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SEQUENCING AND TIMING IN
SKILLED PERCEPTION AND ACTION:
AN OVERVIEW

BY

STEVEN W. KEELE

Technical Report No. 86-1

University of Oregon
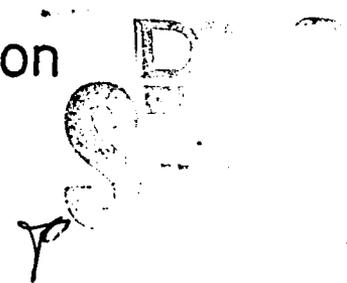
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
ONR 86-1	AD A171 861	

4. TITLE *(and Subtitle)*	5. TYPE OF REPORT & PERIOD COVERED
Sequencing and Timing in Skilled Perception and Action: An Overview	Final Report
	6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
Steven W. Keele	N00014-83-K-0601

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Department of Psychology University of Oregon	NR 667-523

11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
	May 1, 1986
	13. NUMBER OF PAGES
	33

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)*
	Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

DTIC
ELECTE
SEP 1 8 1986

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

sequencing, timing, motor control, hierarchies

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The chapters in this book section are concerned with sequencing and timing in the production and perception of language. Besides giving an overview of each contribution and relating them to some common themes, the present chapter goes a bit further. It is speculated that not only are processes in common to the various manifestations of language--reading, writing, speaking, and listening-- but there may be even more general processes that encompass other tasks as well. These general processes include a certain mode of sequence representation, one of which is hierarchic in nature, and a general timing mechanism. Hierarchic

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Unclassified

20. (cont.)

sequence representation may be the fundamental human achievement in evolution
that allows such a remarkable capability to learn new skills and flexibility alter
them. Another growing body of literature is beginning to suggest that a timing
mechanism, a clock, is in common to diverse motor and perceptual systems. Some
of this latter work has been conducted in the present author's laboratory and
is summarized in the chapter.

Sequencing and Timing in Skilled Perception and Action: An Overview
Steven W. Keele
University of Oregon

Human language often is touted as the prime example of what makes people so astoundingly different from other animals. Yet perhaps it is not far fetched to suggest that language facility is but an offshoot of an even more fundamental achievement in human evolution, that of being able to rapidly learn and modify complex sequences of activity in many domains. Witness the skilled movements of the woodworker, the pianist, the typist, and the gymnast. All of these impressive human skills involve sequencing movements in new ways, feats beyond the capabilities of other animals. It is possible that the evolutionary advances that made them possible also paved the way for a language that involves the ability to arrange words in novel forms.

It is not that many animals do not exhibit extraordinary skill. Rather, humans excel in their extreme flexibility of sequence acquisition, allowing them to acquire arbitrary skills for which evolution had no anticipation. This raises an issue regarding a currently popular approach to both perception and motor control. It is argued by some that skills are best studied by observing natural actions such as reaching for objects, catching balls, or speaking. The argument goes that evolution has invested millions of years in building specialized perceptual and action modules for such actions, and the resultant modules are likely to be narrow in purpose. One should, therefore, study naturally occurring skills if one is to understand skill at all. Very nice examples of this approach are provided by: von Hofsten (1985) for catching movements, who shows that very young infants have the perceptual and motor functions for catching; by Lee, Lishman, and Thomson (1983) and McLeod, McLaughlin, and Nimmo-Smith (1985), who provide some evidence that the apparent "timing" of motor movement directed toward a rapidly approaching object is derived from a simple parameter of expansion of the image on the retina; and by Nashner and Woollacott (1979) and Nashner and McCollum (1985), who provide evidence that a variety of complex postural patterns are tiggered by differing sensory inputs. A variant of this "ecological" approach is that many of the dynamic sequential properties of skill are not dictated by higher-order sequential representation (e.g., Kelso & Kay, 1985). Rather, they are a consequence of such things as mechanical properties of the musculo-skeletal system that carries out the action.

Despite these schools of thought that posit very particular perceptual-motor linkages, ability to acquire an unlimited variety of new sequences of activity of arbitrary type suggests a need to investigate general mechanisms of skill not necessarily intrinsic to particular perceptual-motor acts. Indeed, since the human advantage is the learning of arbitrary sequences, it may often be beneficial to study rather novel skills as well as highly practiced ones, such as piano playing or typing, which are foreign to other animals.

The purpose of this chapter is to introduce and provide additional context for the papers in this section on Sequencing. The general theme of these conference proceedings is that common processes may underlie speech, reading, writing, and listening, all of which are language activities. The other chapters in this section stick largely with language. However, the argument has just been made that critical mechanisms of sequencing may be even more general that applying only to language. Aspects of that issue are explored in this paper.

In addition to the act of sequencing, activity in many skills must also be precisely timed and not just put in the proper order. Such is apparent in a skill like piano playing but may also be the case in a skill like typing (e.g., Grudin, 1981) or speech (e.g., Fowler, 1979). It may be the case that a central timing mechanism, a clock if you will, is drawn upon by disparate activitives of production and perception of speech and non-speech alike.

The current chapter will focus, therefore, on a discussion of general mechanisms of sequencing and timing. The first main section will concentrate on sequencing with a special

emphasis on providing an overview of other chapters in this book section. Another prominent theme in the sequencing section will be the crucial role of hierarchical representation. The second major section will concern timing. Evidence for a general mechanism of timing will be reviewed, and some recent studies from my own laboratory that begin to explore the nature of the timer will be described.

Sequencing

If it is the case that some part or parts of the brain are specialized for sequence control, then there should be a tendency for neuropsychological deficits in sequencing activity in one domain of activity to be accompanied by deficits in another domain. The correlation might be less than perfect, however, because it is possible that different but nearby portions of the same general brain sturcture would be used by the different domains or that homologous portions on the two sides of the brain would be used. Moreover, as will be developed momentarily, a dominant conception of sequence representation is one of hierarchic structure. Different levels of the hierarchy may be represented in different places of the brain. Only some levels may draw on general mechanisms. At the lower levels of the hierarchy responsible for specific motor activity, disparate brain regions may be involved depending on the specific motor system. Alternatively, it might be that hierarchical representation, once evolved, rapidly proliferated into diverse areas, resulting in common functional representation but disparate anatomical representation. These various possibilities may explain why in a study by Lehmkuhl, Poeck, and Willmes (1983) no clear associations were found between disorders of sequencing in speech, that is aphasia, and disorders of non-speech motor sequencing, that is apraxia. The various aphasic patients did show a tendency toward apraxia, but differing types of aphasics (Wernicke, Broca, Amnesic, and Global), did not show differing patterns of apraxia. Since the nature of the apraxic disorder did not covary with the nature of the aphasic disorder, there is no firm basis for relating the two disorders.

Studies by Mateer (1985) raise these issues anew. In one study, she examined fluent and non-fluent aphasics. Fluent aphasics are capable of producing fluent sequences of words but their sentences convey little meaning. Non-fluent aphasics are impaired in the fluency of speech but the choice of words convey appropriate meaning. Mateer tested the patients on both a speech and a non-speech sequencing task. The speech task required an arbitrary sequence of three syllables (not words). The gesture task required the subjects to produce three successive oral-facial gestures, such as sticking the tongue out to one side followed by puckering the mouth and then opening the mouth widely. Although there is some overlap between the muscular systems producing speech and those involved in the non-speech sequences, the latter involves a broader set of muscles, grosser movements, and they produce little or no sound. The same pattern of deficits was found for both the speech and gestural tasks: The fluent aphasics were unimpaired on the single gestures but suffered in sequencing a trio of gestures or utterances. The non-fluent aphasics suffered on both aspects.

In Mateer's second line of studies, various tasks were performed by temporal lobe epileptics during the course of neurosurgery. In an attempt to localize the epileptic focal point, many points of the brain were stimulated at the same time that a variety of tasks--sentence comprehension, picture perception, sequencing, etc.-- were being performed. The effect of stimulation is to interfere with ongoing tasks, but the nature of interference varies tremendously as a joint function of the portion of the brain being stimulated and the task being performed. However, a central core area in the brain appears to be involved in disruptions of sequencing of either speech or the oral-facial gestures. This central core involves the superior portion of the temporal lobe, the very inferior portion of the parietal lobe and inferior portions of the motor and pre-motor cortex.

.Although there is some similarity in the motor systems involved in both the speech and non-speech gestures, Mateer's studies begin to suggest that particular brain areas are particularly adapted to sequence control regardless of the motor system.

A recent and provocative study by Cromer (1983) bears on the issue of whether systems responsible for speech sequencing have more general functions. He examined child receptive and expressive aphasics. Although some of the children could produce and comprehend individual words, they seemed unable to learn to combine words into sentences. Cromer suggested that the deficit involves a failure to use hierarchic structures in guiding activity. To test this idea he showed both the child aphasics and control groups of deaf and of normal children a stick pattern as portrayed in Figure 1. The children were asked to copy the figure with paper and pencil. All groups were able to do a good job of reproduction, but they differed markedly in procedure. The control groups, both deaf and normal children, used a hierarchic strategy in which corresponding portions of the figure on the two sides were drawn in succession. If those children started reproduction at the top, both a left and a right branch would be produced before dropping down a level. The aphasic children, in contrast, tended to produce the figure in linear fashion, starting with a terminal branch and working all the way to the top before beginning another branch. Thus, they showed no tendency to take into account the hierarchic structure involving the encoding of groups and subgroups. Parenthetically, it should be mentioned that since the aphasic children could produce some words, there would appear to be some dissociation of different sequencing systems. Those systems concerned with more global sequencing were affected, leaving at least partially intact more local sequencing systems.
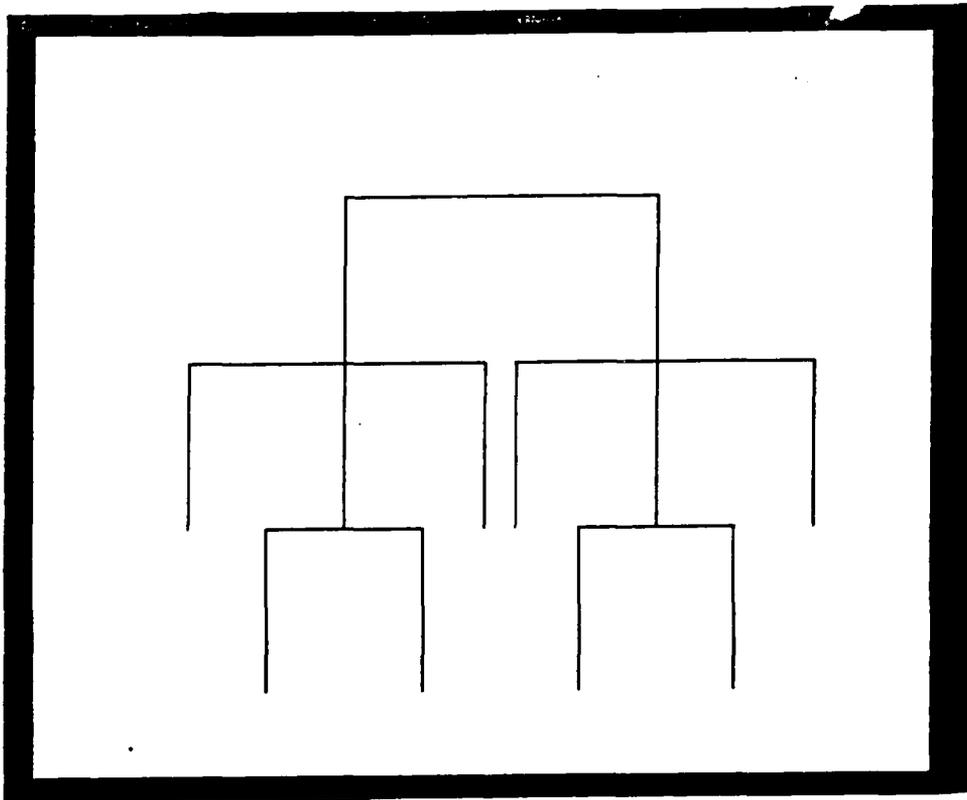

FIGURE 1

Figure 1: A line drawing that Cromer (1983) asked children to copy was drawn in hierarchic order by non-aphasic children and in non-hierarchic order by aphasic children. (From Cromer, 1983).

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The Cromer study addresses a problem sufficiently different from general sequence control that perhaps one should not make too much of it other than to take it for its heuristic value. The study suggests that sequence problems in one domain, that of organizing words into sequence, may result from a deficit to a fundamental mode of representation in common with other domains. That mode of representation is hierarchic.

Hierarchical representation of sequence

A basic point of MacKay's chapter in this section is that a large number of stable, replicable phenomena exist concerning sequentiality, and that any reasonable theory of sequential order must address these phenomena. Some of the phenomena concern sequencing in perception. Very often, the sensory input, on which perception is based, occurs temporally as with speech signals. According to MacKay, some theories either postulate or have implicit a temporal isomorphism between sequential input and perception. That is, it is supposed that perception is sequenced in the same way as the input. MacKay marshals several sources of data against this common assumption.

To the data base which argues against temporal isomorphism should be added the work of Huttenlocher and Goodman presented in this section. A prominent theory of speech perception by Marslen-Wilson (1976) supposes that the speech perception of a word occurs on-line. At any critical point of time in the sequential input of speech at which information becomes available for discriminating between a word and a non-word, the decision is initiated. His own experimental work, in which the temporal position within the speech stream at which the critical information became available was varied, supported his contention. That is, lexical decision reaction time was quicker for non-words that became such at an earlier point in time. However, Huttenlocher and Goodman have pointed out a confounding in some of Marslen-Wilson's examples of non-words that vary in the point at which they become non-words. In particular, non-words which became non-word at an early point appeared to be less phonotactically regular than those non-words that became so at a later point. Phonotactic irregularity would assist the non-word decision, resulting in faster reaction time. In three experiments which attempted to eliminate the confounding, reaction time appeared to be time-locked to the end of an utterance rather than to the point at which it became non-word. This result is consistent with other studies mentioned by MacKay that show a lack of temporal isomorphism between input and perception.

Much of MacKay's presentation is concerned with the data base which must be addressed by theories of sequential action. He argues that a plan that governs action must be prepared before the action occurs. The evidence comes from observations that very often people make anticipatory errors, introducing a part of an upcoming sequence before its time. In addition, upon a signal to respond, preparatory reaction time depends on the number of syllables per word and the number of words that are to follow, as though the utterances are pre-planned (Klapp, Anderson, & Berrian, 1973; Sternberg, Monsell, Knoll, Wright, 1978). MacKay observes also that errors are of definite types. In particular, errors are nearly always of the same class as the intended item: nouns substitue for nouns, adverbs substitute for adverbs, syllables substitute for syllables, etc. What does not happen, for example, is that a word substitutes for a syllable.

Preparatory reaction time and the within-class nature of errors argue that sequence representation is hierarchic in nature. Such a concept posits that sequential control passes from general to more specific representations. Reaction time is slightly longer for two-syllable words than for one-syllable words, suggesting that control must pass from a word to a syllabic level before reaching a phonemic level. Likewise, errors indicate that when control is on one level, errors come only from that level. A study that further clarifies this meaning of hierarchical control is provided by Povel and Collard (1982). Subjects in their study produced rapid sequences of key presses. The four fingers of one hand rested on keys labeled 1 through 4 from left to right. An example of one of many different sequences performed by

subjects is 123321.... Subjects are shown the sequence of numbers, and then they tap the pattern repetitively as rapidly as possible with their fingers, cycling back to the beginning of the sequence after the end. It might be instructive for the reader to tap out the pattern. Another sequence was 332112... and yet another was 233112.... For each of these sequences, the subjective experience is that the successive responses are organized into groups with relatively fast intertap intervals between members of a group and longer intervals separating groups. In fact the data in figure 2a, from Povel and Collard, illustrate exactly this: for the sequence, 123321.... A relatively long gap occurs after the 123 portion of the sequence and before the 321, and a relatively long pause transpires again after the 321 and before the 123. For the second sequence, 332112..., pauses occur after 332 and after 112 (see figure 2b); for the sequence 233112... pauses occur after 233 and after 112 (figure 2c). Thus, the temporal structure exhibits a grouping.
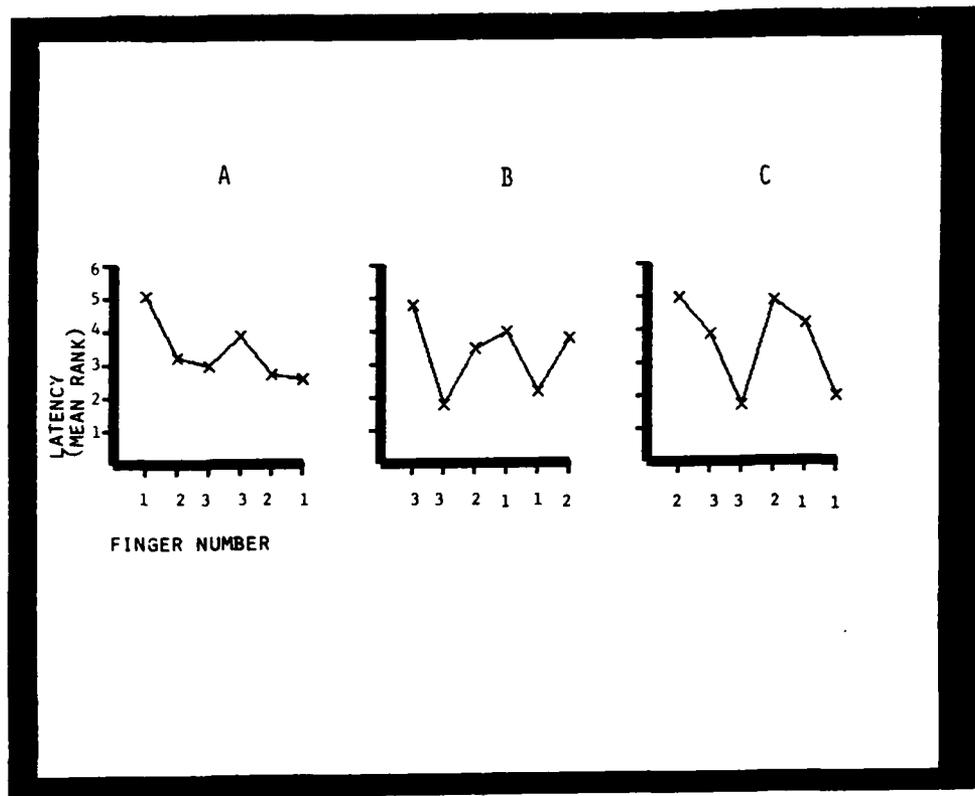

FIGURE 2

Figure 2: Subjects cyclically tap a six element pattern. The order of finger presses is shown on the abcissa. The mean rank of the intertap interval, averaged over subjects, is shown on the ordinate. (From Povel & Collard, 1982).

What may have escaped notice is that the three examples above are exactly the same sequence except for starting position. Despite the fact that the fingers follow one another in the same order in each of the three cases, subjects clearly have differing mental representations for the three which guide the course of action in different ways. The nature of

the internal representation determines the intertap pause structure. That representation has a hierarchic structure ranging from general to specific. It is as though the performer first retrieves a group of items, and then from the group a specific movement is retrieved. Within the group, retrieval times of individual elements are relatively fast. When the group is exhausted, a time-consuming retrieval of the next group occurs, and then within the group the first element is chosen. It might be noted that such a temporal structure may be hidden in skills so practiced that their speed is limited by the maximum rate of motor activity rather than by retrieval time.

The utility of the Povel and Collard study is that hierarchic structure is manifest in the on-line production of a sequence, but the essential conclusion of hierarchic representation is also arrived at from the analyses of errors (MacKay, 1982 and the chapter in this book section) and reaction time (Keele, 1986; Rosenbaum, Kenny, & Derr, 1983).

Hierarchical representation and transfer

A reason why hierarchic representation is useful to the organism is that it provides tremendous flexibility in learning new sequences of activity. The flexibility derives from the transportability of subsequences into new arrangements. Upper levels of a hierarchy can be rearranged, making use of already existing lower levels. Thus, it is argued that in human speech, phonemes, or at least low-order segments, are fundamental units that can be rearranged in new ways to form new words. The new words are not constructed from scratch but make use of the sub-units already acquired in other contexts (the fact that errors of word pronunciation often involve segmental substitutions argues for small segments as speech units more fundamental than words: see MacKay, in this volume section). Likewise, words once acquired can be reorganized into new frameworks without the necessity of learning new words.

The chapter by Gordon and Meyer in this section examines the transportability of subunits of speech activity and pits three theories of sequence representation against one another. Subjects learned patterns of speech involving sequences of four consonant-vowel syllables (e.g., Bee-Bay-Bah-Boo). Subjects would prepare to speak one such pattern, but on occasion the signal to begin response would require that a different sequence be produced instead. One possibility is that the sequence string is represented hierarchically. Thus the sequence Bee-Bay-Bah-Boo would be stored at one level as two subgroupings, (Bee-Bay) and (Bah-Boo). Suppose the sequence the subject was prepared to speak was stored in this manner. Then if the response signal required a different sequence, it should be easier for a new sequence like Bah-Boo-Bee-Bay, which preserves the subgroups and simply reverses their order, than for a sequence like Boo-Bee-Bay-Bah, in which adjacent portions of the prepared for sequence largely maintain their adjacency in the unexpectedly required sequence. As predicted by the hypothesis of hierarchic structure, subjects showed greater ease of switch to new arrangments that maintained subunit pairing in the prior sequence than to new arrangments that created different subunits while maintaining adjacency. Moreover, in other situations reported in their chapter, transfer that maintained subunit structure was better than transfer that involved some of the same syllables remaining in the same temporal position of the sequence but with a breakup of the subunit structure.

Gordon and Meyer's study makes two important points. It adds transfer of preparation from one sequence to another to the list of procedures which has yielded evidence favoring hierarchic sequence structure over other forms of sequence structure. It also illustrates why hierarchic representation of sequences is such a powerful mode of representation. Such representation allows subsequences to be transposed in their entirety into new sequences without the necessity of a complete relearning of the entire structure, thereby endowing the human learner with enormous flexibility.

Earlier, MacKay and Bowman (1969) had also used a transfer paradigm of a somewhat different sort to provide evidence for hierarchic representations of sequence. Subjects

committed novel sentences to memory and then repeated them several times as rapidly as possible. With practice, sentence production became faster, approaching an asymptote by 12 repetitions. All subjects were German-English bilinguals, and after the 12th practice trial they switched to another sentence in the other language. On some occasions the transfer sentence remained the same both in meaning and in basic word order with the only change being from English to German or vice versa. This particular condition resulted in perfect transfer--subjects produced the first four transfer sentences with the same speed that they had attained by the last four practice trials of the preceding utterance. Of course, if the meaning of the sentence as well as the language was changed, speed of utterance slowed down and no transfer resulted.

In another condition, subjects practiced repeating a string of words that did not constitute a sentence. Again, practice speeded production, but in this case, when each word was translated to the other language, no transfer whatsoever occurred.

The interpretation by MacKay (1982) of the MacKay and Bowman results is that the sentence is encoded in hierachic form. Practice strengthens the connections between hierarchy levels. The structure provides meaning to the sequence of words. Thus, at the highest level below a sentence node, a simple sentence is represented as a noun phrase and a verb phrase. Below that level the noun phrase and the verb phrase are broken into their constituents. These levels are purely conceptual in that the same concepts can be attached either to English or to German words. Since the subjects were experienced bilinguals and were very familiar with all the individal words in the sentences, the practice effects with 12 repetitions presumably were restricted to strengthening the hierarchic sentence structure above the level at which concepts are translated to words. That is, the links between concepts and words were already quite strong because of the past history of learning, and the short practice of 12 repetitions probably had little effect at that level. However, the particular word order is novel, so considerable short-term practice effects would occur at that level of representation. During transfer of the sentence to the other language, the hierarchic superstructure could be transported in its entirety. For a non-meaningful arrangement of words, transfer failed to occur, according to MacKay, because an individual word can take many meanings (think of the number of possible meanings of the word "right" in English). When a word is embedded in a sentence, the sentence structure pinpoints a particular meaning of the word, making apparent the proper translation. For a meaningless string of words, however, practice strengthens a structure that fails to specify the meaning of individual words, and hence when langage is switched, transfer fails to occur.

As with the Gordon and Meyer study, the study by MacKay and Bowman illustrates the enormous flexibility that hierarchic sequence structure provides the learner. In this latter case, the entire upper levels of a hierarchy, not just subunits, can be transferred to a new motor system. To appreciate the power with which hierarchic representation endows the learner, consider an _expert_ with two musical instruments, say trumpet and trombone. Suppose the expert practices a new piece of music with one instrument and then transfers to the other instrument. Despite the fact that the motor activity is quite different for the two instruments, one might expect nearly perfect, if not perfect, transfer because what the highly experienced musician learns is not particular finger or arm sequences, but a more abstract structure that dictates what finger or arm movements to make.

A particularly important implication of these various studies that suggest hierarchic representation is that motor control in humans cannot be divoriced from abstract, cognitive representations. The argument advanced suggests that the brain systems that directly control movement do not "learn" motor sequences. Instead the sequence is embedded in hierarchic, perhaps cortical, representation. That representation dictates sequence, and the more motoric brain systems simply accept orders from above. Such a mode of operation may constitute one aspect of the fundamental evolution of human skill capabilities.

Dynamic and synergistic contributions to sequencing

Ultimately if action is to occur, abstract representations of sequence must be interfaced with motor systems to carry out the activity. An issue has been raised whether all sequential properties of the movement are represented in the program or neural wiring that directs movement or whether some of the sequential behavior is a result of dynamic properties of the bio-mechanical motor system itself (e.g., Kelso & Kay, 1985). Consider, for example, pioneering work by Bizzi, Polit, and Morasso (1976). Monkeys were trained to make head movements toward a light spot that appeared in an otherwise dark room. As the head began to turn, the spot turned off, removing all visual feedback. Sometimes, via a clutch system attached to the monkey's head, a spring would temporarily retard movement before being released, or weights would be added thereby increasing the rotational inertia of the head. Despite increased inertia, the head reached the target, though more slowly. Once a retarding spring was removed the head moved to the intended target. The crucial observation was that these "corrective" movements were made without visual feedback, without vestibular feedback (as the monkeys had vestibular senses removed), and without kinesthetic feedback (due to deafferentation). Since no feedback source is available to initiate corrections, it appears that the "corrections" are simply due to dynamic characterstics of the mechanical system of the monkey's head and muscles.

An analogy can be made between the head with sets of opposing muscles that turn it one way or the other and a cafe door with opposing springs that keep it centered. If one of the opposing door springs is replaced with a stiffer one, the door will immediately begin to move and it will re-center in a new position. Contracting a muscle is analogous to setting its stiffness, and simply resetting stiffness appropriate to a new centering location will cause the head to turn. The temporal properties of the head-turning, like the cafe door, depend on things like mass. Changing the mass will alter movement speed, and may induce oscillation, but will not change centering position. If a retarding spring is added and then removed, the centering position will assume an intial position and then change with removal of the spring. The major point is that details of the temporal behavior are a result of the nature of the mechanical system in response to changes in things like stiffness setting of the muscles. A superordinate program may specify the times at which changes in muscle setting are to occur and the mechanical system's response fills in temporal details.

Not only are some temporal details dependent on mechanical properties rather than being learned and controlled by program, but it also appears that many sequences draw on assemblages of movements as subunits that are more-or-less innate. Such assemblages are called synergies.

To provide a concrete example, Nashner and Woollacott (1979) studied postural responses such as occur when one slips on ice and the feet move forward with respect to the body, thereby rotating the feet relative to the ankles. They simulated such a situation by moving forward or backward a platform on which subjects stood. The response is a patterned array of muscle activity, involving the gastrocnemius, tibialis, hamstring, and quadriceps muscles as well as other muscles. Such activity normally helps retain posture. The same pattern is triggered, however, when a platform upon which people stand is rotated. In this case, the perturbation has little direct influence on posture but, nonetheless the same pattern of muscular activities is triggered. Paradoxically, in this case the pattern destabilizes the body. It appears, therefore, that a complex synergy is pre-organized and can be triggered by ankle rotation even when the pattern is inappropriate. One might speculate that such synergies are available to be incorporated into new skills such as when one learns to dance.

Part of the enormous flexibility of humans in building new sequences may depend, therefore, on exploiting both mechanical properties and innate programs. Substantial evidence exists for both of these propositions and is reviewed more thoroughly in Keele (1981, 1986).

Timing

In discussing the sequencing of motor activity, people sometimes fail to distinguish it from the timing of sequential activity. Yet MacKay in his chapter in this section points out that timing control must be partly independent of sequence representation. One reason, he claims, is that the same sequence can be conducted at differing rates with near constancy in the relative timing of the different components. For example, Carter and Shapiro (1984) trained subjects to move a handle back-and-forth in an arbitrary temporal pattern in which the duration of the movements bore no correspondence to the metric length of the movements. When subjects were asked to speed up, the relative temporal relationships stayed about the same. Such a result indicates that tempo can be controlled independently of sequence structure.

This book examines processes common to various language activities--reading, writing, speaking, and listening. It has been argued that the latter three involve timing beyond mere sequencing. Rhythmic timing in speech production appears to facilitate speech perception (e.g., Martin, 1972; see also the chapter by Cutler in this volume). Likewise handwriting would appear to require precise timing (e.g., Wing, 1978). Although each of these tasks require timing, it is not necessarily the case that they share a common timing system. The following sections explore whether a common timer underlies production and perception and begin to delve into the nature of the timing system.

Though there is a large literature concerned with timing, much of it focusses on the subjective experience of time over intervals of seconds, minutes, or even longer periods (see Allan, 1979 for a review). There is no reason for supposing that timing over such long intervals shares any of the same mechanisms with the timing systems involved in relatively fast-paced motor and perceptual activity as occurs, for example, in the production or perception of music. In recent years several investigations have appeared concerning timing of fast-paced motor and perceptual activity. In the following sections, selected work will be reviewed that suggests a timing mechanism common to different activities. Although most of that work is not concerned with language per se, it is closely related to the them of common processes of this volume. In addition, a couple studies will be mentioned that specifically investigate whether language production draws upon a timer shared with other motor activities. A final section previews some current work that is coming out of our own laboratory that is concerned with the nature of the timing mechanism itself. This brief review leaves out other important topics in timing, particularly of rhythm. The interested reader may consult important papers by Deutsch (1983), Povel (1981, 1984), Essens and Povel (1985), and Vorberg and Hambuch (1984).

The separation of central and peripheral components of timing variability.

One important development has involved efforts to differentiate between central and peripheral sources of timing variability. Wing and Kristofferson (1973) showed that if timing variability is affected by two independent sources, clock variability and variability in the duration of the motor processes that implement movement, then these sources can be separated by examining the temporal structure of a sequence. Clock variability and motor variability sum to produce total variability in the timing of successive movements such as a series of taps. However, motor variability also induces a sequential dependency among successive intervals. If by chance motor implementation time is short for one event, that will shortern the interval since the last observable motor event, and assuming the clock output is unaltered, lengthen the interval before the next observable motor event. Likewise, a randomly long duration of motor implementation will lengthen the time since the last event and shorten the time before the next. Put another way, randomly varying motor implementation times will induce a negative covariation of the durations of intervals between successive motor events. That negative covariation serves as an estimator of timing variance due to motor processes, and by

subtracting that component from total time variance, a residual is left that represents variance of the clock system.

By this model one would expect that the longer the time interval metered out by the clock, the greater would be clock variance. However, the duration for implementing movement should be independent of the interval since the last movement. Wing investigated this prediction in a study in which people attempted to produce a series of even taps at a variety of target intertap intervals. The total timing variance was then parsed into that due to clock and that due to motor processes. The results are shown in Figure 3 (this and other evidence for separable processes are reviewed in Wing, 1980). The fact that clock variance climbs with increasingly long intervals while motor variance remains constant provides striking confirmation of the model.
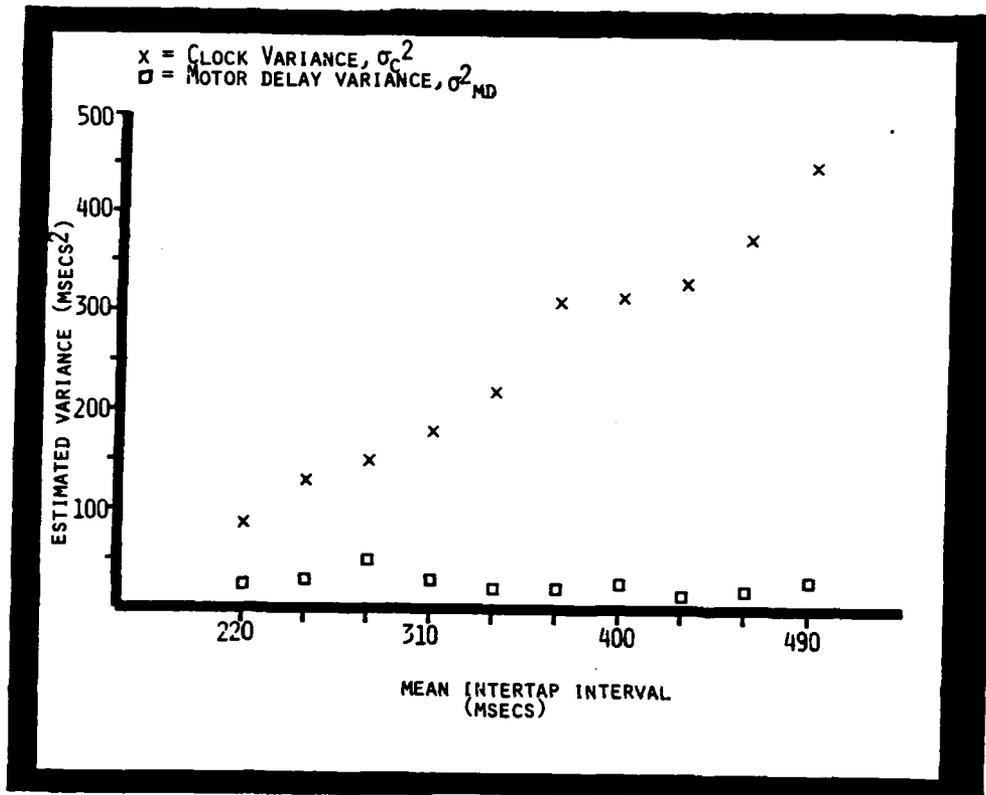

FIGURE 3

Figure 3: Subjects repetitively tap at mean intervals ranging from 220 msec to 490 msec. The total intertap variance is decomposed into clock variance and motor variance, and such variance is plotted against mean interval. (From Wing, 1980).

A model that is different from that of a central timer is one in which timing is governed by the feedback from a preceding movement. For example, in one version (Adams and Creamer, 1962), a decaying proprioceptive trace from one movement serves as the basis for timing another movement. When the trace reaches a target level, the succeeding movement is

triggered. Some evidence speaks against feedback-based timing, however. For one thing, a feedback model predicts that since timing of a subsequent movement does not begin until after the receipt of feedback from the preceding movement, whether the preceding interval was randomly shorter or longer than normal would have no influence on the subsequent interval, whose timing is independent of the preceding interval. In contrast, Wing (1980) explains how the clock model predicts negative covariation of adjacent intervals. That is, a short interval tends to be followed by a long one and vice versa (see the earlier discussion of how the negative covariation yields an estimate of motor variability). Since such negative covariation is found, the evidence speaks against a feedback model, which makes no such prediction.

To more direcly test a feedback based model of timing, Wing (1977) sometimes slightly altered the timing of a feedback tone resulting from a finger tap by advancing it 10 msec before its normal time of occurrence or delaying it by 30 or 50 msec. These changes were so small that subjects did not notice them. If the time of the next response was dependent on the receipt of the preceding feedback, then alterations in feedback time should be matched by equivalent changes (on the average) in the time before the next response. Such was not the case, leading Wing to reject a feedback model of timing. In a similar study by Conrad and Brooks (1974), monkeys moved a handle back-and-forth between a pair of mechanical stops. Unexpectedly altering the position of the stops caused the movement to strike the stops earlier or later than the expected time thereby advancing or retarding the time of proprioceptive feedback that results from hitting the end. Such alterations did not alter the time at which the monkeys reversed movement. Such results argue that feedback, either auditory or proprioceptive, does not serve as the basis for timing. Instead, timing seems to be centrally generated. Of course, when feedback indicates a large departure from intended time, the timing may be altered. However, it appears that such feedback is used to adjust a clock but is not itself the clock.

Acknowledgments

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