conditions relating to operational constancy involved three groups of subjects in the experiment. These three groups represent two different manipulations of operational constancy and one control group in which operational constancy was not varied. The groups will be referred to as the Keyboard Shift group (KBS), the Sequence Shift group (SES), and the No-Shift group (NS). All shifts were imposed at the same point in practice, immediately before the second test period (T2).

Subjects in the Keyboard Shift (KBS) group were faced with a seemingly random rearrangement of the keys on the keyboard. The experimenter removed the switch caps from the pushbutton switches, shuffled them, and replaced them on the keyboard in a new pattern. Thus, the motoric patterns which map out the keypressing digits were changed, while the digits themselves and their corresponding sequence labels remained the same. This might be viewed as a "low-level" manipulation of operational constancy since it affected the sub-goals under a digit identity rather than the digit identities themselves (which would be dominated by the overall trial goal in the goal structure). In general, an increase in task concurrence costs following this type of shift would support a unitization interpretation.

A particularly interesting way of interpreting the keyboard shift situation lies in the possibility that performing the keypressing sequences has developed into a unitary motor program (Keele & Summers, 1976), triggered by the sequence label. In this case, performance of the keypressing sequences may no longer be mediated by the maintenance of digit identities in working memory (which is consistent with the notion of unitization). The keyboard shift manipulation would then force the subject to fall back on the digit identities to mediate their new mappings into motoric patterns. This would be consistent with Anderson's (1982) claim about the drop-out of verbal mediation in skill acquisition. In the context of motor program theory, then, a substantial increase in concurrence costs following the keyboard shift would be strong evidence for unitization. However, it must be noted that motor program theory assumes learning that is <u>sequence specific</u>. This assumption causes an interpretational problem whose redress is one of the functions of the sequence shift group.

Subjects in the Sequence Shift (SES) group were asked to learn an entirely new set of sequences and sequence labels. The keyboard layout, however, remained the same. This shift condition represents a higher-level manipulation of operational constancy than the KBS group. Since all task parameters were essentially the same with the exception of the identity and order of operations, any detrimental effects associated with the SES would be attributed to sequence-specific learning. The degree to which performance was robust against the sequence shift would indicate a role for such factors as attention switching, keyboard knowledge, and fine-tuning of motor responding and eye-hand coordination. If unitization did play a significant role in mediating working memory demands, then task concurrence costs should increase following the SES. There is, however, one version of an attention switching hypothesis that could account for an increase in task concurrence costs in this group. This is the argument that the SES has disrupted the temporal organization of the task, and hence the strategy for switching attention between tasks. The key question for this formulation is why the temporal organization of the task was disrupted in the first place. In order for the attention switching explanation to replace a unitization interpretation, the locus of the problem caused by the SES must lie outside of working memory processes. Otherwise, one cannot explain the original cause of the temporal disorganization without referring back to unitization, with a resulting formulation which necessarily involves both unitization and attention switching. For attention switching to completely explain the SES effect, the source of the disruption must lie in some sort of peripheral interference. There are a couple of considerations mitigating against this sort of interpretation. First, it is difficult to envision a way in which the SES could precipitate peripheral interference that was not present before the shift. Second, since there was no opportunity to practice dual-task trials between T1 and T2, it seems unlikely that an attention switching strategy would be able to develop. Additional considerations concerning the emergence of time sharing strategies are discussed below.

The SES group also provides information about optimization factors that may have been affected by the keyboard shift condition. These factors would support an explanation of the change in task concurrence costs over practice in terms of knowledge of the keyboard rather than sequence-specific knowledge. If, for example, the reduction of interference is due to knowledge of key positions and/or the development of a generalized set of keypressing motor programs, then the KBS condition would produce a recurrence of interference that would be indistinguishable from the predicted effect of unitization. The SES condition can disambiguate these possibilities. If all working memory savings can be attributed to keyboard knowledge rather than sequence knowledge, then the SES should not affect the load on working memory. If there is any recurrence of task concurrence costs, then unitization must play at least a partial role.

The No-Shift (NS) condition provided a baseline against which the effects of the other shift conditions could be compared. The shift effects could also be compared with each other, as well as against initial performance at T1.

In addition to the three groups mentioned above, a control group was used which did not experience dual-task trials until late in practice at T2. This group, referred to as the no-shift/no dual-task group (NS-NDT), served as a check on the possibility that the interaction of practice and task concurrence could be explained by the emergence of time-sharing strategies, since subjects in this group did not have an opportunity to experience the demands of concurrent performance.

It should be noted that all of these effects involving the shift conditions could be present in the TTR measure, the fluency measure, or both. Analysis of which shift conditions affected which components of performance would provide additional analytic detail about the mechanisms mediating reductions in the workig memory demands of performance.

Manipulation of Sequence Length.

The variation of sequence length draws its motivation from research by Henry & Rogers (1960), Sternberg, Monsell, Knoll, & Wright (1978), and Rosenbaum, Saltzman, & Kingman (1984). The relevant finding in these experiments has been that the latency to initiate a sequence of motor movements, and the rapidity with which elements in the sequence are completed, are an increasing function of the number of elements in the sequence. This sequence length effect has been found in sequential arm movements (Henry & Rogers, 1960), in speech and typewriting (Sternberg et al, 1978), and in simple finger movements (Rosenbaum et al, 1984). It has held in both simple (Sternberg et al, 1978) and choice (Rosenbaum et al, 1984) tasks. It has also occurred across a variety of different foreperiod conditions, ranging from the unavailability of any advance information about the sequence to be performed (Rosenbaum et al, 1984), to as much as four seconds of advance time with countdown signals every one second (Sternberg et al, 1978). Length effects have also been found in conditions with variable foreperiods (Sternberg et al, 1978).

The sequence length effect has uniformly been interpreted in terms of a motor program buffer concept (Sternberg et al, 1978; Rosenbaum et al, 1984). While there are a variety of different instantiations of the concept, each yielding a slightly different model (Sternberg et al discuss six models, Rosenbaum et al entertain three models, one of which has two versions), all of the explanations of the sequence length effect have in common the idea that the elements of the sequence to be performed are loaded as independent entities into the program buffer which is then searched serially for each element to be executed. Thus, the time taken to find the first element, as well as the time taken to find the remaining elements when they are due to be performed, is a function of the number of items in the motor buffer.

For present purposes, the relevant observation is that this sort of formulation seems to be inconsistent with the sort of performance structure that would result from unitization. The concept of unitization would hold that practice with specific sequences would result in the formation of direct associations between the elements in a sequence. The process of searching a motor buffer, indicating a piecemeal treatment of sequence elements, would seem at odds with the idea that performance consists of executing an integrated motor program.

This would be a problem for the concept of unitization if the experiments reporting the sequence length effect used extensive practice with specific sequences, bringing about the conditions where unitization is supposed to occur. While the Sternberg et al experiments allowed extensive practice, the sequences to be performed were changed after every block of trials, which ranged from three to a maximum of twenty-five sequence repititions. The Rosenbaum et al study had somewhat lower, yet still fairly extensive, practice levels, but also varied the sequences to be performed after every twenty-five trials. Thus, the condition of operational constancy was not met in these studies and the development of unitization would not be expected.

The question, then, is whether or not practice under conditions of operational constancy would reduce or negate the sequence length effect. If so, then the sequence length effect and the program buffer idea would be characteristic of non-automatic performance, while the notion of sequence-specific learning, involving the formation of a unitized goal structure with direct associations between elements in the performance sequence, would characterize of performance mediated by unitization.

In view of these considerations, the present experiment incorporated the manipulation of sequence length. Each subject was asked to learn six sequences, two sequences consisting of two keypresses, two sequences with four keypresses, and two with six keypresses. The measures of TTR and fluency should increase as sequence length increases during initial practice (T1). At T2, the sequence length effect should be significantly attenuated, according to predictions that would follow from unitization.

Manipulation of Sequence Frequency.

Another condition to be addressed involves the amount of practice allowed on each sequence. Half of the sequences used (one sequence at each level of length) were designated as high-frequency sequences, to be practiced extensively in the practice period between T1 and T2. The remaining sequences, the low-frequency sequences, were practiced only occasionally in the practice period. During the test phases at T1 and T2 all sequences occurred equally often.

The potential significance of the manipulation of frequency is that it can provide additional evidence regarding the role of optimization and time sharing. The outcome of interest is if task concurrence costs for low-frequency sequences are greater than for high-frequency sequences. (This analysis would be based on T2 performance since the frequency manipulation was not established at T1.) This would indicate that low-frequency sequences have higher working memory requirements than high-frequency sequences, despite the fact that both types of sequences are performed with the same degree of overall task experience. The operation of most optimization mechanisms could not play a role in the effect, since these mechanisms should work equally well for both types of sequences.

Analysis of Serial Position.

In addition to the major independent variables described above, another variable was derived by breaking down the fluency measure for the six-element sequences (L=6). This involved the analysis of the key-to-key transition latencies for each of the five transitions present in an L=6 sequence, which permitted the comparison of keypressing rates as subjects proceeded through the sequence. This analysis becomes interesting in relation to MacKay's (1982) model, which uses a concept of anticipatory priming wherein performance of a sequence is supposed to speed up later in the sequence due to forward-spreading activation in the motor program. In regard to the concept of unitization, one might expect forward-priming of the goal structure after unitization but not before. Thus, seeing a trend toward speed-up later in practice but not early in practice could provide a converging operation on the emergence of unitization. The analysis could also reveal the presence of pauses or hesitations in performance, perhaps indicative of on-line motor planning processes.

CHAPTER 4

Review of Experimental Procedures and Design

Subjects.

Sixty-four volunteers were recruited by advertisement in a local student paper announcing the availability of payment for participation in psychological research. Two of the 64 participants had to be dropped because of their inability to memorize and execute the keypressing sequences. These were replaced with two additional participants who were associates of the experimenter. All subjects were naive regarding the variables and predictions in the experiment, but were candidly informed of the overall topic of the research.

Of the 64 participants whose data was used, 63 were in the college age bracket between roughly 18 and 25 years of age. Approximately two-thirds of the participants were female. Two of the participants were fluent but nonnative speakers of English. All participants described themselves as basically right-handed (and used their right hand only in the keypressing task), with the exception of one left-hander that was assigned to the sequence shift group. Informed consent was obtained after the initial description by the experimenter of the purpose and nature of the research.

Design.

The independent variables in the experiment were practice (T1 and T2), task concurrence (single-task and dual-task), shift condition (KBS, SES, NS, and NS-NDT), sequence length (2, 4, or 6 keypresses), and sequence frequency (high or low). Shift condition was a between subjects variable and the remaining conditions were varied within subjects.

The dependent variables were Time To Respond (TTR), Fluency, and error rates. Fluency was calculated by taking the mean of the inter-keypress latencies across a sequence. In addition, the recall error rate in the digit span task on dual-task trials was recorded. The digit span error rates were analyzed in terms of practice, shift condition, sequence length, and sequence frequency.

Apparatus.

The experiment was conducted on an Apple II+ microcomputer equipped with a custom-made interface package. The keypressing keyboard was mounted on a wooden box with the face tilted about twenty degrees toward the subject. The keyboard was placed on a platform in front of the CRT, both of which were directly in front of the subject.

The switches were standard single-throw pushbutton switches with about a 4 mm throw. The switch caps were square, approximately 1.6 cm a side. Each switch was labelled with a number between 1 and 6, printed on an address label affixed to the switch cap. In the KBS condition, the switch caps, along with the affixed labels, were simply transferred from one switch to another.

The switches were arranged in a circular pattern around a central switch which was used as a starting point. The numeric identity given to the switches was not orderly with respect to position. Instead, the assignment of digit identities around the circle appeared random to the subject. (Actually, the arrangement of digit identities was sharply constrained by counterbalancing requirements.) The apparent randomness of digit-to-switch assignment was necessary because of the KBS condition, wherein rearranging the switches would ruin any orderly layout, causing the KBS manipulation to be confounded with transitioning from a systematic to an unsystematic layout. The distance from the center of a key to its nearest neighbor on either side was constant around the circle (approximately 4.5 cm).

Procedure.

The experiment began with a preliminary description of the purpose and nature of the experiment prior to obtaining informed consent. Subjects were then asked to memorize the digit sequences for the keypressing task. This involved learning the sequence label (a single consonant letter) and the two, four, or six digits associated with each label. After initial presentation, the subject was drilled to a criterion on producing the digits in correct order when provided with the sequence label. The criterion was getting all sequences right five times consecutively.

When the sequence learning criterion was reached, the subject was presented with the keyboard and the mapping of the digit sequences into keypressing sequences was explained. Subjects were instructed to make their keypressing as rapid and accurate as possible, using the index and middle fingers of the dominant hand held together to depress the switches. On dual-task trials, subjects were told to protect performance on the digit-span task at the cost of speed on the keypressing task, if some interference between the tasks seemed unavoidable.

For the digit span task, subjects were coached to use a verbal rehearsal strategy involving subvocal reptition of the span digits in the retention interval. This approach to the problem of strategy variance in digit span performance was motivated by the pilot project and by theoretical considerations following from Chase & Ericcson (1982). With regard to the pilot study, the sub-vocal repetition strategy was (perhaps surprisingly) not immediately discovered by many subjects. Despite the apparent fact that most people use such a means for short-term retention of phone numbers and other lists, their initial reaction to the dual-task trials was to drop the digits completely while engaging the keypressing task. The attempt to reconstruct the span digits after finishing was usually futile, resulting in dual-task costs loading on digit span performance rather than on keypressing speed, where the contrast between single-task and dual-task trials is needed to fuel the task concurrence by practice interaction. Explicit coaching in the maintenance of a verbal rehearsal "loop" during keypressing was intended to ensure the discovery (and hopefully the use) of the same strategy by all subjects at the beginning of the experiment, and to help make task concurrence costs load on keypressing rather than digit span performance. The continued use of the strategy was also encouraged at T2.

The second consideration, from Chase & Ericcson (1982), is that the use of a verbal rehearsal strategy tends to prevent the emergence of more sophisticated strategies later in performance. The goal in this respect was to ensure that subjects persisted in the use of the verbal rehearsal strategy so that the working memory demands of the digit span task would remain roughly constant over the amount of practice allowed in the experiment (48 trials).

After these instructions were given, the keypressing phase of the experiment was begun. The sequence of events on the single-task trials was as follows: First, a message was printed on the CRT indicating that the following trial was a single-task trial. This message was left on the screen for the same amount of time as the digits would have remained on the screen had it been a dual-task trial. The screen was then cleared, followed about 1 second later by a fixation stimulus (a plus sign), which was replaced by the sequence label after approximately 3 sec, which was left on the screen until the end of the timing interval (6.4 seconds). After the timing interval had elapsed, a feedback screen was presented which showed the latencies for each keypress in the sequence and which indicated what the correct sequence should have been. The computer then waited for the subject to press the ready key in the center of the keyboard, indicating readiness for the next trial.

On dual-task trials, the sequence of events was the same as described above except that digits were presented in lieu of the "single-task" message and the subject was asked to recall the digits prior to the presentation of the feedback screen. Recall was recorded by having the subjects repeat the memory span digits out loud. Subjects were instructed to give ordered recall. The feedback screen for dual-task trials included all of the information given for single-task trials, and included in addition information on recall accuracy in span performance.

The central key on the keyboard (called the "ready" key) was not used in the keypressing sequences themselves but served as a starting point on each trial. Subjects were instructed to depress the key at the beginning of a trial and to release it only after the sequence label appeared on the screen. Its use was intended to ensure equal hand travel distance to the beginning of any sequence. Trials in which the ready key was released prematurely were flagged as missing data.

The initial test phase consisted of the first 48 trials in the experiment, which has been referred to previously as T1. This consisted of eight repetitions of each of the six sequences, with four single-task trials and four dual-task trials for each. The order of sequence presentations was randomized independently for each subject with the constraint that each half of the test block (the first 24 and the second 24 trials) contained half of all trial types (i.e., each sequence was seen four times with two trials each under single- and dual-task conditions).

The next 300 trials in the experiment, which were all single task trials, constituted the practice block. The trials in this block were spread out over two days. The first day included the first test phase (T1) followed by 132 trials of the practice phase. These 132 trials consisted of 126 repetitions of the high frequency sequences (42 trials per sequence), and 6 repetitions of the low frequency sequences (2 trials per sequence). The second day continued the practice phase with 156 single-task trials, 144 high frequency trials (48 trials per sequence) and 12 low frequency trials (4 repetitions per low frequency sequence). In total, the practice phase yielded 270 trials of practice on the high frequency sequences (90 trials each), and 18 trials of practice on low frequency sequences (6 trials each).

The shift conditions were imposed at the end of the practice phase, immediately prior to the beginning of the final test phase (T2). At this time, the sequence shift group stopped to learn new sequences and the keyboard shift group had their keyboard rearranged. In sum, the keyboard shift group did old sequences on a new keyboard layout, the sequence shift group did new sequences on an old keyboard layout, and the no-shift group did old sequences on an old keyboard layout. Like the no-shift group, the NS-NDT group was not confronted with a shift condition.

The final testing phase (T2) began at the conclusion of the practice period. This was organized in the same manner as T1, with the same number of trials and the same randomization algorithm.

Materials and Counterbalancing.

The digits for the memory span task on dual-task trials consisted of the digits 0 through 9, excluding 7, and were selected and ordered randomly for each dual-task trial independently for each subject. Ordered recall instructions were given.

The design of the keypressing sequences was guided by six major constraints: (1) No two-key combination was used twice in the set of six sequences active for a subject at a given time. (2) All sequences within a sequence set began on different keys. Since there were six sequences and six keys, all the keys had one sequence which began on them. (3) Sequences within each level of length were roughly equated in terms of the total distance to be traversed by the hand during execution. (4) The total distance to be traversed by the hand in the four-key sequences (L=4) was exactly equal to the distance of the first four keypresses in the L=6 sequences, allowing direct comparison of keypressing fluency at equivalent serial positions between these lengths. (5) No sequence was allowed to return to a key that was already pressed in that sequence.

(6) Sequences were designed to avoid highly characteristic, unique, or symmetric mapping patterns that might cause some sequences to stand out.

In general, the counterbalancing of the sequences relative to the independent variables in the design generated three categories of control. The first category included the variables for which sequences served as their own control. This applied for the variables of practice and task concurrence, since each sequence appeared at each level of these variables within a subject. The second category was where sequences served as their own control through counterbalancing across subjects rather than within subjects. This was the case for sequence frequency, which was handled by varying sequence assignment within groups. The third category was where the properties of sequences had to be equated rather than counterbalanced, which held for the variables of shift condition and sequence length.

The complication presented by the shift conditions was that changing the keyboard layout radically altered the motor mapping pattern of the sequences. The solution to this required the derivation of two different keyboard layouts which, when a set of sequences was to be transferred from one to the other, maintained the structural constraints described above. In conjunction with this, two sets of sequences were developed that could be mapped out on either keyboard within the same constraints. Control for the properties of the sequences across the shift conditions was then accomplished by varying the keyboard layout and sequence set assignments within a group so that all of the possible combinations occurred before and after the shifts.

The difficulty with the sequence length manipulation was in ensuring that hand travel distances across different lengths were approximately equal when averaged over the keypresses in each sequence. To accomplish this, the use of short, medium, and long key-to-key transitions was balanced across sequence length, keyboard layout, sequence set and sequence frequency so that the average hand travel distance between keypresses turned out about the same for all lengths. The means were 6.50 cm for L=6, 6.49 cm for L=4, and 6.90 cm for L=2.

Finally, the sequences in the L=6 condition were designed so that the key-to-key transition distance, when averaged over the sequences in the two sequence sets, came out to be approximately equal across the five different serial positions present in L=6 sequences. This was completed to enable the analysis of fluency broken down by serial position that was mentioned previously.

CHAPTER 5

Description of Results

Overview of Variables and Data Analysis Procedures.

The principle chronometric dependent variables of the design, as described previously, were Time To Respond (TTR), and Fluency. The TTR measure was taken as the latency from the presentation of the sequence label to the switch closure of the first keypress in the appropriate keypressing sequence. The fluency measure was computed by taking the average of the interkey latencies between all of the keypresses in the sequence. In addition, a total time measure was computed by multiplying the average fluency by five and then adding the corresponding TTR value. This procedure adjusts the total time for sequences of length two and four to what they would have been had six keypresses been performed at the same rate. Thus, gross differences in total time across sequences of different length are filtered out, allowing only the computationally independent measures of TTR and fluency to influence variation of the means across levels of length. The rationale behind the development of the total time measure was to provide an overall performance metric reflecting both TTR and fluency. Having established overall performance differences through total time analyses, the data can then be broken down into the more analytic measures of TTR and fluency to determine if variation comes from one or both measures or, in the case of no total time variation, if that is achieved through constancy in both TTR and fluency or through tradeoffs between them.

Two additional chronometric analyses were performed by breaking down the fluency measure into separate interkey latencies for each key-to-key transition. In one analysis, the average interkey latency across each serial position was examined for sequences of six keypresses (L=6). In the other, the first three latencies in L=6 sequences were compared with the three latencies of L=4 sequences.

In addition to the chronometric analyses, the error rates on keypressing and the digit span task were recorded. These variables provide checks for tradeoffs between speed and accuracy and between primary and secondary tasks.

For the total time, TTR, fluency, and keypressing error rate measures the independent variables were Group (no-shift, keyboard shift, sequence shift), Practice (T1 or T2), Task Concurrence (single-task or dual-task), Sequence Frequency (high-frequency or low-frequency), and Sequence Length (2, 4, or 6 keypresses). The serial position analysis for L=6 sequences included in addition five levels of serial position (first through fifth interkey latency), but did not include sequence length (since this analysis used only L=6 sequences). The contrast of L=6 and L=4 included three levels of serial position (first through third) and two levels of length (L=6 and L=4). The analysis of digit span error rates was carried out with the same variables as total time, minus task concurrence (since the digit span task was performed on dual-task trials only).

The analyses pertaining to the NS-NDT group (which performed dual-task trials at T2 only) were planned comparisons carried out in light of the issues concerning the effects of practice on the digit span task and the contributions of practice on dual-task trials at T1. Thus, the questions to be addressed with respect to this group were: (1) whether this group was different from the other groups at T2 in digit span performance, and (2) whether the task concurrence costs for this group were any larger or smaller than the T2 task concurrence costs for each of the other groups. To address these questions, the NS-NDT group was compared individually against the no-shift, keyboard shift, and sequence shift groups in the analysis of T2 performance alone for the dependent variables of total time, TTR, fluency, keypressing error rates, and digit span error rates.

The description of the results is broken down into six general sections: (1) overall group and practice effects; (2) effects involving task concurrence, practice, and group; (3) effects associated with the NS-NDT group at T2; (4) effects associated with the serial position analyses; (5) effects involving the manipulation of sequence frequency in the practice period; and (6) effects involving sequence length, practice, and group.

Group And Practice Effects.

Overall main effects for practice were large and robust for all dependent variables with the exception of keypressing error rates. For total time, TTR, fluency, digit-span performance, and in the serial position analysis, the F-ratios ranged from 49.32 (for TTR) to 177.57 (for fluency). In the keypressing error data the practice effect was marginal, $F(1,45) = 3.25$, $p < .08$, with the means showing a small overall reduction in error rates from 13.5% at T1 to 10.7% at T2. The direction of the trend is inconsistent with a speed-accuracy tradeoff account.

The interaction of group and practice was significant for total time, TTR, fluency, and in the serial position analysis, with F-ratios ranging from 6.30 to 14.21 ($p < .01$). The means (presented in Table 2) showed a systematic decrease in the size of the practice effect across the no-shift, keyboard shift, and sequence shift groups. In the TTR data, the mean practice effect was 1629 ms for the no-shift group (from 2850 ms at T1 to 1221 ms at T2), 822 ms for the keyboard shift group (from 2620 ms at T1 to 1798 ms at T2), and 250 ms for the sequence shift group (from 2536 ms at T1 to 2286 ms at T2). In the fluency data, the corresponding means were 190 ms (434 ms to 244 ms), 126 ms (434 ms to 308 ms), and 98 ms (459 ms to 361 ms).

The group by practice interaction was only marginal in the digit span task, $F(2,45) = 2.05$, $p < .15$, and in the keypressing error rates, $F(2,45) = 2.70$, $p < .08$. In both cases, however, the trend was in the same direction as in the chronometric analyses.

Taken together, the group by practice interactions indicate that the keyboard shift and sequence shift conditions served to attenuate the size of the practice effect. The difference between the two shift conditions suggests in addition that changing sequences was more disruptive than changing keyboards.

Effects of Task Concurrence.

In the overall analyses, using the no-shift, keyboard shift, and sequence shift groups at both T1 and T2, the main effect of task concurrence was significant at the .01 level for all dependent variables as well as in the two serial position analyses. F-ratios ranged from 10.67 in the keypressing error rates to 65.70 in the total time

TABLE 2

Cell Means in the Interaction of Group and Practice for TTR, Fluency, and Keypressing Errors.

	T1	T2	Difference
TTR (ms)			
No-Shift Group	2850	1221	1629
Keyboard Shift Group	2620	1798	822
Sequence Shift Group	2536	2286	250
Fluency (ms)			
No-Shift Group	434	244	190
Keyboard Shift Group	434	308	126
Sequence Shift Group	459	361	98
Keypressing Errors (percent error)			
No-Shift Group	13.0	5.6	7.4
Keyboard Shift Group	12.4	10.2	2.2
Sequence Shift Group	15.0	16.3	-1.3

analysis. For all measures, the means indicated better performance on single-task trials than on dual-task trials. In total time, the single-task mean was 3706 ms and the dual-task mean was 4463 ms, yielding a difference of 757 ms. The corresponding means in the TTR data were 1960 ms and 2477 ms, with a difference of 517 ms. For the fluency data, the means of 349 ms and 397 ms yielded a 48 ms effect. The keypressing error data revealed a 10.5% error rate on single-task trials and a 13.6% error rate on dual-task trials.

The role given to operational constancy in the development of unitization suggests that task concurrence costs should decline with practice for the no-shift group, but not for the keyboard shift and sequence shift groups. Thus the theory predicts a three-factor interaction between group, practice, and task concurrence. This interaction produced a trend toward significance in the analysis of total time, $F(2,45) = 2.82$, $p < .07$. As expected, the no-shift group showed a significant reduction in task concurrence costs from T1 to T2, $F(1,15) = 7.26$, $p < .05$ (see Table 3). This effect was due mainly to reductions in TTR, since the same interaction occurred in the TTR data, $F(1,15) = 7.26$, $p < .05$, but was not significant in fluency or keypressing errors. The means showed a 591 ms reduction in task concurrence costs with practice for total time and a 485 ms reduction in TTR. In contrast to the no-shift group, neither the keyboard shift group nor the sequence shift group produced a task concurrence by practice interaction in any dependent measure. Thus operational constancy, both of key location as indicated by the keyboard shift group and of the sequence of key identities as indicated by the sequence shift group, does appear to be a major factor in the reduction of task concurrence

TABLE 3

Cell Means (ms) for the Interaction of Group, Practice, and Task Concurrence in the Total Time Analysis.

	T1		T2	
	ST	DT	ST	DT
No-Shift Group	4443	5594	2160	2719
Keyboard Shift Group	4412	5164	2949	3730
Sequence Shift Group	4776	5189	3799	4385

costs with practice.

The total time means for the keyboard shift group showed a 752 ms task concurrence cost at T1 and a 781 ms task concurrence cost at T2, yielding a slight (nonsignificant) increase in task concurrence costs over practice. Somewhat strikingly, this failure to reduce dual-task interference occurred despite an overall practice effect of 1148 ms, from 4788 ms at T1 to 3340 ms at T2 (in total time). In contrast, the sequence shift group showed task concurrence costs of 713 ms at T1 and 588 ms at T2, yielding a slight (nonsignificant) 125 ms decrease in dual-task interference, while at the same time showing a significantly smaller overall practice effect of 740 ms, $F(1,30) = 9.26$, $p < .01$. This outcome suggests that overall improvements in performance level are not necessarily associated with concomitant changes in capacity demand.

In sum, the evidence concerning the role of the group manipulation in mediating the reduction of task-concurrence costs over practice is relatively clear cut. With respect to the keyboard shift group, it seems quite safe to conclude that changing keyboards late in practice prevents the savings in task concurrence costs that are possible without such a change, since that group's task concurrence effect actually increased a bit at T2 relative to T1. Though the sequence shift group's task concurrence costs did go down at T2, the change was not significant, suggesting that in this case, as well, an absence of operational constancy interfered with practice-induced savings in task concurrence.

Analyses with the NS-NDT Group.

As described previously, the NS-NDT group experienced dual-task trials at T2 only, having performed single-task trials up until the last

48 trials in the experiment. The importance of this group lies in the observation that there was no opportunity to develop or refine the temporal coordination of the keypressing and digit span tasks during concurrent performance. Hence, this group can act as a control for the emergence of time-sharing or resource management strategies which might otherwise be advanced as explanations of the task concurrence reduction effect shown by the no-shift group. In addition, this group did not have the opportunity to practice the digit span task. Thus, changes in the task concurrence effect attributable to practice effects in digit performance can also be examined by comparing this group's performance to that of the other groups. Since the NS-NDT group did not produce dual-task data at T1, the following analyses were carried out with the T2 data only.

Turning first to the question of whether the NS-NDT group showed greater task concurrence costs than the no-shift group--which would indicate a role for time sharing or optimization factors--the interaction of group and task concurrence was significant for total time, $F(1,30) = 5.89$, $p < .05$, and for TTR, $F(1,30) = 4.36$, $p < .05$, but was only marginal in the keypressing error rates, $F(1,30) = 3.70$, $p < .07$ (see Table 4). Surprisingly, the means for total time and TTR revealed that the task concurrence costs for the NS-NDT group were smaller than for the no-shift group, which is the opposite from what would be expected if experience on dual-task trials played a role in the task concurrence reduction effect seen in the no-shift group. For the NS-NDT group, the single-task mean was 2306 ms and the dual-task mean was 2559 ms, yielding a 253 ms task concurrence effect. For the no-shift group, the corresponding means of 2160 ms and 2720 ms yielded a 560 ms

TABLE 4

Cell Means in the Interaction of Group and Task Concurrence Contrasting the No-Shift Group With the NS-NDT Group at T2 for Total Time, TTR, and Keypressing Error Rates

	ST	DT	Difference
Total Time (ms)			
No-Shift Group	2160	2720	560
NS-NDT Group	2306	2559	253
TTR (ms)			
No-Shift Group	1044	1397	353
NS-NDT Group	1076	1252	176
Keypressing Errors (percent error)			
No-Shift Group	4.9	6.2	1.3
NS-NDT Group	5.5	10.9	5.4

effect. However, the marginal group by task concurrence interaction in keypressing error rates suggested that the reversed interactions shown in total time and TTR were offset by a tendency for the NS-NDT group to be biased toward keypressing speed on dual-task trials. On single-task trials, the error rates for both groups were exactly equal, while on dual-task trials the NS-NDT group showed a 6% increase in error rates against a 1% increase in the no-shift group.

This pattern was augmented by the comparison of digit span error rates, which produced a marginal main effect of group, $F(1,30) = 2.91$, $p < .10$, showing a 16% error rate for the no-shift group and a 25% error rate for the NS-NDT group. The analysis also produced an interaction of group and length, $F(2,60) = 3.89$, $p < .05$, showing a 15% difference between groups at L=6, a 6% difference at L=4, and a 5% difference at L=2.

In sum, the evidence indicates that the NS-NDT group was somewhat worse at digit span performance but showed smaller task concurrence costs than the no-shift group. This pattern suggests that practice at the digit span task helped, but not by allowing the formation of a task control structure that maximized performance on both tasks. Instead, it resulted in a greater emphasis on digit span performance at the expense of keypressing speed on dual-task trials. Overall, the results do not indicate that the net interference shown by the NS-NDT group was any greater than that of the no-shift group. Thus, there is no evidence that time sharing or optimization factors played a significant role in the task concurrence reduction effect shown by the no-shift group.

The second question regarding the NS-NDT group is whether this group's task concurrence effect was any smaller than that of the keyboard shift and sequence shift groups. Comparing the NS-NDT group with the keyboard shift group produced a significant interaction of group and task concurrence for total time, $F(1,30) = 8.28$, $p < .01$, and in TTR, $F(1,30) = 5.87$, $p < .05$. The interaction was marginal in the fluency data, $F(1,30) = 3.17$, $p < .09$, and nonsignificant in the keypressing error rates. The means revealed a task concurrence effect of 781 ms for the keyboard shift group against the 253 ms task concurrence effect for the NS-NDT group reported above. The means in TTR and fluency followed the total time means, and the groups were not significantly different in digit span performance. Thus with respect to the keyboard shift group, there is straightforward evidence that task concurrence costs were smaller for the NS-NDT group.

The results regarding the sequence shift group were not so clear cut, however. The interaction of group and task concurrence was barely marginal in the total time data, $F(1,30) = 2.26$, $p < .15$, and nonsignificant in TTR, fluency, and keypressing errors. While the means in all instances favored the NS-NDT group, analysis of the cell deviations in the total time analysis suggested that greater error variance associated with the sequence shift group may have prevented the effects from reaching statistical significance. In addition, there were no significant differences in digit span performance between the groups. Given this outcome, it seems appropriate to conclude that the results of the comparison with the sequence shift group are equivocal, failing to inform the issue one way or the other.

Overall, the results of the NS-NDT group help to establish two claims relevant to the occurrence of unitization. The first is that the task concurrence reduction effect shown by the no-shift group is probably not due to time sharing or optimization factors resulting from experience with the capacity demand characteristics of dual-task trials at T1. This is established by the contrast of the NS-NDT group with the no-shift group and is indirectly supported by the interaction of group and task concurrence with the keyboard shift group. The second is that the maintenance of operational constancy produces evidence of unitization apart from prior experience with dual-task trials, relative to conditions where dual-task practice did occur but operational constancy was not maintained. This is established by the interaction of group and task concurrence with the keyboard shift group, but is compromised somewhat by the failure of the corresponding interaction to attain significance with the sequence shift group. Thus, the first point seems solid but the second point must be taken with greater caution.

Serial Position Analyses.

Two sets of analyses were performed on the fluency data broken down by serial position. The first, which compared the five interkey latencies in L=6 sequences, bears on the prediction following from MacKay (1982) that speed-up in keypressing rate at the later serial positions may reflect forward-spreading activation in the motor program. In addition, this analysis may show systematic patterns in interkey latency over serial position that may reflect on-line planning processes. The second serial position analysis contrasted the first three serial positions in L=6 sequences with the three serial positions in L=4 sequences. This analysis addressed the question of whether keypressing rates varied between lengths over equivalent serial positions.

Moving first to the L=6 analysis, which included the no-shift, keyboard shift, and sequence shift groups for both T1 and T2, the main effect of serial position was significant, $F(4,180) = 16.99$, $p < .01$. The means, from initial to final serial positions, were 445 ms, 434 ms, 507 ms, 356 ms, and 273 ms, suggesting that the effect consists of two components: a tendency to produce a peak interkey latency at serial position three, and a tendency to increase the keypressing rate at the latter two serial positions.

The peak interkey latency at position three takes on added interest in connection with the interaction of serial position and task concurrence, $F(4,180) = 4.11$, $p < .01$. The mean task concurrence costs taken across serial positions 1 through 5 were 63 ms, 54 ms, 122 ms, 43 ms, and 16 ms, reflecting a peak task concurrence effect at position three and diminishing task concurrence effects at the two later positions (see Table 5).

The pattern was further elaborated in the three-factor interaction of group, practice, and serial postition, $F(8,180) = 2.16$ $p < .05$. The means, presented in Table 6, indicate that the size of the position three "bump" effect was reduced over practice by 262 ms for the no-shift group, 179 ms for the keyboard shift group, and actually increased by 58 ms for the sequence shift group.

Taken together, these effects suggest that subjects may have been using a "divide and conquer" strategy in the L=6 sequences, pausing after the completion of three keypresses to load, prepare, or plan the execution of the remaining keypresses. It is also possible that, on dual-task trials, subjects were using the halfway point as a break to reinforce the memory span digits. In either case, the interaction of

TABLE 5

Cell Means (ms) in the Interaction of Task Concurrence and Serial Position in the L=6 Serial Position Analysis.

	Serial Position				
	1	2	3	4	5
Single Task	413	407	446	334	265
Dual Task	476	461	568	378	281
Difference	63	54	122	44	16

TABLE 6

Cell Means (ms) for the Interaction of Group, Practice and Serial Positions for Sequences of Length 6.

	Serial Position				
	1	2	3	4	5
No-Shift Group					
Time 1	500	551	569	367	309
Time 2	248	311	307	237	209
Keyboard Shift Group					
Time 1	467	527	586	484	291
Time 2	389	363	407	324	208
Sequence Shift Group					
Time 1	593	471	557	379	344
Time 2	470	381	615	397	277

group, practice, and serial position, showing that the bump effect was attenuated more for the no-shift group than for the other groups, suggests that the tendency to "divide and conquer" lessens when operational constancy is maintained. The modest attenuation of the bump effect shown by the keyboard shift group might be viewed as an intermediate case where the constancy of the keypressing digits reduces the bump effect to reflect only the costs associated with planning the new motor mapping. In general, the results are consistent with the idea that practice with constant sequences and motor mapping patterns gives rise to the development of an integrated motor program with a corresponding trend away from piecemeal treatment of sequence elements.

A final point to bring out in the L=6 analysis regards the question of speed-up across serial position. Previously, it was noted that MacKay's (1982) model of skill acquisition advanced a concept of forward-spreading activation in the motor program. In the model, such feed-forward activation is said to prime upcoming elements in a motor sequence, producing a speed-up in the rate of responding as one progresses through the sequence. As noted above, examination of the means presented in Table 6 does reveal a tendency toward speeded execution at the later serial positions, though the effect is complicated by the ubiquitousness of the "bump" effect at serial position three. There is also a trend for task concurrence costs to get smaller toward the end. It is interesting to consider whether the construct of feed-forward activation in the motor program should be advanced as an account of the effect, or if the trend can be more readily interpreted as a cost associated with the planning of upcoming motor movements. Examination of the means in Table 6 suggests that the tendency toward speed-up holds generally in all conditions--at T1 as well as T2 and in the keyboard shift and sequence shift conditions as well as the no-shift and NS-NDT groups. Inasmuch as the effect holds in conditions such as T1 and in the sequence shift group, where the evidence suggests that performance was piecemeal in nature rather than the result of a previously established motor program, it seems clear that the more parsimonious option involving planning of upcoming motor movements ought to be preferred.

The final serial position analysis to discuss is the contrast of the first three keypresses of L=6 sequences with the three total keypresses in L=4 keypresses. As described previously, this contrast provides a test of the length effect over equivalent serial positions. The analysis, using two levels of length (L=6 and L=4), and three levels of serial position (first, second, and third) produced a main effect of length, $F(1,45) = 30.08$, $p < .01$, an interaction between length and serial position, $F(2,90) = 10.14$, $p < .01$, and a three-factor interaction involving length, task concurrence, and serial position. Looking at the means of the length by serial position interaction, the values for the L=6 sequences of 445 ms, 434 ms, and 507 ms across positions one through three reflect of course the same trend as noted previously. The corresponding means for L=4 of 396 ms, 423 ms, and 337 ms reveal a negligible bump effect at serial position two, corresponding to the halfway latency between keypresses two and three in L=4 sequences. Thus, at equivalent serial positions the keypressing rate is faster for the L=4 sequences than for L=6 sequences. This is especially true at position three, where the two lengths diverge sharply, reflecting an increase to the bump at position three for L=6 sequences.

The means for the three-factor interaction again show the tendency for L=6 sequences to show large task concurrence effects at position three, going from 63 ms at position one to 54 ms at position two and 122 ms at position three. In contrast, the mean task concurrence effects across serial positions one through three for L=4 sequences are 72 ms, 42 ms, and 51 ms. It seems reasonable to attribute the lack of a task concurrence peak in the L=4 sequences to the difference in size, producing less of the tendency to "divide and conquer" that was seen in the L=6 sequences. In sum, the contrast of L=6 and L=4 performance over equivalent serial positions indicated that keypressing rates for L=4 were faster at all serial positions held in common, and that no major trends toward bump effects were found in the shorter sequences.

Effects Involving Sequence Frequency.

As described above, the sequence frequency variable involved differential amounts of practice across sequences in the practice period intervening between T1 and T2. High frequency sequences were practiced 90 times in the practice period while low frequency sequences were practiced only 6 times. To offset a possible "surprise" effect the three low frequency sequences were always presented once just prior to the beginning of T2. Since there was no difference in practice levels across sequences at T1, the frequency variable was meaningful only at T2. Similarly, the total change in sequence labels and elements faced in the sequence shift group made sequence frequency a dummy variable in this condition.

The importance of the frequency manipulation resides in the ability to test for the effects of practice on specific sequences with overall exposure to the task controlled. Thus, it provides a converging operation on the role of time sharing and optimization factors in the reduction of task concurrence costs over practice. This is because the finding that task concurrence costs varied across levels of frequency would indicate that working memory demands differed as a function of practice with specific sequences irregardless of the degree of overall exposure to the task, whereas most time sharing accounts would expect time sharing strategies to be equally effective over all sequences. Thus, the prediction following from the concept of unitization would be that task concurrence costs are greater for low-frequency sequences than for high-frequency sequences, particularly in the no-shift and NS-NDT groups where operational constancy was maintained.

It is also important to consider how the test for frequency effects ought to be conducted. Since frequency is meaningless at T1 for all groups, and meaningless at T2 for the sequence shift group, it seems appropriate to test for frequency effects at T2 only for the no-shift, keyboard shift, and NS-NDT groups. The inclusion of data in which frequency is a dummy variable could only result in a loss of power, since random variation associated with the levels of frequency under these conditions would be partitioned into the error term for the corresponding F-test.

Significant main effects for frequency were found in total time, $F(1,45) = 8.75$, $p < .01$, in TTR, $F(1,45) = 5.44$, $p < .05$, and in fluency, $F(1,45) = 5.62$, $p < .05$, with the means indicating better overall performance on high-frequency sequences than on low-frequency sequences. In TTR, the means were 2641 ms for high-frequency sequences and 2833 for low-frequency sequences, yielding a 192 ms overall frequency effect. In addition, the interaction of group and frequency was significant for total time, $F(2,45) = 8.39$, $p < .01$, and in TTR, $F(2,45) = 7.94$, $p < .01$, but narrowly missed significance in the fluency measure, $F(2,45) = 3.45$, $p < .06$. The total time means revealed a net frequency effect of +442 ms for the no-shift group and +309 ms for the NS-NDT group. Interestingly, the keyboard shift group showed a modest reversal of the frequency effect, indicating a 176 ms advantage for low-frequency sequences over high-frequency sequences.

Thus far, the data indicate that the manipulation of frequency produced a strongly facilitative effect for the no-shift and NS-NDT groups, but actually produced some interference for the keyboard shift group. The interference effect would be sensible, since subjects in this group would have to inhibit the well-established mapping patterns learned on the old keyboard. If this were so, then inhibition might be more difficult under dual-task conditions when the digit span task is competing for attention that could be devoted to the new keyboard mapping. For this group, then, the theory predicts that task concurrence costs may be greater for high-frequency sequences, whereas for both the no-shift and NS-NDT groups task concurrence costs should be greater for the low-frequency sequences. An important question, then, is whether frequency interacted with task concurrence and group. Unfortunately, this interaction was not quite marginal in the total time measure, $F(2,45) = 2.42$, $p < .11$, and nonsignificant in the other dependent measures. While the means, as predicted, showed the reversed task concurrence by frequency interaction for the keyboard shift group, the simple effects test on the keyboard shift group alone failed to reach significance. Thus, there is no support for the role of task concurrence in the frequency reversal pattern of the keyboard shift group.

However, other evidence regarding the interaction of frequency and task concurrence was obtained in the planned analyses including the no-shift and NS-NDT groups that were discussed in connection with the NS-NDT group findings. While these analyses were conducted to test for interactions of group and task concurrence, it seems appropriate to examine them for effects involving frequency--to look for frequency effects where theory predicted they would be strongest. By combining these groups, the frequency by task concurrence interaction can be tested without the influence of the frequency by task concurrence reversal pattern shown by the keyboard shift group.

These analyses produced significant interactions of frequency and task concurrence in fluency, $F(1,30) = 6.71$, $p < .05$, and in the L=6 serial position data, $F(1,30) = 7.94$, $p < .01$. For the fluency measure, examination of the means revealed task concurrence effects of 17 ms on high-frequency sequences and 40 ms on low-frequency sequences. A similar trend was shown in the L=6 means.

In the L=6 analysis, the variables of frequency and task concurrence also participated in the four-factor interaction with group and serial position, $F(4,120) = 3.32$, $p < .05$ (the means are provided in Table 7). In approaching this interaction, it is useful to keep in mind the general pattern of the serial position analysis for L=6, which showed a "bump" effect at the midpoint of the sequence which was shown to vary as a function of practice and task concurrence. In the present interaction, it can be seen that the "bump" effect is larger for low-frequency sequences than for high-frequency sequences. One indication of this is that the position three latencies average out to

264 ms in the high-frequency sequences and 329 ms in the low-frequency sequences. In view of the task concurrence by serial position interaction from the overall L=6 analysis, it might also be expected that task concurrence costs tend to be larger at position three, which is also the case here. In addition, the means indicate that the task concurrence costs at position three are greater for low-frequency sequences than for high-frequency sequences, the means indicating a 50 ms task concurrence effect for high-frequency and a 122 ms effect for low-frequency sequences. This establishes a relatively coherent pattern for the three-factor interaction of task concurrence, frequency, and serial position.

The entry of the fourth factor--group--may be approached by recalling the task concurrence tradeoff pattern previously noted concerning the no-shift and NS-NDT groups. That effect indicated that the NS-NDT group seemed less inclined to allow keypressing speed to vary in the face of the additional load imposed on dual-task trials. An analogous effect in the present interaction would predict that the NS-NDT group showed less variation across the cells of the three-factor interaction of task concurrence, frequency, and serial position. An examination of the means in Table 7 indicates that while a case could be made that way, it is not quite that simple. To anticipate the eventual conclusion, the pattern indicates that while the NS-NDT group was biased toward constant keypressing rates across the levels of task concurrence, they in fact did allow keypressing rates to vary more fully with respect to sequence frequency.

One way of getting at this conclusion is to look at the total amount of variation in keypressing latencies across serial position.

TABLE 7

Cell Means (ms) for the Interaction of Group, Task Concurrence, Frequency, and Serial Position in the T2 Analysis Contrasting the No-Shift Group With the NS-NDT Group.

	Serial Position				
	1	2	3	4	5
No-Shift Group					
High Frequency					
Single-Task	217	231	226	203	194
Dual-Task	259	282	310	222	208
Low Frequency					
Single-Task	244	268	291	241	200
Dual-Task	270	464	403	281	233
NS-NDT Group					
High Frequency					
Single-Task	347	285	251	258	205
Dual-Task	247	277	267	261	205
Low Frequency					
Single-Task	269	345	245	248	205
Dual-Task	322	339	378	248	222

This can be computed by summing the absolute values of the differences between each serial position and the one following it. The result is a measure of the overall fluctuation of keypressing rate over the whole sequence. For the no-shift group at high-frequency, this measure comes out to 51 ms on single-task trials and 153 ms on dual-task trials. The higher variability on dual-task trials reflects in part differences in the size of the "bump" effect. The corresponding variation measures for the NS-NDT group on high-frequency sequences are 156 ms for single-task trials and 102 ms on dual-task trials, yielding a difference of -54 ms. The difference of +102 ms for the no-shift group against the -54 ms difference for the NS-NDT group indicates that on high-frequency sequences the NS-NDT group maintained a more nearly constant rate of keypressing as they progressed through the sequence, with relative indifference to task concurrence. Comparison of the same measures for the low-frequency sequences reveals basically the same pattern, indicating that the NS-NDT group also resisted variation in keypressing rates over levels of task concurrence on low-frequency sequences, relative to the no-shift group. However, looking at the same measures contrasting variations in keypressing rates over frequency indicates that the NS-NDT group did allow fluctuation with respect to frequency, although still less than the no-shift group. Collapsing across task concurrence, the no-shift group showed an average of 102 ms variation for high frequency sequences and 282 ms of variation on low-frequency sequences. The NS-NDT group showed 129 ms of variation on high-frequency sequences and 217 ms on low-frequency sequences, yielding a difference of 88 ms.

Additional support for this interpretation comes from the digit span and keypressing error data contrasting these groups (these analyses were carried out in the NS-NDT group tests described in a previous section). In the digit data, the tradeoff of digit span performance for keypressing speed on dual-task trials would lead one to predict a larger difference between high-frequency and low-frequency trials for the NS-NDT group than for the no-shift group. The means of the group by frequency interaction in the digit span data indicate, instead, a nonsignificant trend for the difference to be smaller for the NS-NDT group (a 1% difference against a 4% difference). Similarly, as described in the previous section addressing the NS-NDT group results, the interaction of group and task concurrence in the keypressing error data (which was marginal, $p < .07$) supports the tradeoff with respect to task concurrence. However, the corresponding interaction between group and frequency shows no trend toward a tradeoff, with the difference between high-frequency and low-frequency sequences being 3% for the no-shift group and only 1% for the NS-NDT group. Thus, the overall pattern seems consistent with the proposition that the NS-NDT group resisted variations in keypressing rate over levels of task concurrence but not so much over the levels of frequency, where they seemed more willing to allow variations in performance to show up in keypressing speed than in keypressing errors. Given that the task concurrence manipulation is a highly conspicuous variable from the subjects' point of view, while the frequency manipulation is relatively subtle and innocuous, this kind of differential tradeoff seems a plausible outcome.

Further evidence suggestive of the effects associated with the frequency manipulation was obtained in an analysis of keypressing error patterns at T2 for the no-shift, keyboard shift, and NS-NDT groups. This analysis focused on keypressing errors where part or all of one sequence was substituted for the appropriate sequence to be performed. According to the predictions that would follow from a unitization interpretation, it would be expected that such intrusions would come from high-frequency sequences more than from low-frequency sequences. Examination of the occurrence of these "sequence-confusion" errors indicated that high-frequency sequences tended to intrude on low-frequency sequences twice as often as low-frequency sequences intruded on the performance of high-frequency sequences. Of the thirty keypressing errors which unambiguously indicated an intrusion from another sequence in the sequence set, twenty were high-frequency sequences being substituted in whole or part for low-frequency sequences. While the test for significance was only marginal, $F(1,45) = 3.36$, $p < .07$, the effect is consistent with the idea that the sequence elements in high-frequency sequences were more strongly interassociated. In addition, it is possible that high-frequency sequences were more "dominant" or readily activated response patterns.

Taken overall, the distribution of effects involving frequency are highly suggestive, but must be approached with caution. The overall facilitation effect is consistent with the emergence of an integrated motor program, as indicated in the serial position analysis described in the previous section. The reversed frequency effect evident in the means for the keyboard shift group is also consistent with the idea of an integrated motor program. Otherwise, the tendency toward interference with high-frequency sequences cannot be explained, since only the keyboard mapping patterns were changed. If the interaction of frequency and task concurrence in the analysis combining the no-shift and NS-NDT groups is accepted, there is fairly direct evidence that task concurrence costs varied over levels of frequency in spite of exactly equal degrees of overall exposure to the task--a result that would be inconsistent with most time sharing or optimization accounts. The four-factor interaction of frequency, task concurrence, group, and serial position is also consistent with the idea that performance on high-frequency sequences was mediated by the emergence of an integrated motor program, indicative of a general trend away from piecemeal treatment of sequence elements during keypressing. The overall pattern is consistent with the idea that the task concurrence reduction effect shown by the no-shift group is specific to the sequence and to the motor pattern in which it is realized, not in the juggling and balancing of resource demands over time made possible by experience with the demands of concurrent processing.

Effects Involving Sequence Length.

The importance of the sequence length effect derives from the research cited previously (Sternberg et al, 1978; Rosenbaum et al, 1984) which indicated that sequence length effects generally failed to be attenuated with practice. In the present experiment, in which the concept of unitization is associated with the emergence of an integrated motor program, it was anticipated that sequence length effects would be attenuated given practice under conditions of operational constancy. This would suggest a trend away from the piecemeal treatment of sequence elements which is implied in the "motor program buffer" account of the sequence length effect advanced by the Sternberg et al (1978) and Rosenbaum et al (1984) studies, wherein operational constancy was not present over practice. Thus, the present framework would predict that sequence length effects should be attenuated over practice, showing less dependence on the number of elements in the sequence in initiating responding and in the rate of keypressing once started.

Overall, sequence length effects were robust and ubiquitous, producing significant (all $p < .01$) F-ratios for all dependent variables (except in the serial position analysis for L=6, in which length was not a variable). The F-ratios ranged from 41.83 in the digits to 117.31 in the total time analyses. In general, the shape of the length function was very orderly, indicating better performance on shorter sequences. For example, in the TTR data, the means for sequences of 6, 4, and 2 keypresses were 2628 ms, 2505 ms, and 1523 ms, respectively. The corresponding means in the fluency data were 417 ms, 399 ms, and 302 ms.

It is also worth noting that the bulk of the variance across length was between L=4 and L=2 sequences, with L=6 performance being typically fairly close to L=4. This phenomenon may be largely attributable to the "divide and conquer" strategy noted above in connection with the serial position analysis for L=6. The use of the "divide and conquer" strategy could mean that subjects were treating the L=6 sequences like two three-element sequences, resulting in better performance on L=6 sequences than would be expected on the basis of a linear length function. In addition, some subjects reported greater difficulty in learning the L=4 sequences, and, while the reason for this seems unclear, it is possible that L=4 performance may have been somewhat poorer than would be expected from assuming a linear length function. In some of the interactions involving length to be reported below, the tendency toward non-linearity varied somewhat across the cells of the interacting variable, resulting in the possibility that a component of the F-ratio was inflated by the variation in the differences between L=6 and L=4 performance, which would be partitioned into the treatment sums of squares for the F-ratio. To safeguard against the possibility that theoretically irrelevant variability associated with differences between L=6 and L=4 performance contributed substantially to the interaction, all of the length effect analyses were carried out twice, once in the straightforward way where length is represented as a three-level variable, and once with L=6 and L=4 performance averaged together, making length a two-level variable (long vs. short). This latter procedure provides a good estimation of the slope of the length function, while filtering out the variance associated with non-linearity. In the interactions to be reported below, all of the effects were significant in both analyses. The F-ratios and means are from the regular analyses with three levels of length.

The overall interaction of length and practice was significant for total time, TTR, and in digit span performance (all $p < .01$). This was nonsignificant in the keypressing error data, in the fluency measure, and in the L=6 vs. L=4 contrast on serial position. The means, detailed in Table 8, indicate that the length effect tended to diminish from T1 to T2.

The interaction of practice, length and group was significant in the total time data, $F(4,90) = 2.68$, $p < .01$, and was marginal in the serial position analysis contrasting L=6 with L=4, $F(2,45) = 2.99$, $p < .07$, but did not attain significance in TTR, fluency, or keypressing errors. Expressing the slope of the length function as the difference between L=6 and L=2 performance in the total time data, the no-shift

TABLE 8

Cell Means for the Interaction of Practice and Sequence Length

Measure/Analysis	Time	6	(6-4)	4	(4-2)	2	(6-2)	Sig.
Total Time	T1	5519	45	5474	1828	3646	1873	p<.01
	T2	3923	394	3529	1109	2420	1503	
Time to Respond (ms)	T1	3113	31	3082	1272	1810	1303	p<.01
	T2	2124	196	1928	692	1236	888	
Fluency (ms)	T1	481	2	479	112	367	114	N.S.
	T2	356	36	320	83	237	119	
Keypressing Errors (percent errors)	T1	21	6	15	11	4	17	N.S.
	T2	17	6	11	7	4	13	
Digit Span (percent errors)	T1	41	11	30	6	24	17	p<.01
	T2	23	3	20	7	13	10	
L=6 vs. L=4 (ms)	T1	537	149	388	--	--	--	N.S.
	T2	461	152	309	--	--	--	

group showed a 1683 ms length effect at T1 and a 737 ms length effect at T2, yielding a length attenuation effect of 946 ms. The keyboard shift group presented a 488 ms length attenuation effect, with the length effect decreasing from 1934 ms at T1 to 1446 ms at T2. The sequence shift group showed a 2001 ms length effect at T1 which actually increased to 2505 ms at T2, yielding a negative length attenuation effect of -504 ms. This pattern indicates that operational constancy played an important role in the attenuation of the length effect.

As would be expected, the analyses including the NS-NDT group at T2 also produced significant interactions of group and sequence length ($p < .01$ for total time, TTR, fluency, and keypressing error rates). In the total time means, the NS-NDT group presented a length effect of 808 ms, from 2821 ms for L=6 to 2013 ms for L=2, against length effects of 737 ms for the no-shift group, 1446 ms for the keyboard shift group, and 2505 ms for the sequence shift group. Thus, the length effect at T2 for the NS-NDT group was roughly comparable to that of the no-shift group, while the keyboard shift and sequence shift groups showed much larger length effects.

In the overall analyses, the length by task concurrence interaction was significant for total time, TTR, fluency, and keypressing errors (all $p < .01$, except for keypressing errors, where $p < .05$). In the serial position analysis contrasting L=6 with L=4, the two-factor interaction of length and task concurrence was not significant, but the three factor interaction with serial position was significant at the .05 level. Task concurrence was not a variable in the digit span data.

In general, the shape of these interactions are about what one would expect, showing greater task concurrence costs on the longer sequences. The means also showed that task concurrence costs for L=6 and L=4 sequences were approximately equal, with the bulk of the variance arising from the difference in task concurrence costs between the two longer sequences and the L=2 sequences. In the total time data, the means were 4266 ms for single-task trials and 5175 ms for dual-task trials, yielding a task concurrence effect of 909 ms. The corresponding means for L=4 were 4008 ms and 4995 ms, yielding a slightly larger task concurrence effect of 987 ms. For L=2, the means of 2846 ms and 3220 ms yielded a task concurrence effect of 374 ms. The corresponding patterns in the TTR and fluency data were almost exactly parallel. In the keypressing error data, the size of the task concurrence cost--expressed as the difference in error percentages--was 5% for L=6, 4% for L=4, and 0% for L=2.

Taken together, the effects involving sequence length are consistent with the predictions that would follow from unitization--to the extent that effects were found. On the one hand, there was relatively solid evidence, based on the interaction of group, practice, and length, that length effects are attenuated when operational constancy is maintained. When motor patterns were changed, as in the keyboard shift group, the degree of attenuation was reduced. When sequence elements were changed, there appeared to be no attenuation at all. This pattern would be expected if practice with unchanging sequences and motor mapping patterns is associated with the emergence of an integrated motor program and a trend away from piecemeal treatment of sequence elements. On the other hand, however, sequence length effects at T2 were still relatively large (464 ms for TTR, 54 ms for fluency, overall), and there was no evidence that the task concurrence by length interaction got smaller with practice, or that length interacted with sequence frequency. These latter effects would also be expected on the basis of unitization.

With respect to the size of the length effects at T2, it is possible that further practice could enable a flat length function. This remains an open question. It does seem clear, however, that the "motor program buffer" models now need to incorporate features which can account for the effects of motoric and compositional specificity.

The lack of evidence for the three-factor interaction of practice, task concurrence, and length, along with the failure for length to interact with frequency, can be approached in two ways. One is to accept the null result, with the subsequent suggestion that length effects have two components, one that is sensitive to practice with operational constancy, and one that is sensitive to task concurrence loads. The task concurrence component is insensitive to practice, which is why length does not interact with frequency. The other approach is to accept the pattern as being basically uninformative, in view of the fact that null results can be obtained for a variety of reasons (particularly the lack of power), only one of which would be consistent with the first approach. Given the high degree of variability apparent in the data, the latter approach seems preferable.

CHAPTER 6

Discussion and Conclusions

Evidence of Unitization.

In review, the concept of unitization was developed in the introduction as one of several logically possible ways in which the capacity demands of a task may be reduced with practice. Unitization is advanced as a specific and analytic formulation of one of the mechanisms underlying the emergence of automaticity in skill acquisition, with the goal in mind of being able to distinguish the contribution of unitization from the contribution of other processes, such as time-sharing (Broadbent, 1982) or "restructuring" (Cheng, 1985), which are also capable of reducing the apparent capacity demands of task performance. Given an unambiguous demonstration of the operation of unitization in skill acquisition, it is hoped that the issues of attention and automaticity in skill acquisition may be addressed with more precision and systematicity than before, and that the operation of other mechanisms mediating capacity demand may eventually be defined and documented.

In the present experiment, unitization is conceptualized as the emergence with practice of a unified motor program that can be called and executed as a unit rather than constructed in a piecemeal fashion from information held in working memory. Unitization is hypothesized to be made possible by the formation of direct associations between elements in the motor sequence. It is held to be applicable only when there is fixity in the order and identity of elements in the sequence, and produces the effect of reducing capacity demand by obviating the need to store sequence elements in working memory during performance.

The evidence for unitization begins with the observation of the practice by task concurrence interaction shown in the no-shift group. This establishes, first, that there was interference between the tasks during initial practice. That the locus of the interference lay in working memory is supported by noting that the secondary task, digit span performance, required no perceptual input or motoric output during the time in which keypressing took place. Second, the amount of interference between the tasks, as reflected in the difference in keypressing latencies between single-task and dual-task trials, was shown to decrease with practice. This indicates that there was some type of change, occurring over practice, which enabled the tasks to be carried out more independently of each other.

At this point, four hypotheses can be advanced to account for the decrease in dual-task interference, so long as the locus of the initial interference is accepted to be working memory. First, it is possible that the capacity demands of the keypressing task decreased with practice, allowing a speed-up in keypressing rates without trading off secondary task performance. Second, it is possible that the capacity demands of the digit span task decreased with practice. Third, it is possible that the capacity demands of both tasks were reduced with practice. Fourth, it may be that capacity demands were not changed for either task, but merely redistributed over time to give only the appearance of a reduction in capacity demand.

These possiblities can be largely disambiguated by considering the results of the NS-NDT group, which did not practice the digit span task or perform under dual-task conditions until the final test period late in practice. First, this group showed no significant main effect differences in digit span performance on dual-task trials at T2, relative to the keyboard shift and sequence shift groups, despite the fact that the NS-NDT group had no opportunity to practice the digit span task prior to that point in the experiment. This suggests that practice at the digit span task per se did not play a major role. The marginal effect contrasting the NS-NDT group with the no-shift group in digit performance, and the interaction between group and length, is offset by the reversed interaction between group and task concurrence which appeared in the total time and time-to-respond data. This showed a smaller task concurrence effect for the NS-NDT group than for the no-shift group. In sum, the data indicate that changes in digit span performance alone cannot account for the task concurrence reduction effect shown by the no-shift group, though such changes may have played a role.

The hypothesis proposing the temporal redistribution of capacity demands is also strained by the results of the NS-NDT group. This hypothesis would seem to require that subjects have experience with the capacity demand profile of concurrent performance before they would be capable of formulating an efficient resource deployment strategy. In fact, however, the NS-NDT group had no prior opportunity to experience the demand profile of dual-task trials yet showed about the same amount of interference as the no-shift group, which did have experience with dual-task trials. If the emergence of a time sharing strategy had played a role in the task concurrence reduction effect for the no-shift group, one would expect them to produce less interference than the NS-NDT group. It could be suggested that a very quickly developing time sharing strategy was possible, but this could not explain the strength of the interference effect at T1 or the persistence of interference for the keyboard shift and sequence shift groups, for whom the gross temporal structure of the keypressing task did not change.

The data reviewed so far indicates that the reduction in the size of the task concurrence effect shown by the no-shift group is primarily due to changes in the capacity demands of the keypressing task. It is worthwhile now to determine if the nature of the task concurrence reduction effect is consistent with the concept of unitization as addressed above. These considerations will also provide additional evidence concerning the possible role of time sharing.

An important issue to consider is whether the appearance of unitization is controlled by the constancy of sequence elements. In the keyboard shift and sequence shift groups, the variation of sequence elements and their motoric realizations should have prevented any reliance on unitization that may have developed during practice. The interaction of group, practice, and task concurrence showed that task concurrence costs were reduced substantially for the no-shift group, only slightly (and nonsignificantly) for the sequence shift group, and not at all for the keyboard shift group. Thus, the effects of operational constancy were consistent with a unitization account of the findings. In connection with a time sharing view, it is apparent that if a time sharing strategy was operating it did not survive the shift to a new keyboard, as could reasonably be expected.

The results of the frequency manipulation provide additional converging support of the unitization account. In the two groups where frequency effects were predicted to be the strongest, the no-shift and NS-NDT groups, task concurrence costs were greater for low-frequency sequences than for high-frequency sequences. Thus, task concurrence costs were seen to vary over specific sequences within a fixed level of overall exposure to the task. In the serial position analysis, changes in the rate of keypressing over practice for the L=6 sequences were consistent with a trend toward the formation of an integrated motor program. The overall analysis also revealed a trend for the keyboard shift group to experience interference on high-frequency sequences, which is also suggestive of the emergence of an integrated motor program.

Taken together, the frequency data support the unitization account in two ways. The first is that better performance on low-frequency sequences in the keyboard shift group reflects difficulty in inhibiting the more established motor patterns for high-frequency sequences. If performance were not being mediated by motor programs prior to the shift in keyboards, why should changing to new keyboards produce interference, since only the motor patterns have changed? Secondly, the effect of frequency facilitation is suggestive of the incremental build-up of interassociations between elements of the keypressing sequence.

Additional evidence can be garnered from the L=6 serial position analysis. The interaction of task concurrence and serial position showed a much larger task concurrence cost at the position 3 "bump" than at the other positions, suggesting that subjects may have been dividing the sequences into two three-element halves, pausing at the completion of the first half to prepare for the second half. The interactions with practice and group indicated that the size of the position 3 "bump" was markedly attenuated after practice for the no-shift group and less so for the keyboard shift and sequence shift groups. These results imply that the no-shift group transitioned from what could be called a piecemeal performance strategy to performance more in line with the idea of an integrated motor program. The overall increases in keypressing speed, the smoothing out of variability in keypressing rate across serial position, and the decrease of task concurrence costs at the midpoint are all consistent with such an interpretation. Interestingly, the data permit the speculation that time sharing may indeed have played a role in performance at T1, with subjects using the break at position 3 to reinforce memory span digits on dual-task trials. This would be consonant with the increased size of the task concurrence costs at position 3. The pattern shown by the no-shift group over practice might then reflect the abandonment of this demonstrably ineffective strategy when the sequence elements were bound into a unified motor program.

Less direct evidence for unitization is presented by the sequence length manipulation. The effects of sequence length were attenuated more for the no-shift group than for the keyboard shift and sequence shift groups, suggesting that practice with unchanging sequences and motor mapping patterns is a necessary condition in the reduction of length effects. The attenuation shown by the no-shift group indicates that response times and keypressing rates came to be less dependent on the number of elements in the sequences, again suggesting a trend away from piecemeal treatment of sequence elements in performance. This pattern must be regarded with more caution, however, because length effects at T2 for the no-shift group were still relatively large, leaving open the question of whether the length function would eventually flatten out. In addition, there was no evidence that the reduction of the length effect also related to reduction of task concurrence costs. While length interacted with task concurrence in the manner that would be expected, the higher order interaction with practice was not statistically significant. While it could be argued that length effect reduction reflects changes in the internal dynamics of the motor program that are independent of capacity reduction, it is also possible that the nonsignificance of the higher-order interaction is merely a type II error. Pending a more powerful test, it should probably be regarded as uninformative.

Taken as a whole, the data appear to converge on the proposition that the nature of the task concurrence reduction effect shown in the no-shift group is a result of changes in the memory demands of the keypressing task. In turn, the changes in memory demand appear related to the emergence of an integrated or "compiled" motor program whose elements no longer need to be represented in working memory during performance. This pattern is consonant with the conceptualization of unitization.

With regard to time sharing and the more general class of factors referred to previously as "optimization", there is little evidence that such processes played a substantial role in the findings. The only exception to this might be the "divide and conquer" strategy indicated in the serial position analyses, which the data suggest was replaced by unitization whenever possible. It should be noted, however, that a suitably committed and imaginative theorist could still probably construct an account of the results in terms of time sharing, though the path might be tortuous. To do so would be to miss the point, however, that the data are strikingly consistent with unitization at every turn.

It seems worthwhile to question, on the other hand, why the present experiment failed to produce evidence of time sharing or optimization. One consideration is to note the possibility of time sharing in the serial position "bump" effect noted above. The tendency for the task concurrence peak at the midpoint of the sequence to drop out later in practice would suggest that the emergence of an integrated motor program obviated the need to "take a break" from keypressing to reinforce the memory span digits. Thus, the mechanism by which unitization was demonstrated in this experiment may have worked against the continued use of time sharing strategies. Such an interpretation suggests that in cases where unitization is possible it may replace rather than augment time sharing adaptations.

It is also useful to note that the present task is somewhat austere relative to the more complex task environments (such as typing, playing a musical instrument, or operating a control system) which are typically viewed as a promising arena for the operation of time sharing factors (Logan, 1985). In the present task, allowing only very restricted practice at the digit span task with explicit instruction to use a verbal rehearsal strategy, it is possible that spending any time at all away from active rehearsal of the memory span digits may have produced immediate detrimental effects in span performance. Thus, the task may be viewed as being highly constrained in its temporal organization, relative to more continuous and multifaceted tasks such as those mentioned above. This sort of interpretation would be consistent with the outcome from Logan's (1979) experiments which also used digit span performance as a secondary task, and which also failed to find any evidence for time sharing. These considerations suggest that the demonstration of time sharing effects might be best approached through the study of a more temporally indeterminate task where the options for perceptual processing, memory and control functions, and output processes are more subject to strategic variation. At the same time, it would be necessary for the task to be amenable to the same type of analytic scrutiny possible in the present experiment to disentangle the effects of time sharing from the effects of unitization or automaticity.

Overview and Conclusions

Granted it has been established that the concept of unitization provides a sensible and useful account of the results, what can be said about the issues of attention and automaticity in skill acquisition? At bottom, the answer lies in having pinpointed with confidence and precision one particular way in which capacity demands in skilled performance may be mediated with practice. Having identified one plausible capacity reduction mechanism, with an accompanying model of how, when, and why it works, we seem better prepared to advance a general conceptual framework in which the plethora of remaining questions can be framed and resolved.

The characteristics of the conceptual framework to be advanced flow logically from the nature of the capacity reduction mechanism identified in this research. In the present case, the formation of a unitized representation of the elements in a performance sequence changed the working memory requirements of performance, suggesting that the working memory representation of elements in a performance sequence can be made unnecessary. This appears to be made possible by a type of learning, presumably involving the formation of direct interassociations between the elements of the sequence, that enables the performance sequence to be treated as a single unit. The process is analogous to the concept of chunking (Miller, 1956), and could aptly be described as the chunking of performance sequences. It is likely that this type of learning is dependent on constancy in the order and identity of the components in the sequence.

The underlying point in this development is that the concept of unitization ought to be extended beyond the domain of motor programming--to include the idea that mental operations which are not directly tied to output processes may also be bound into unified "programs" (Anderson, 1982; Carr, 1979; Reason, 1979). While it seems plausible that central processing mechanisms should be organized in the same general ways as motor planning and responding, it would also seem worthwhile to examine current models of information processing in light of the relationship between capacity demand and operational constancy that has been revealed in the present research. At the same time, it seems important to move beyond the overarching binary classification of mental processes into "automatic" and "controlled" processes (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977), to a finer-grained analysis of the mechanisms which allow "automatic" processes to occur (see Logan, 1985).

One suggestion produced by this interpretation is that the acquisition of skill in other tasks can be addressed in terms of the effects of unitization and examined for the type of sequence constancy needed for unitization to occur. Equipped with well founded hypotheses regarding how and why capacity demands may be reduced, we are better able to distinguish between the possibilities.

In a more general vein, the interpretation suggests that the concept of limited capacity, along with the idea that different processes may mediate the demands made upon it, ought not to be abandoned in lieu of the more vaguely formulated alternatives coming from multiple resource theory (Navon and Gopher, 1979; Allport, 1980), and from the work of Neisser, Hirst, and Spelke (1981; Hirst, Spelke, Reaves, Caharack, and Neisser, 1980). As outlined previously, assuming a hybrid model of processing resources with both central and non-central resources can accommodate the empirical challenges to the central capacity view while providing at the same time a large advantage in theoretical utility over the "Neisserian" approach, in which "skill" is an unanalyzed explanatory construct rather than a phenomenon that is itself to be explained. In the present case it has been proposed that working memory, serving a temporary storage function for task-relevant data, is a central resource likely to be required by tasks of diverse natures. Having documented the operation of a process which mediates demand on this resource, it can be argued that the limited central capacity concept still has considerable utility, so long as it is augmented with a hybrid model of processing resources and is not too simplistically conceived. This approach has the additional advantage of preserving the link with our phenomenologically-based perceptions of skill acquisition.

It is abundantly clear, however, that even if the preceeding points are established and agreed upon, numerous difficult issues and problems remain. Despite their apparent diversity, I would like to propose that these problems boil down to a profound lack of resolution in two areas. One lies in the nature of "resources" or "capacity"; in the inability to specify or agree upon a functional basis for deciding what "resouces" do and how "capacity" relates to the execution of the mental operations which we presume to process information (Navon, 1984). The second, which is closely related, is the lack of generality, coherence, and completeness in our contemporary descriptions of mental operations themselves.

An excellent illustration lies in Cheng's (1985) criticism of the "automatic vs. controlled processing" distinction of Shiffrin and Schneider (1977; Schneider and Shiffrin, 1977). Cheng offers a reinterpretation of the results presented in Shiffrin and Schneider (and in related research) which they interpret as evidence of automatic processing. In Cheng's view, the improvements in performance seen under consistent mapping conditions can be better explained by the concept of "restructuring"--a change in the task algorithm--rather than in the emergence of "automatic" processing. Such an argument implies a rather strange definition of automaticity--a process which enables capacity-free processing without changes in the information processing algorithm by which performance is achieved. Finding evidence for that type of automaticity would seem a losing proposition considering the difficulty in imagining a process which changes capacity demands without altering, at some level of description, the mental operations underlying performance. The point is that arguments of this nature can proceed indefinitely if our descriptions of information processing algorithms or mental operations are not linked to the concepts of attention and capacity. It is precisely in the interplay of the mental operations or algorithms used to achieve performance and their respective demands for temporary storage, perceptual processing, control, and output that constitutes the area which most deserves systematic scrutiny in regard to skill acquisition.

The present research has taken its cue from these considerations. The effort has been to identify a particular function traditionally associated with the concept of central resources and to track changes in the demand for this function as a result of changes in the information processing algorithm underlying performance. Additional research with this strategy in mind (see also Anderson, 1982), geared toward the identification of particular functions and specific mental operations which relate to them, may eventually disambiguate the confusion of process and content which plagues this area.

LIST OF REFERENCES

Allport, D. A. Parallel encoding within and between elementary stimulus dimensions. Perception and Psychophysics, 1971, 10, 104-108.

Allport, D. A. Word recognition in reading. In P. A. Kolers, M. E. Wrolstad, & H. Bouma (Eds.), Processing of Visible Language (Vol 1). New York: Plenum Press, 1979.

Allport, D. A. Patterns and actions: Cognitive mechanisms are content specific. In G. Claxton (Ed.), Cognitive Psychology. London: Routledge & Kegan Paul, 1980.

Allport, D. A., Antonis, B., & Reynolds, P. On the disproof of the single channel hypothesis. Quarterly Journal of Experimental Psychology, 1972, 24, 225-235.

Anderson, J. R. Language, Memory, and Thought. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1976.

Anderson, J. R. Acquisition of cognitive skills. Psychological Review, 1982, 89, 369-406.

Atkinson, R. C. & Juola, J. F. Search and decision processes in recognition memory. In D. H. Luce and P. Suppes (Eds.), Contemporary Developments in Mathematical Psychology (Vol 1). San Francisco: Freeman, 1974.

Atkinson, R. C. & Shiffrin, R. M. Human memory: A proposed system and its control processes. In K. W. Spence and J. T. Spence (Eds.), Advances in the Psychology of Learning and Motivation: Research and Theory (Vol 2). New York: Academic Press, 1968.

Baddeley, A. D. The Psychology of Memory. New York: Basic Books, 1976.

Baddeley, A. D. and Hitch, G. Working memory. In G. Bower (Ed.), Recent Advances in Learning and Motivation (Vol 8). New York: Academic Press, 1974.

Bahrick, H. P. and Shelly, C. Time sharing as an index of automatization. Journal of Experimental Psychology, 1958, 56, 288-293.

Broadbent, D. E. Perception and Communication. Pergamon Press, 1958.

Broadbent, D. E. Task combination and the selective intake of information. Acta Psychologica, 1982, 50, 253-290.

Broadbent, D. E. The maltese cross: A new simplistic model for memory. Behavioral and Brain Sciences, 1984, 8, 198-214.

Bryan, W. L. and Harter, N. Studies in the physiology and psychology of the telegraphic language. Psychological Review, 1897, 4, 27-53.

Bryan, W. L. and Harter, N. Studies on the telegraphic language: The acquisition of a hierarchy of habits. Psychological Review, 1899, 6, 344-375.

Carr, T. H. Consciousness in models of human information processing: Primary memory, executive control, and input regulation. In G. Underwood and R. Stevens (Eds.), Aspects of Consciousness (Vol 1). London: Academic Press, 1979.

Chase, W. G. and Ericcson, K. A. Skill and working memory. In G. H. Bower (Ed.), The Psychology of Learning and Motivation (Vol 16). New York: Academic Press, 1982.

Chase, W. G. and Simon, H. A. The mind's eye in chess. In W. G. Chase (Ed.), Visual Information Processing. New York: Academic Press, 1973.

Cheng, P. W. Restructuring versus automaticity: Alternative accounts of skill acquisition. Psychological Review, 1985, 92, 414-423.

Damos, D. L. and Wickens, C. D. The identification and transfer of time sharing skills. Acta Psychologica, 1980, 46, 15-39.

Deutsch, J. A. and Deutsch, D. Attention: Some theoretical considerations. Psychological Review, 1963, 70, 80-90.

Fitts, P. M. Perceptual-motor skill learning. In A. W. Melton (Ed.), Categories of Human Learning. New York: Academic Press, 1964.

Francolini, C. M. and Egeth, H. E. On the nonautomaticity of 'automatic' activation: Evidence of selective seeing. Perception & Psychophysics, 1980, 27, 331-342.

Gopher, D., Brickner, M., and Navon, D. Different difficulty manipulations interact differently with task emphasis: Evidence for multiple resources. Journal of Experimental Psychology: Human Perception and Performance, 1982, 8, 146-157.

Gopher, D. and North, R. A. Manipulating the conditions of training in time-sharing performance. Human Factors, 1977, 19, 583-593.

Graboi, D. Searching for targets: The effects of specific practice. Perception & Psychophysics, 1971, 10, 300-304.

Griffith, D. and Johnston, W. A. Stage 2 processing and the divided attention effect. Memory & Cognition, 1977, 5, 597-601.

Hasher, L. & Zacks, R. T. Automatic and effortful processes in memory. Journal of Experimental Psychology: General, 1979, 108, 356-388.

Hatano, G. & Inagaki, K. Two courses of expertise. Paper presented at the Conference on Child Development in Japan and the United States. April, 1983, Stanford Ca.

Henry, F. M. & Rogers, E. E. Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. Research Quarterly of the American Association for Health, Physical education, and Recreation, 1960, 31, 448-458.

Hirst, W. Is there a fixed limit on attentional capacity? Paper presented at the American Psychological Association, Washington, D. C., 1982.

Hirst, W., Spelke, E., Reaves, C., Caharack, G. & Neisser, U. Dividing attention without alternation or automaticity. Journal of Experimental Psychology: General, 1980, 109, 98-117.

James, W. The Principles of Psychology (2 Vols). Dover Publications, 1950. (Originally published by H. Holt & Co., 1890)

Johnston, W. A. & Dark, V. J. In defense of intraperceptual theories of attention. Journal of Experimental Psychology: Human Perception and Performance, 1982, 8, 407-421.

Johnston, W. A., Greenberg, S. N., Fisher, R. P. & Martin, D. W. Divided attention: A vehicle for monitoring memory processes. Journal of Experimental Psychology, 1970, 83, 164-171.

Jonides, J. Voluntary versus automatic control over the mind's eye's movement. In J. Long & A. Baddeley (Eds.), Attention and Performance IX. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1981.

Jonides, J. & Gleitman, H. The benefit of categorization in visual search. Perception & Psychophysics, 1976, 20, 289-298.

Kahneman, D. Attention and Effort. Englewood Cliffs, N. J.: Prentice-Hall, 1973.

Kahneman, D. & Wright, P. Changes of pupil size and rehearsal strategies in a short-term memory task. Quarterly Journal of Experimental Psychology, 1971, 23, 187-196.

Kahneman, D. & Treisman, A. M. Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), Varieties of Attention. New York: Academic Press, 1984.

Kantowitz, B. H. & Knight, J. L. Testing tapping timesharing. Journal of Experimental Psychology, 1974, 103, 331-336.

Kantowitz, B. H. & Knight, J. L. Testing tapping timesharing II: Auditory secondary task. Acta Psychologica, 1976, 40, 343-362.

Keele, S. W. Compatibility and time-sharing in serial reaction time. Journal of Experimental Psychology, 1967, 75, 529-539.

Keele, S. W. & Summers, J. J. The structure of motor programs. In G. Stelmach (Ed.), Motor Control: Issues and Trends. New York: Academic Press, 1976.

Kristofferson, M. W. Effects of practice on character classification performance. Canadian Journal of Psychology, 1972, 26, 54-60.

Kristofferson, M. W. The effects of practice with positive sets in a memory scanning task can be completely transferred to a different positive set. Memory & Cognition, 1977, 5, 177-186.

LaBerge, D. Acquisition of automatic processing in perceptual and associative learning. In P. M. A. Rabbit & S. Dornic (Eds.), Attention and Performance V. New York: Academic Press, 1975.

LaBerge, D. Automatic information processing: A review. In J. Long & A. Baddeley (Eds.), Attention and Performance VI. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1977.

Lachman, R., Lachman, J. L., & Butterfield, E. C. Cognitive Psychology and Information Processing: An Introduction. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1979.

Logan, G. D. Converging evidence for automatic perceptual processing in visual search. Canadian Journal of Psychology, 1976, 30, 193-200.

Logan, G. D. Attention in character-classification tasks: Evidence for the automaticity of component stages. Journal of Experimental Psychology: General, 1978, 107, 32-63.

Logan, G. D. On the use of a concurrent memory load to measure attention and automaticity. Journal of Experimental Psychology: Human Perception and Performance, 1979, 5, 189-207.

Logan, G. D. Short-term memory demands of reaction-time tasks that differ in complexity. Journal of Experimental Psychology: Human Perception and Performance, 1980, 6, 375-389.

Logan, G. D. Skill and automaticity: Relations, implications, and future directions. Canadian Journal of Psychology, 1985, 39, 367-386.

Lucas, M. & Bub, D. Can practice result in the ability to divide attention between two complex tasks? Comment on Hirst et al. Journal of Experimental Psychology: General, 1981, 110, 495-498.

MacKay, D. G. The problems of flexibility, fluency, and speed-accuracy tradeoff in skilled behavior. Psychological Review, 1982, 89, 483-506.

Miller, G. A. The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 1956, 63, 81-97.

Miller, G. A., Galanter, E., & Pribram, K. H. *Plans and the Structure of Behavior*. New York: Henry Holt & Co., 1960.

Navon, D. Resources—A theoretical soupstone? *Psychological Review*, 1984, *91*, 216-234.

Navon, D. Attention division or attention sharing? Laboratory for Information Processing and Decision Making, Report No. 20, January, 1985.

Navon, D. & Gopher, D. On the economy of the human processing system. *Psychological Review*, 1979, *86*, 214-255.

Neely, J. H. Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General*, 1977, *106*, 226-254.

Neisser, U. *Cognitive Psychology*. New York: Appleton, 1967.

Neisser, U., Hirst, W. & Spelke, E. S. Limited capacity theories and the notion of automaticity: Reply to Lucas and Bub. *Journal of Experimental Psychology: General*, 1981, *110*, 499-500.

Neisser, U., Novick, R., & Lazar, R. Searching for ten targets simultaneously. *Perceptual and Motor Skills*, 1963, *17*, 955-961.

Norman, D. A. Toward a theory of memory and attention. *Psychological Review*, 1968, *75*, 522-536.

Norman, D. A. & Rumelhart, D. E. *Explorations in Cognition*. New York: W. H. Freeman & Co., 1975.

Paap, K. R. & Ogden, W. Letter encoding is an obligatory but capacity-demanding operation. *Journal of Experimental Psychology: Human Perception and Performance*, 1981, *7*, 518-528.

Posner, M. I. Cumulative development of attentional theory. *American Psychologist*, 1982, *37*, 168-179.

Posner, M. I. & Snyder, C. R. R. Attention and cognitive control. In R. L. Solso (Ed.), *Information Processing and Cognition*. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1975.

Reason, J. Actions not as planned: The price of automatization. In G. Underwood & R. Stevens (Eds.), *Aspects of Consciousness* (Vol. 1). London: Academic Press, 1979.

Regan, J. E. Involuntary automatic processingin color-naming tasks. *Perception & Psychophysics*, 1978, *24*, 130-136.

Regan, J. E. Automaticity and learning: Effects of familiarity on naming letters. *Journal of Experimental Psychology: Human Perception and Performance*, 1981, *7*, 180-195.

Rosenbaum, D. A., Saltzman, E., & Kingman, A. Choosing between movement sequences. In S. Kornblum & J. Requin (Eds.), Preparatory States and Processes. Hillsdale, N. J.: Lawrence Erlbaum associates, 1984.

Schneider, W. Attention, learning, and the transition from controlled to automatic processing. Paper presented to the annual conference of the Psychonomic Society, San Antonio, Texas, November, 1984.

Schneider, W. & Fisk, A. D. Concurrent automatic and controlled visual search: Can processing occur without resource cost? Journal of Experimental Psychology: Learning, Memory, and Cognition, 1982, 8, 261-278.

Schneider, W. & Shiffrin, R. M. Controlled and automatic human information processing I: Detection, search, and attention. Psychological Review, 1977, 84, 1-66.

Shallice, T. Dual functions of consciousness. Psychological Review, 1972, 79, 383-393.

Shiffrin, R. M., Dumais, S. T., & Schneider, W. Characteristics of automatism. In J. Long & A. Baddeley (Eds.), Attention and Performance IX. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1981.

Shiffrin, R. M. & Schneider, W. Controlled and automatic human information processing II: Perceptual learning, automatic attending, and a general theory. Psychological Review, 1977, 84, 127-190.

Stanovich, K. E. & West, R. F. The effect of sentence context on ongoing word recognition: Tests of a two-process theory. Journal of Experimental Psychology: Human Perception and Performance, 1981, 7, 658-672.

Sternberg, S., Monsell, S., Knoll, R. L. & Wright, C. E. The latency and duration of rapid movement sequences: comparisons of speech and typewriting. In G. E. Stelmach (Ed.), Information Processing in Motor Control and Learning. New York: Academic Press, 1978.

Treisman, A. M. Verbal cues, language, and meaning in selective attention. American Journal of Psychology, 1964, 77, 206-219.

Treisman, A. M. & Riley, J. G. A. Is selective attention selective perception or selective response? A further test. Journal of Experimental Psychology, 1969, 79, 27-34.

Trumbo, d. & Noble, M. Secondary task effects on serial verbal learning. Journal of Experimental Psychology, 1970, 85, 418-424.

Waugh, N. C. & Norman, D. A. Primary memory. Psychological Review, 1965, 72, 89-104.

APPENDICES

APPENDIX A

Cell Means (ms) in the Overall Analysis From T1 and T2 Including the No-Shift, Keyboard Shift, and Sequence Shift Groups.

TOTAL TIME

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Time 1				
Length=6	4772	4984	6417	5771
Length=4	4929	5113	6624	6399
Length=2	3412	3448	4065	4286
Time 2				
Length=6	2149	2598	2754	3388
Length=4	2021	2574	2603	3249
Length=2	1745	1871	2040	2285
Keyboard Shift Group				
Time 1				
Length=6	4874	5147	6054	5789
Length=4	4646	5014	5907	5898
Length=2	3336	3456	3602	3732
Time 2				
Length=6	3377	3344	4554	4148
Length=4	3388	3139	4572	3916
Length=2	2178	2270	2497	2694
Sequence Shift Group				
Time 1				
Length=6	5242	4955	6090	6129
Length=4	4938	4766	5432	6027
Length=2	3643	3313	3929	3526
Time 2				
Length=6	4805	4943	5090	5920
Length=4	3894	3676	4547	4766
Length=2	2727	2747	3027	2959

APPENDIX A

Cell Means (ms) in the Overall Analysis From T1 and T2 Including the No-Shift, Keyboard Shift, and Sequence Shift Groups.

TIME TO RESPOND

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Time 1				
Length=6	2607	2847	3900	3422
Length=4	2774	3063	4095	3697
Length=2	1551	1746	2132	2367
Time 2				
Length=6	1071	1302	1450	1699
Length=4	975	1300	1411	1772
Length=2	733	884	939	1109
Keyboard Shift Group				
Time 1				
Length=6	2529	2823	3511	3124
Length=4	2582	2784	3487	3478
Length=2	1631	1734	1762	1998
Time 2				
Length=6	1660	1744	2475	2302
Length=4	1846	1594	2735	2121
Length=2	1150	1167	1347	1434
Sequence Shift Group				
Time 1				
Length=6	2826	2780	3413	3577
Length=4	2512	2454	2821	3236
Length=2	1689	1559	1945	1612
Time 2				
Length=6	2621	3056	2858	3464
Length=4	2141	1963	2671	2602
Length=2	1386	1462	1649	1566

APPENDIX A

Cell Means (ms) in the Overall Analysis From T1 and T2 Including the No-Shift, Keyboard Shift, and Sequence Shift Groups.

FLUENCY

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Time 1				
Length=6	433	428	503	470
Length=4	431	410	506	540
Length=2	372	340	387	384
Time 2				
Length=6	216	259	261	338
Length=4	209	255	238	295
Length=2	202	197	220	235
Keyboard Shift Group				
Time 1				
Length=6	469	465	508	533
Length=4	413	446	484	484
Length=2	341	344	368	347
Time 2				
Length=6	344	320	416	369
Length=4	308	309	367	359
Length=2	206	221	230	252
Sequence Shift Group				
Time 1				
Length=6	483	435	535	510
Length=4	485	462	522	558
Length=2	391	351	397	383
Time 2				
Length=6	437	377	446	491
Length=4	350	343	375	433
Length=2	268	257	276	279

APPENDIX A

Cell Means (ms) in the Overall Analysis From T1 and T2 Including the No-Shift, Keyboard Shift, and Sequence Shift Groups.

KEYPRESSING ERROR RATES
(percent error)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Time 1				
Length=6	25.0	15.6	29.7	15.6
Length=4	12.5	9.4	14.1	14.1
Length=2	4.7	3.1	4.7	7.8
Time 2				
Length=6	6.3	7.8	6.2	12.0
Length=4	3.1	4.7	6.2	10.9
Length=2	1.6	6.2	0.0	1.6
Keyboard Shift Group				
Time 1				
Length=6	12.5	12.5	12.5	26.6
Length=4	14.1	9.4	25.0	20.3
Length=2	3.1	7.8	1.6	3.1
Time 2				
Length=6	12.5	12.5	15.6	12.5
Length=4	9.4	9.4	18.8	17.2
Length=2	3.1	1.6	9.4	0.0
Sequence Shift Group				
Time 1				
Length=6	23.4	18.8	26.6	37.5
Length=4	23.4	12.5	10.9	20.3
Length=2	0.0	1.6	3.1	1.6
Time 2				
Length=6	26.6	25.0	25.0	40.6
Length=4	7.8	20.3	14.0	14.0
Length=2	7.8	4.7	6.2	3.1

APPENDIX A

Cell Means (ms) in the Overall Analysis From T1 and T2 Including the No-Shift, Keyboard Shift, and Sequence Shift Groups.

DIGIT SPAN PERFORMANCE
(percent error)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Time 1				
Length=6	--	--	42.4	35.5
Length=4	--	--	33.4	32.4
Length=2	--	--	23.6	24.6
Time 2				
Length=6	--	--	13.1	17.6
Length=4	--	--	15.2	24.2
Length=2	--	--	15.0	11.3
Keyboard Shift Group				
Time 1				
Length=6	--	--	34.2	36.9
Length=4	--	--	27.5	27.1
Length=2	--	--	25.4	22.5
Time 2				
Length=6	--	--	22.3	22.5
Length=4	--	--	15.6	15.8
Length=2	--	--	12.1	14.5
Sequence Shift Group				
Time 1				
Length=6	--	--	44.9	49.8
Length=4	--	--	27.3	33.0
Length=2	--	--	24.8	24.6
Time 2				
Length=6	--	--	34.0	31.2
Length=4	--	--	23.8	26.2
Length=2	--	--	13.3	15.2

APPENDIX B

Cell Means (ms) in the Serial Position Analyses for L=6 and L=4 Sequences

	Task Concurrence									
	Single-Task					Dual-Task				
	Serial Position					Serial Position				
	1	2	3	4	5	1	2	3	4	5
No-Shift Group										
TIME 1										
High Frequency										
Length=6	454	565	484	350	277	640	688	692	352	316
Length=4	450	426	358	--	--	411	530	428	--	--
Low Frequency										
Length=6	394	473	504	406	314	514	480	596	360	330
Length=4	407	475	326	--	--	492	649	431	--	--
TIME 2										
High Frequency										
Length=6	217	231	226	203	195	259	281	310	222	208
Length=4	197	216	215	--	--	206	267	236	--	--
Low Frequency										
Length=6	244	268	291	241	201	270	464	403	281	233
Length=4	227	300	229	--	--	296	311	255	--	--

APPENDIX B

Cell Means (ms) in the Serial Position Analyses for L=6 and L=4 Sequences

	Task Concurrence									
	Single-Task					Dual-Task				
	Serial Position					Serial Position				
	1	2	3	4	5	1	2	3	4	5
Keyboard Shift Group										
TIME 1										
High Frequency										
Length=6	492	477	416	444	278	494	579	734	426	285
Length=4	452	419	338	--	--	469	494	414	--	--
Low Frequency										
Length=6	431	517	541	424	286	450	535	654	642	317
Length=4	432	483	360	--	--	469	516	389	--	--
TIME 2										
High Frequency										
Length=6	365	370	376	306	202	486	394	452	316	221
Length=4	296	333	246	--	--	393	372	273	--	--
Low Frequency										
Length=6	321	349	362	320	199	386	337	438	354	210
Length=4	298	338	266	--	--	370	420	284	--	--

APPENDIX B

Cell Means (ms) in the Serial Position Analyses for L=6 and L=4 Sequences

	Task Concurrence									
	Single-Task					Dual-Task				
	Serial Position					Serial Position				
	1	2	3	4	5	1	2	3	4	5
Sequence Shift Group										
TIME 1										
High Frequency										
Length=6	621	483	494	354	327	526	514	740	402	348
Length=4	422	628	392	--	--	544	558	414	--	--
Low Frequency										
Length=6	511	442	472	357	327	713	443	520	402	376
Length=4	429	501	437	--	--	670	467	525	--	--
TIME 2										
High Frequency										
Length=6	408	373	692	331	326	391	479	588	433	276
Length=4	340	379	278	--	--	387	387	338	--	--
Low Frequency										
Length=6	496	333	494	278	251	588	339	686	346	256
Length=4	370	323	294	--	--	484	358	352	--	--

APPENDIX B

Cell Means (ms) in the Serial Position Analyses for L=6 and L=4 Sequences

	Task Concurrence									
	Single-Task					Dual-Task				
	Serial Position					Serial Position				
	1	2	3	4	5	1	2	3	4	5
NS-NDT Group										
TIME 1										
High Frequency										
Length=6	--	--	--	--	--	--	--	--	--	--
Length=4	--	--	--	--	--	--	--	--	--	--
Low Frequency										
Length=6	--	--	--	--	--	--	--	--	--	--
Length=4	--	--	--	--	--	--	--	--	--	--
TIME 2										
High Frequency										
Length=6	347	285	251	258	205	247	277	267	261	205
Length=4	258	226	237	--	--	269	230	246	--	--
Low Frequency										
Length=6	269	345	245	248	205	322	339	378	248	222
Length=4	228	276	225	--	--	232	329	243	--	--

APPENDIX C

Cell Means in the T2 Analyses Including the NS-NDT Group With the No-Shift, Keyboard Shift, and Sequence Shift Groups.

TOTAL TIME
(ms)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Length=6	2149	2598	2754	3388
Length=4	2021	2574	2603	3249
Length=2	1745	1871	2040	2285
Keyboard Shift Group				
Length=6	3377	3345	4554	4148
Length=4	3388	3139	4572	3916
Length=2	2178	2270	2497	2694
Sequence Shift Group				
Length=6	4805	4943	5090	5920
Length=4	3894	3676	4547	4677
Length=2	2727	2747	3027	2959
NS-NDT Group				
Length=6	2494	2877	2666	3245
Length=4	2186	2398	2519	2750
Length=2	1803	2076	1998	2174

APPENDIX C

Cell Means in the T2 Analyses Including the NS-NDT Group With the No-Shift, Keyboard Shift, and Sequence Shift Groups.

TIME TO RESPOND
(ms)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Length=6	1071	1302	1450	1699
Length=4	975	1301	1412	1772
Length=2	733	884	939	1110
Keyboard Shift Group				
Length=6	1660	1744	2475	2302
Length=4	1846	1594	2735	2121
Length=2	1150	1167	1347	1434
Sequence Shift Group				
Length=6	2621	3056	2858	3464
Length=4	2141	1963	2671	2602
Length=2	1386	1462	1649	1566
NS-NDT Group				
Length=6	1152	1523	1379	1639
Length=4	980	1185	1270	1401
Length=2	732	883	880	944

APPENDIX C

Cell Means in the T2 Analyses Including the NS-NDT Group With the No-Shift, Keyboard Shift, and Sequence Shift Groups.

FLUENCY
(ms)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Length=6	216	259	261	338
Length=4	209	255	238	296
Length=2	202	197	220	235
Keyboard Shift Group				
Length=6	344	320	416	369
Length=4	308	309	367	359
Length=2	206	221	230	252
Sequence Shift Group				
Length=6	437	377	446	491
Length=4	350	343	375	433
Length=2	268	257	276	279
NS-NDT Group				
Length=6	268	271	257	321
Length=4	241	243	250	270
Length=2	214	238	224	246

APPENDIX C

Cell Means in the T2 Analyses Including the NS-NDT Group With the No-Shift, Keyboard Shift, and Sequence Shift Groups.

KEYPRESSING ERROR RATES
(percent error)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Length=6	6.2	7.8	6.2	12.0
Length=4	3.1	4.7	6.2	10.9
Length=2	1.6	6.2	0.0	1.6
Keyboard Shift Group				
Length=6	12.5	12.5	15.6	12.5
Length=4	9.4	9.4	18.8	17.2
Length=2	3.1	1.6	9.4	0.0
Sequence Shift Group				
Length=6	26.6	25.0	25.0	40.6
Length=4	7.8	20.3	14.0	14.0
Length=2	7.8	4.7	6.2	3.1
NS-NDT Group				
Length=6	14.0	7.8	17.2	20.3
Length=4	4.7	4.7	10.9	17.2
Length=2	0.0	1.6	0.0	0.0

APPENDIX C

Cell Means in the T2 Analyses Including the NS-NDT Group With the No-Shift, Keyboard Shift, and Sequence Shift Groups.

DIGIT SPAN PERFORMANCE
(percent error)

	Single-Task		Dual-Task	
	High Frequency	Low Frequency	High Frequency	Low Frequency
No-Shift Group				
Length=6	--	--	13.1	17.6
Length=4	--	--	15.2	24.2
Length=2	--	--	15.0	11.3
Keyboard Shift Group				
Length=6	--	--	22.3	22.4
Length=4	--	--	15.6	15.8
Length=2	--	--	12.1	14.5
Sequence Shift Group				
Length=6	--	--	34.0	31.2
Length=4	--	--	23.8	26.2
Length=2	--	--	13.3	15.2
NS-NDT Group				
Length=6	--	--	32.6	28.3
Length=4	--	--	24.2	28.3
Length=2	--	--	17.8	18.8