4 The Comparative Study of Serially Integrated Behavior in Humans and Animals

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INTRODUCTION

An enduring problem for psychology is whether it should be kept from reductionist dissolution in a sea of neurological details. Those psychologists who view such reduction as a scientific necessity focus on the learning of single responses. They indefinitely postpone study of the "chaining" of such isolated responses into "higher order" structures. Single stimulus-response connections are interpretable in terms of isolated behavioral units for which there is hope of finding sensory-motor analogues.

Yet, most behavior involves highly organized *sequences* of "responses," a fact that forces the question of how an organism represents the transition from one response to the next. The obvious recourse of the reductionist is to argue that a given response *itself* serves as the stimulus for the next response. This *leger de pensee* creates a coherent description but one that is empirically inadequate for a variety of well-known reasons. Response sequences can occur too fast for each one to be separately stimulated; response sequences themselves can be organized into subsequences, and an entire sequence can have a goal or meaning quite independent of the goal or meaning of each response unit in the sequence.

Such facts force us to refer to "mediating central processes" that bind and organize a response sequence. But even here one often hopes to keep the "mediator" close to the sensory-motor ground; "In a single rapid series of skilled movements, highly practiced, it is possible that behavior may be momentarily without sensory guidance—*but only momentarily.*" (Hebb,

1958, p. 63, emphasis ours.) In the case of most sequential behaviors, however, the only available evidence about their organization is what appears at the sensory-motor level itself. Language is a singular exception to this and has often been idealized as the "sequential behavior *par excellence*," which illuminates our understanding of all other sequential behaviors. At the outset, one must admit that a response–response chaining model is inadequate to describe language behavior: "No one...has succeeded in explaining a speaker's sentence construction, during the course of ordinary speech, as a series of (conditioned responses) linked together by feedback alone." (Hebb, 1958, p. 60).

Language is many things—*too* many to serve as a clean case study of serially ordered behavior. "Evidence concerning speech is complex, and may not be decisive" (Hebb, 1958, p. 60). What can we do to make it more decisive? In this paper we present two related investigations of serial behavior. These investigations show how we have tried to break the problem down into natural constituents. First, we show that certain serial constraints on sentence structures may be due to the interaction of speech comprehension mechanisms with experimentally distinguishable cognitive search strategies. Then we show that it is possible to vary and test models of how animals represent and execute serial behaviors. Our results demonstrate that similar theoretical mechanisms can underlie serial behavior in humans and animals.

This coincidence suggests that our effort to simplify the study of serial behavior by using simple paradigms and studying animals has boomeranged: In humans, we found that serial search strategies are under immediate subconscious control and can be instantly shifted. We found evidence that animals deploy complex mechanisms similar to those that humans use to organize and perform sequences. That is, rather than reducing the complexity of a serial behavior by studying it in animals, we may have discovered that they have unsuspected processing capabilities. Our studies suggest that, once a sequential behavior is acquired, it is organized in terms of internal processing mechanisms. Those mechanisms presuppose a serial representation of the behavior and utilize operations that are not directly modeled on the overt behaviors. Because of this lack of isomorphism, the mechanisms cannot be simple "maps", "plans," or internal, sequentially triggered "(cell) assemblies." Rather, they are internal processes that operate to yield the observed serial behaviors. This is part of the answer to a classical property of complex integrated behavior: Originally isolated responses "consolidate" into a coherent structure (cf. Hebb, 1963). In our view, the first step is to recognize that the organism develops an abstract organizing structure, which is not necessarily isomorphic to the behavior, but which underlies it. This chapter concentrates on the internal nature of such structures and their application to behavior in different species.

THE SOURCES OF LINGUISTIC STRUCTURES

Language is the most elaborate serially organized behavior known to us. Linguists search for universal contraints that are true of the grammars of all languages. These universals comprise the body of a hypothetical Universal Grammar, a store of what every child is prepared to learn at birth. A major part of our research over the past few years has been devoted to showing that specific universal properties of languages are not contained in Universal Grammar, but rather are true of all languages because of constraints on the way language is *learned* and *used*.

Consider some obvious cases. No language has complete ambiguity of the underlying grammatical relations in every sentence. No language has a word consisting of 20 consonants in a row. No language relies on half a quarter-tone as a distinctive acoustic feature. Every language has at least one verb for existence (to be). Every language distinguishes the first person from others. Every language has a way of expressing requests.

Each of the previously mentioned universals of languages is not necessarily a property of Universal Grammar, because each would have to be true in any case for language to be usable by humans. Consequently, it would be a mistake to require that such universals of language be an intrinsic part of Universal Grammar. Of course, the achievements of recent linguistic investigations have been to isolate language universals of far greater interest than the previous six obvious ones. The following are directly related to serial properties of language.

The Most-General-First Principle

There are several principles governing how to apply a rule to a structure that offers more than one point at which the rule could apply. The basic constraint is that the rule applies to the "most general" instance or domain of application available. In syntax, one version of this principle is known as the "A-over-A principle." This principle governs how a syntactic rule is applied to a hierarchy in which a constituent subject to the rule appears more than once. The principle requires that the rule always apply to the highest available instance of that constituent. For example, if a rule applies to a "noun phrase" in a sentence in which one of the noun phrases dominates another, then the rule applies to the dominating noun phrase.

A parallel constraint has been suggested that governs the application of a phonological rule to a sequence containing a subsequence that could also be affected by the rule. The phonological principle is to check first for the longest domain that the rule can apply to, and only apply it to a shorter domain if a longer domain is not available.

These principles are technical contraints that operate internally within grammar. As such, they appear to be prima facie examples of "pure" linguistic universals, true of grammars because of the nature of Universal Grammar. This may be so; however, it is intriguing that the principles ensure that the most general application of a rule will occur whenever it can. This is an intuitively appealing generalization, independent of its application to language. Furthermore, there is some evidence from the literature on serial pattern learning in humans that this principle is true in nonlinguistic domains. However, it could be the case that human subjects import their mastery of language into nonlinguistic domains and that such experiments do not serve as nonlanguage tests of the principle. It becomes clear, however, in the following section that such questions *can* be addressed with nonspeaking animals, thereby making it possible to see if such principles apply to subjects that do not know a human language.

Save the Hardest for the Last

This principle applies to rules (both in syntax and phonology) that reorder constituents of differing complexity. The generalization is that placing the more complex constituents after the simpler constituents is stylistically preferred and sometimes obligatory (see J. R. Ross, 1968). We can interpret this in light of constraints on short-term memory. The order "hard-task/easy-task" requires that the hard task be held in immediate memory while waiting for the subsequent processing. The opposite order requires that only the easy task be held, making for less overall computational complexity.

The Penthouse Principle

This is an observation across languages about the distribution of rules that apply to main and subordinate clauses. The basic insight (due to J. R. Ross, 1968) is that optional reordering rules in syntax apply more freely to main clauses than to subordinate clauses. For example, (1a) is an optional version of (1b), but (2a) is not an optional version of (2a):

- 1a. Quickly John left.
- 1b. John left quickly.
- 2a. *After quickly John left, Mary was upset.
- 2b. After John left quickly, Mary was upset.

Why should this be true? There is no obvious or intuitive explanation for this difference between main and subordinate clauses. Perhaps here we see an unambiguous instance of a true property of Universal Grammar. Recently, we have been exploring the way that information in main and subordinate

clauses is stored during immediate processing. We have found that main clause information is accessed in parallel, whereas subordinate clause information is accessed serially. This offers an explanation of why more word rearrangement is allowed in main clauses—they are processed in parallel anyway, so rearranging the order of the words in itself can have no deleterious affect on processing. Subordinate clause processing, on the other hand, would be impaired by reordering the words, out of the standard behavioral order because subordinate clauses are accessed initially in serial form (see Townsend & Bever, 1978).

This explanation is consistent with the facts, but there is a potential circularity. The difference in accessing style could itself be a processing accommodation to the linguistic universal, rather than its cause. That is, it could be argued that main clauses are accessed in parallel *because* their serial form is subject to greater reordering; subordinate clauses are accessed serially because they more reliably present a canonical phrase order. One way to resolve this question is to show that the different kinds of accessing style can occur in homogeneous materials that are not linguistic. We did this, and found subjects can allocate a serial search to one part of a string and a parallel search to another part of the same string, depending on how important it is to encode each part correctly. This strengthens our claim that the Penthouse Principle could be a linguistic consequent of different scanning strategies for main and subordinate clauses.

The scanning explanation of the Penthouse Principle presupposes that subjects can rapidly shift the way in which they access sequential material— scanning a main clause in "parallel," but scanning a subordinate clause "serially." We studied this in two steps. First, we demonstrated that subordinate clauses are accessed serially, whereas main clauses are accessed in parallel. Then we showed that humans have the ability to shift rapidly from a serial recognition access technique to a nonserial access in a nonlinguistic domain.

Propositional Processing Theory

Our findings about the serial and parallel processing of clauses are set within a particular framework of a model of speech comprehension. In the study of speech comprehension, considerable research has also been devoted to the reception and comprehension of sentences and clauses (see Clark & Clark, 1977, Chapter 2; Fodor, Bever, & Garrett, 1974, Chapter 6; Johnson-Laird, 1974). The main focus has been on how listeners isolate propositions in clauses and the relations between them.

The end of the first surface structure clause in a complex sentence defines a major break in the structural description of the sentence. The surface

structure clause can function as a unit during comprehension in at least three ways (Fodor, Bever, & Garrett, 1974):

1. The listener determines the location of major surface structure breaks during listening. This segmentation process is shown by experiments demonstrating that detection of a nonspeech noise is poorer when it occurs within a clause than when it occurs between clauses (Garrett, 1965; Garrett, Bever, & Fodor, 1966; Holmes, 1970; Holmes, & Forster, 1970; see also Bever, & Hurtig, 1975; Bever, Hurtig, & Handel, 1977; Bever, Lackner, & Kirk, 1969; Chapin, Smith, & Abrahamson, 1972; Dalyrymple-Alford, 1976; Forster, 1970; Reber & Anderson, 1970; Wingfield & Klein, 1971).

2. The listener applies perceptual mapping rules to assign the words of a clause to their semantic roles. Strategies for this mapping operation may include the use of semantic constraints, which suggest the more plausible logical subject (Bever, 1970; Slobin, 1966; but see Forster & Olbrei, 1973; Glucksberg, Trabasso, & Wald, 1973, for instances where semantics is irrelevant), direct mapping of words onto underlying structure on the basis of the order of elements in underlying structure (Baird & Koslick, 1974; Tanenhaus, 1977; Wanner & Maratsos, 1971), and mapping on the basis of syntactic properties of individual words occurring within the clause (Fodor & Garrett, 1967; Hakes & Cairns, 1970; Holmes & Forster, 1972).

3. As the listener determines a set of underlying logical relations within a clause and an interpretation for the clause, the exact word sequence of the clause fades. This process of "erasure" of words from immediate memory is shown by experiments that demonstrate abrupt shifts in verbatim recall and word recognition performance at clause boundaries (Caplan, 1972; Jarvella, 1971; Jarvella & Herman, 1972; Perfetti & Goldman, 1976). The process of deciding about an underlying structure for a clause, and removal of the exact wording from immediate memory has typically been assumed to have occured by the clause boundary (Bever, Garrett, & Hurtig, 1973).

Relations Between Clauses

Recent research has emphasized the effect of "functional completeness" on the processes of segmentation and semantic recoding. For example, in the following sentences, there is a progressive deterioration of the extent to which the explicit information in the italicized clause determines what the semantic representation is:

3a. *I felt sorry for the old bum* so I gave him a dollar.
3b. *After the crook stole the woman's bag* he ran for safety.
3c. *Meeting the pretty young girl* was the highlight of Peter's trip.
3d. *The old painted wooden pipe* was on display at the local museum.

This has been shown by Tanenhaus and Carroll (1975) to be reflected in the extent to which recoding of the sequence has occurred. For example, if a probe word is presented following the different kinds of clauses, the latency to report the next word is greater when the stimulus word is the last word of a clause that is functionally more complete. This is taken as reflecting the fact that those clauses are more strongly sequential and semantically recoded.

This line of argument has been extended to relations between clauses themselves. For example, Carroll, Tanenhaus, & Bever (1977) report stronger segmentation after main clauses than after subordinate clauses. This could be so because the main clause can always be semantically recoded, whereas a subordinate clause may have to be held in memory while one listens to the main clause, in order to recode the subordinate clause in a manner consistent with the meaning of the main clause. This variable has been explored systematically by Townsend & Bever (1978). They followed sentence fragments such as,

4a. Bob did put down some tiles in the . . .
4b. Bob did put some tiles down in the . . .
4c. While Bob did put down some tiles in the . . .
4d. While Bob did put some tiles down in the . . .

with either a synonomy judgment task (is "covering a floor" consistent with the meaning of this fragment?) or a word probe task (was "down" in the fragment?). Table 4.1, summarizes the results of this study. They found that listeners accessed the meaning of main clauses more quickly than the meaning of subordinate clauses, whereas there is evidence of a serial scanning strategy in the word probe task in subordinate clauses and not in main clauses.

TABLE 4.1
Response Times (Sec) to Initial Main and Subordinate Clauses[a]

	Subordinate		Main	
Meaning				
Probe	1.3		1.2	
F (1,16)		4.85,	$p < .05$	
	Early	Late	Early	Late
Word				
Probe	1.1	1.2	1.1	1.1
F (1,16)	6.35 $p < .05$		$< .1$ ns.	

[a]From Townsend and Bever (1978, tables 2 & 4). Copyright 1978 by Academic Press, Inc. Reprinted by permission.

Townsend and Bever (1978) also found that both of these effects were reliably influenced by the kind of subordinating conjunction that introduced the subordinate clause. Certain conjunctions showed more effects of "closure," e.g., "if." Other conjuctions showed weak effects of closure, e.g. "though." They suggest that this is related to the extent to which the information in the subordinate clause is semantically independent of the information in the main clause in the comprehension of the entire sentence. According to this view, the information in an "if" clause can be analyzed entirely independently as a whole, but the information in a "though" clause must be held in abeyance because the appropriate part of it has to be related to the main clause information in order to understand the relevance of the use of "though."

These studies extend the originally structurally determined theory of clausal processing into a more functional interpretation. We can view the listener's task as attempting to organize propositional relations corresponding to the sequence.

The original purpose of this investigation was to show that the Penthouse Principle could be explained by a difference in immediate access technique between main and subordinate clauses. To a first degree of approximation, our results confirm that there is a difference. However, they also reveal that the clause difference in immediate access technique is a function of the type of subordinating clause conjunction—clauses with conjunctions introducing relatively functionally independent material (e.g., "if") more often are responded to as if they were main clauses than other conjunctions (e.g., "although"). It follows that the Penthouse Principle effects may also be weaker in clauses with functionally independent subordinating conjunctions. Again, to a first degree of approximation, this is a correct observation: Consider the relative acceptability of the following clauses (with the noncanonical placement of the adverb). They appear to be ordered according;

5a. That loudly John left...,
5b. ? Why loudly John left...,
5c. ?? If loudly John leaves...,
5d. *after loudly John left...,

to acceptability, with the only difference being the extent to which the clause is dependent propositionally on what follows. However, it is possible that the Penthouse Principle is codified for all subordinate clauses without exceptions for specific conjunctions because of the simplicity of formulating it as applicable to *all* subordinate clauses of certain structured types.

Our primary concern here is to isolate for study some properties of sentence processing that can occur in all serially organized behavior. Regardless of the individual differences between conjunctions, we can argue that the initial

representation of main and subordinate clauses differ, with related consequences for immediate access of meaning and lexical material in each type of clause.

Different Kinds of Serial Access Strategies

What does this show about human processing capacity? If it is not limited to language, it demonstrates that humans can rapidly organize adjacent sequential material with different *kinds* of representations, and can access those representations in distinct ways. Many demonstrations of serial "chunking" in humans show that distinct parts of a sequence can be represented separately; but it is characteristic of such phenomena that the distinct chunks are represented and accessed in the *same way*. Our results show that in language comprehension, listeners make simultaneous use of different kinds of representational systems for different verbal "chunks." To study this in an area outside of language, we adapted standard studies of nonlinguistic serial processing. We found that humans can also rapidly shift the kind of representation and access pattern with nonlinguistic materials.

LIST SEARCH IN HUMANS

In the well-known Sternberg (1966, 1969) paradigm, a subject is presented with a set of digits, letters, or words. After seeing the set, the subject is shown a probe item from the same class as the items in the set. The subject is instructed to indicate as quickly as possible whether or not the probe was contained in the set. Sternberg's results show that reaction time (RT) increases with the size of the memory set, and the slope of this RT function is similar for positive and negative trials. In addition, Sternberg reports that RT does not vary with the serial position of the target item within the memory set. The fact that RT increases with set size rules out a parallel scan, in which the subject simultaneously compares all memory set items with the probe. The lack of serial position effects the similar slopes for positive and negative trials, and the equality of RTs to positive and negative trials all rule out a self-terminating scan, in which the subject compares the memory set items with the probe one at a time and responds as soon as a match occurs. Instead, Sternberg interprets his data to indicate that subjects conduct a serial exhaustive scan in which items are compared one at a time with the probe, but a response is not made until all items have been compared with the probe.

Within the limits of Sternberg's procedures, his findings have been replicated numerous times and are now fairly well accepted as an established, though perhaps curious, fact about retrieval from active memory. The current research considers whether Sternberg's serial position results are a general

sequence of scanning in active memory, or whether different types of serial position effects are obtained under different conditions. In our experiments, we manipulated the conditions of scanning within a memory set and hence provide the strongest test that different serial position effects are obtained under different conditions. To the extent that different serial position effects are indicative of different scanning strategies, our experiments demonstrate that different scanning strategies can be applied to different portions of a list.

Although the exhaustive models have received broad support, several investigators have found reason to doubt the generality of the exhaustive model (see Sternberg, 1975, for a review). One source of doubt is the frequent presence of serial position effects in memory scanning experiments. Recency effects have been found in several experiments (Baddely & Ecob, 1973; Burrows & Okada, 1971; Clifton & Birnbaum, 1970; Corballis, 1967; Corballis, Kirby, & Miller, 1972; Corballis & Miller, 1973; Juola & Atkinson, 1971; Kennedy & Hamilton, 1969; Morin, DeRosa, & Stultz, 1967), although some of these effects could be explained in terms of a sensory store, which retains the final items of the memory set. Even more problematical for the exhaustive serial model are those studies that found that RTs increase with the serial position of the target (Burrows & Okada, 1971; Corballis, Kirby, & Miller, 1972; Kennedy & Hamilton, 1969; Klatzy & Atkinson, 1970; Klatzky, Juola, & Atkinson, 1971; Sternberg, 1967). These increasing serial position curves suggest a self-terminating scan and certainly cannot be explained in terms of a sensory store. In addition, two of these studies (Corballis et al., 1972; Klatzky & Atkinson, 1970) obtained greater slopes for negative trials than for positive trials, which also suggests the self-terminating scan.

A second source of doubt about the generality of the exhaustive model is evidence that shows scanning can be limited to a part of the memory set. Several studies (Clifton & Gutschera, 1971; Darley, Klatzky, & Atkinson, 1972; Naus, 1974; Naus, Glucksberg, & Ornstein, 1972; Williams, 1971) indicate that one portion of the memory set can be omitted from a subject's exhaustive scan. Other studies suggest that subjects use a self-terminating scan within sets of letters partitioned by a pause (Wilkes & Kennedy, 1970a) or within different constituents of a sentence (Kennedy & Wilkes, 1969; Shedletsky, 1974; Townsend & Bever, 1978; Wilkes & Kennedy, 1969; Wilkes & Kennedy, 1970b).

The hypothesis that different scanning strategies can be used on different portions of a memory set was examined by providing subjects with incentives for responding accurately to only one portion of the set. Although previous experiments (Banks, cited in Atkinson, Hermann, & Wescourt, 1974; Swanson & Briggs, 1969) have found that subjects do not use substantially different scanning strategies when given incentives for accuracy versus speed on different memory sets, these studies have not shown the effect of incentives on scanning strategy within a memory set.

EXPERIMENTS

We used 10-item auditory lists of 5 adjacent randomly organized letters and 5 randomly organized digits (e.g., 6a, 6b following). The sequences were recorded at the rate of 3 items/sec.

6a. 5 9 4 7 2 X B N R F–TONE–PAUSE–PROBE (e.g. "N")
6b. X B N R F 5 9 4 7 2–TONE–PAUSE–PROBE (e.g. "N")

A brief tone marked the end of each segment followed by a one-half-second pause and then a probe letter or digit. The subjects' task on each trial was to signal as fast as possible whether the probe occurred in the 10-item list. This technique is typical of the experiments we reviewed earlier, with one important difference. Before each trial, subjects were told whether a correct letter or digit probe would be rewarded; this technique marked one subsequence of each trial as potentially "paid," and the other as "unpaid." Our intention was to make one-half of each sequence more important for the subject as the subject heard it (although the subject could not be sure that the probe would be drawn from the paid subsequence, so the subject also had to attend to the unpaid subsequence (see Townsend, Bresnick, & Bever, 1979, for discussions of these experiments).

We have run a number of paradigms of this sort, all of which generate similar data. Table 4.2 presents a typical set of data, in this case drawn from the last block of trials from eight subjects who had considerable pretraining. Subjects recognized the probes correctly in both paid and unpaid subsequences, with better performance in response to the paid subsequences. A superficial examination of the data suggests that the paid subsequences were searched serially and the unpaid ones randomly; the first four paid positions were responded to with a steady increase in latency, whereas there is no orderly serial effect for the unpaid sequences. Before considering the difference in response latency pattern as indicating different search processes, we must show that there is no systematic trade-off between latency and response accuracy. If there were, it could indicate that subjects shifted their

TABLE 4.2
Reaction Times (Sec) to Recognized Items From Paid and Unpaid 5-Item Lists

	Probe Serial Position					*Mean Identifi- cation*	*Mean Correct Rejections*
	1	2	3	4	5		
Paid	1.24	1.33	1.40	1.59	1.27	1.36	1.68
Unpaid	1.58	1.61	1.50	1.67	1.63	1.59	1.70

accuracy–speed priority between paid and unpaid subsequences but not their item access processes. Several features of the data argue against the trade-off hypothesis. First, the error rate for the paid subsequences is uniformly low ($< 5\%$), whereas the error rate for the unpaid sequences does not increase with serial position—that is subjects do not "compensate" in the unpaid condition for the flat latency curve by allowing the error rate to increase. Second, the false–positive frequencies for the paid and unpaid condition are virtually identical; the subsequences differ only in the correct recognition scores they elicit—that is, subjects are not simply indiscriminate in their responses to unpaid subsequences, nor has their response criterion seriously shifted—rather, they specifically fail to recognize more target items. Finally, the correlation between speed and errors was *positive* both for paid ($r = .31$) and unpaid ($r = .43$) subsequences, that is, the latency pattern tended to correlate positively with the error pattern, a correlation specifically *not* characteristic of a speed–accuracy trade-off.

We can analyze the different latency patterns with some degree of confidence that they are neither caused nor undermined by systematic variations in accuracy. Can we make more precise the observation that the latency response pattern to paid subsequences appears to be consistent with a self-terminating serial search? The fact that there is an orderly inverse in the first few latencies and that correct-rejections are the largest correct response category can be expressed by the following search principle:

7. Search the list for the probe from left-right; if a match appears, respond, "yes"; if the end is reached without a match, respond "no."

The relatively fast recognition time of the item in the fifth position could be accommodated by assuming an echoic "buffer" that stores the last item and the following rule that applies together with (7):

8. Search the buffer immediately for the probe.

These principles are an adequate description, but they do not provide precise predictions, nor do they utilize a general formal technique for representing processes that can be directly related to the unpaid condition, nor to related paradigms with other conditions or kinds of subjects.

So-called information-processing models offer such a formal language (see Simon & Newell, 1977). Characteristically, these models utilize a small set of operations (match–mismatch; read a symbol; change a symbol; move to next symbol on a "tape"; respond) combined in a restricted manner. The latency data from the paid subsequences are generated by such a model in Fig. 4.1. If we set each pointer moving operation as taking 120 msec and assume a base response time of 1220 msec, we can predict the first four response times to a
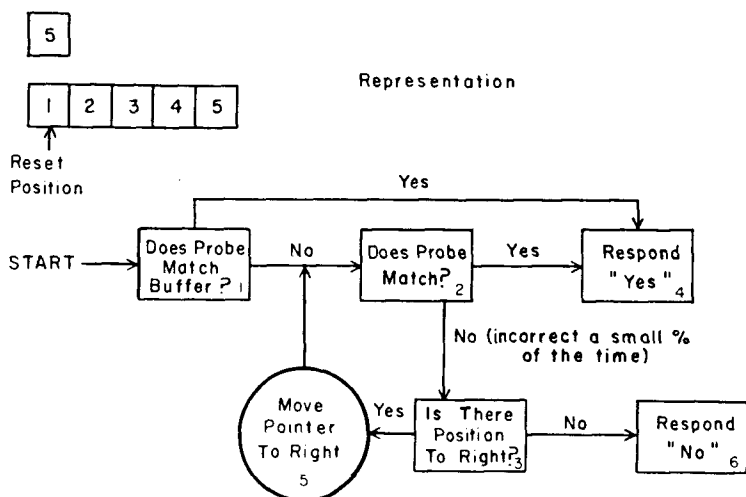
FIG. 4.1. Information-processing model of paid items in serial recognition task. (In the representation, the single box indicates the contents of the buffer, and the sequence of five boxes indicates the representation of the sequences.)

reasonable approximation (see Table 4.3). We also predict that the time for a correct rejection is the equivalent of running through to the fifth serial position (1700 msec) before saying "no," also a reasonably accurate prediction. Finally, the relatively fast latency to identify positively the item in the fifth position is explained by the assumption that the last-heard item is represented in an immediate store, the "buffer." The buffer is checked initially, along with the first position. If we assume a small miss rate, we can also predict that the fifth item will take slightly longer to recognize than the first: This follows from the fact that in a small number of cases the fifth item will be missed in the buffer and then correctly recognized in the fifth position. The empirically derived overall rate of misses is about 6%. This predicts the slightly longer response time for the fifth item shown in Table 4.3.

TABLE 4.3
Reaction Times (Sec) Predicted to Recognized Items (From Experiments in Table 4.2).[a]

	Probe Serial Position					Mean Identification	Mean Correct Rejections
	1	2	3	4	5		
Paid	1.22	1.34	1.46	1.58	1.24	(1.37)	(1.70)
Unpaid	(1.58)	(1.58)	(1.58)	(1.58)	(1.58)	1.58	1.82

[a]Latencies in parentheses represent nonindependent predictions.
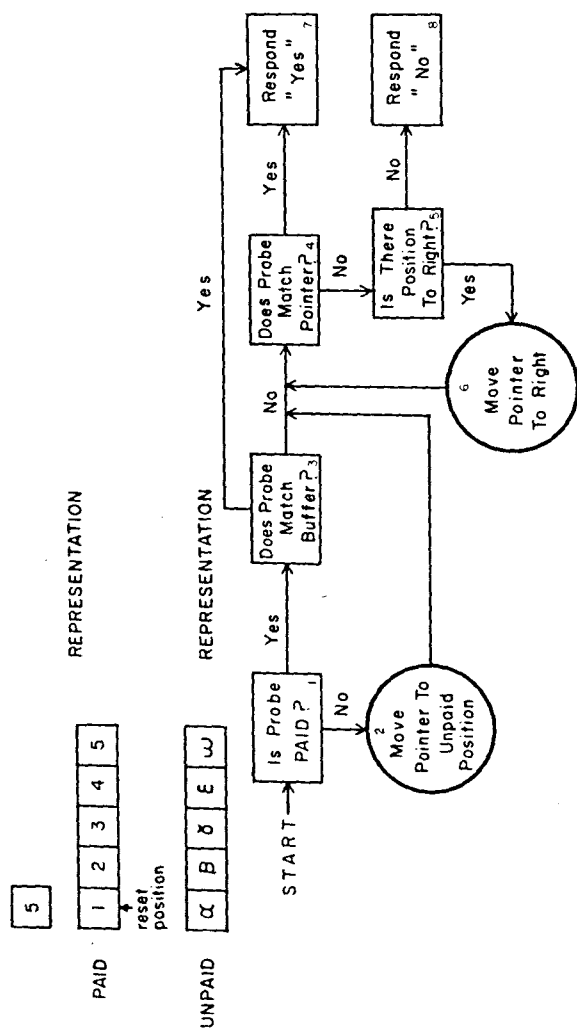
FIG. 4.2. Information-processing model of paid and unpaid items in serial recognition task. (In the representation, the single box indicates the contents of the buffer, and the sequence of five boxes indicates the representation of the sequences.)

This model can be adapted to generate responses to the unpaid condition as well, as shown in Fig. 4.2. Basically, this model assumes that the subject is set to examine the paid list—if the probe is from the unpaid subsequence, then the first operation is to move the pointer to the representation of the unpaid subsequence. Thereafter, the search proceeds serially. However, the unpaid list is assumed to have been represented in a random order so the average recognition time of the pointer is the mean of the time to scan one-half of the list in addition to the initial shift from scanning the unpaid to scanning the paid list. (See Appendix for sample derivations in this model.)

This model uses one latency variable (the time to move the pointer once) and a constant (the time to respond) to predict eight distinct behaviorally observed latencies. The empirical adequacy of this model is hard to demonstrate conclusively. First, it is the case that no observed value is more than one standard error from its predicted value. A further test of such a model is to assess the extent to which it predicts the variance in the observed data. In this case (with the value suggested earlier) more than 96% of the observed variance in the data is accounted for, using fairly simple and intuitive assumptions. (Table 4.4 presents the eight independent predicted latencies paired with the corresponding observed latencies).

TABLE 4.4
Predicted and Observed Probe Latencies (Presented in Increasing Predicted Time)

Predicted	1.22	1.24	1.34	1.46	1.58	1.58	1.70	1.82
Observed	1.24	1.27	1.33	1.40	1.59	1.59	1.68	1.78

We should emphasize that this model is valuable primarily because of the extent to which it allows us to make precise certain aspects of our theory of how the internal search process is organized. There are other, more complex models that could handle the same data with somewhat greater completeness. (For example, there is considerable variation in the individual latencies to the unpaid subsequence position (though, none of them individually departs from the predicted mean latency by more than one standard error). Furthermore, the miss rate is much higher in the unpaid condition, and there is much wider variation in position. Both of these phenomena *could* be accommodated by the assumption that the items in the unpaid condition are lost during the entry phase *into* a memory representation.)

Our subjects were humans, which makes it plausible to infer complex internal processes because such processes could be explicitly carried out by the same subjects. It is useful to consider what we could conclude from such a model if we did not have access to introspective subjective reports from members of the same species performing similar tasks. In its own right the model suggests the following:

9a. Subjects encode a representation of the sequence.

9b. Subjects apply an orderly internal procedure to access the representation.

9c. The representation (and/or) the search procedure differs internally as an interpretable function of external variables. (That is, the external differences are intuitively related to the form of the internal ones.)

Each of these observations centers around the existence of a neutral "representation." Several empirical features indicate that such a representation is "internal," rather than an expressive behavioral habit. First, the hypothesized search speed of 1/8sec per item is faster than the stimulus list and faster than almost any list could be spoken—especially spoken and analyzed as well. Second, the presence of dual representation of the last item, in the buffer and at the beginning of the full sequence, presupposes the distinctness of the latter in processing. Finally, the serial difference in the representation of the unpaid stimulus sequence and the sequence itself suggests further that there is a difference between the actual sequence and its representation.

The observations in (9) may seem abstract and stilted in light of the fact that many human behaviors explicitly demonstrate such representations and processes. But this exercise is useful to give perspective on analogous experiments with nonhuman subjects which we discuss in this next section.

SERIAL LEARNING IN ANIMALS

Serially ordered behavior is the norm rather than the exception in nature. Animals ordinarily execute complex plans, even in such basic tasks as nestbuilding, flying south for the winter, or courting a mate. Such behaviors are composed of many intermediate steps, which are not rewarded by any direct environmental change. In light of such a homely truth, it is striking that virtually all laboratory work with animals has concentrated on the learning and forgetting of separately reinforced responses: Even in the rare instances in which an animal is trained on a sequence, each response in the sequence is separately rewarded. We have developed a paradigm in which the animal is reinforced only after an entire sequence of responses has been executed (see Straub, 1979; Straub, Seidenberg, Bever, & Terrace, 1979). Pigeons are trained to peck a complete sequence of colors in a particular order, e.g., "*A B C D*," presented in randomly varying physical arrangements.

The subjects were trained in an operant conditioning chamber containing four response keys. (During a trial, each key was a different color, e.g., "white, green, red, or blue," hereafter referred to by letters "*A B C D*"). In order to earn a reward the pigeon had to peck the colors in the sequence, regardless of the position of these colors within the array of four keys. For example, on one

trial the left–right arrangement of the simultaneously lit colors might be B A D C. On the next trial the pigeon might be presented with *C B D A*. In each case access to food was provided if and only if the pigeon had pecked the keys in the order "*A B C D*." If the subject made an error, the array was turned off and a new array was presented on the next trial. With the exception of the response to the last color (which was followed by reinforcement), no feedback was provided following correct responses.

Straub et al. started their training by exposing the pigeons only to the last color, "*D*." We did this following the learning-theoretic hypothesis that a backward spread of reinforcement accounts for serial learning. After training on the last color, the birds were shifted to the last two colors, (preparatory to being shifted to the last three, and ultimately to all four). After many fruitless sessions with the last two colors, we shifted the paradigm (with the same birds) so that it built up from the beginning; first they responded to *A*, then *A B*, then *A B C*, and finally to *A B C D*.

During the training phase of the experiment, three subjects were exposed to 15 of the 24 possible physical configurations that could be generated from 4 colors in a left–right array. At the end of the training, the range of trials completed correctly was 59–64%. This performance, though well above chance, could have resulted if the subjects memorized the 15 different arrays and somehow associated a different pattern of responding with each array. Under that interpretation each pigeon would have had to learn 15 different spatially defined orders. If, however, each subject was responding to the sequence *A B C D*, regardless of the position of the colors, they should be able to respond to new arrays at levels above chance.

During subsequent test sessions, four of the original 15 arrays were replaced by four physically novel generalization arrays. Although there was some initial decrement of perfomance on the new arrays, performance in each case was considerably above chance levels. We therefore concluded that the subjects did indeed learn the behavior "peck *A* first, then *B*, then *C*, and then *D*."

Straub et al. present this experiment in detail. However, certain features of their procedures, results, and their interpretation are worthy of comment here. There are two main issues—possible artifacts that could have allowed the subjects to mimic serial behavior without learning it; qualitative analyses that provide positive evidence for the claim that the birds acquired a "representation" of the sequence, rather than a pair-by-pair chain of responses.

Possible Artifacts.   Two aspects of the procedure of Straub et al. might have allowed subjects to construct a nonserial set of independent responses. First, they allowed subjects to generate an arbitrary number of "repeat" pecks on each correct key without counting them as errors—for example, a possible

"correct" sequence was "*A B B C D.*" This allowed subjects, conceivably, to "pace" themselves and to create potential ways of discriminating the next response without attending specifically to the preceding response. For example, subjects might have differentiated each color according to the time from the beginning of the trial (e.g., "peck *A* at time 0; peck *C* at 1 sec;..."). The "repeat" pecks could have been used to "fill" intervals (cf. Heise, Keller, Kharari, & Laughlin, 1969) and allowed the subjects to peck a sequence on the basis of independent time-discrimination. Straub et al. analyzed this by examining the temporal distribution of correct and incorrect pecks with and without repeats and found no independent effects as a function of time. They performed a similar analysis to check on the possibility that subjects were differentiating the responses by "counting" the previous number of pecks (e.g., "after 0 pecks, peck *A*; after n pecks, peck *B*; after n + m pecks, peck *C*..."). This analysis also failed to show any systematic effects. Finally, as a more general check on the possible effects of allowing "repeats," they analyzed the number of correct responses to the next key that did and did not follow a repeat on the previous key—again there was no effect on correct performance to the key. In brief, we do not know how important the possibility of "repeat" pecks is to the birds' capacity—but they do not appear to be the source of obvious artifacts in the birds' serial behavior.

The second way that birds could have mastered the task without learning the color sequence would be if they had mastered the 15 independent training configurations as independent problems. For example, the subjects might have followed a general rule of not going back and pecking a previously pecked key (which brings the probability of a correct sequence up to ca. .04. If they also mastered the rule "at trial start, peck *A*," the probability would rise to ca. .18. Although this is considerably less than their performance on both the training and generalization arrays, it could provide a solid base for the birds to work from—for example, if they learned in addition the physical instructions necessary to peck white after green that differ for each array (e.g., "on the array *B A D C,* peck key 4 after key 1; on *B C A D,* peck key 2 after 1..."), their performance would rise to 50%. Of course, such separate "physical routing" learning for each array, would be quite a prodigous achievement in its own right and one that includes serial order learning differing for each array. However, the fact that it is in terms of "physical ordering" would be consistent with a peripheralist interpretation of what the subjects learn (see the following discussion).

Several features of the data suggest that the role of separate array learning is minimal. There are no consistent correlations across birds of the relative difficulty of each array. No pattern of difficulty is obvious that accounts for the relative difficulty of the arrays. Finally, the immediate above-chance performance on the novel generalization physical arrays indicates that the subjects were sensitive to the color sequence itself.

TABLE 4.5
Response Times (Sec) and Frequencies (in Brackets)
from Three Pigeons, Initially Given Backward Training

	Response			
	A	B	C	D
Position or last key pecked				
Start	1.5 (86%)	2.3 (12%)	3.0 (2%)	.8 (< 1%)
A	.5 (34%)	1.0 (54%)	1.6 (12%)	2.0 (1%)
B	.9 (1%)	.4 (41%)	.9 (53%)	1.4 (4%)
C	.1 (< 1%)	.7 (1%)	.3 (63%)	.9 (36%)

ªFrom Straub et al. (1979, table 1—about 8000 pecks). Copyright 1979 by University of Indiana. Reprinted by permission.

Representation Versus Chain.   We have emphasized the fact that our paradigm is one of "simultaneous chaining," in which the birds are presented with all colors simultaneously and do not receive any step-by-step feedback after each correct response. This makes it possible to assume that what they learn is the entire sequence in some form of "representation" (physical or central, see the following). This would be in contrast to a sequential chaining of separate S–R links. Several features of the data are consistent with the view that the pigeons have acquired a representation of the sequence.

Table 4.5 presents the data from the last three sessions of the three birds, a data pool of almost 10,000 pecks. This table demonstrates several important features of the birds' response patterns. First, the probability of an error decreases the further "downstream" it is from the correct response. The overall probability of a one-step error is larger than that for a two-step error, which is larger than that for a three-step error. Furthermore, the response latency to an error also increases the further downstream the error is.

These facts are most consistent with the view that forward errors are generated when the bird "runs through" the sequence internally and skips over a key without pecking it—this adds increased latency but decreasing likelihood of errors as they occur further downstream. Of particular import is the presence of backward errors—a representation model allows for them as a function of losing one's place in the representation—a forward S–R chaining model cannot account for them, because there are no backward associations. A second argument concerns the speed of responding—we found a class of extremely fast correct sequences, roughly .1 sec per response—faster than studies on pigeon discrimination learning response suggest are possible as separate responses.

The best demonstration that the birds' achievement was not an artifact or fluke is to replicate it with other birds, with slightly varying techniques.

TABLE 4.6
Training Procedures for Serial Learning Experiments[a]

	(Straub et al.) *Backwards*	(Straub, Group 1) *Forwards*	(Straub, Group 2) *Pair*
Pretraining	D, CD	A,B,C,D,(separate)	AB,BC,CD
Training	A	A	A
Phases	AB	AB	AB
	ABC	ABC	ABC
	ABCD	ABCD	ABCD

[a]From Straub et al. (1979).

Straub (1979) succeeded in training two groups of birds on a simultaneously presented four-color sequence. The new groups responded in a chamber that had six keys, rather than four, making possible many more physically unique color arrays. The training method also differed from our original experiment. Rather than receiving initial "backward" training on *D*, one group of four pigeons received "forward" training only, progressing from *A, A B, A B C, A B C D;* another group of three birds received initial adjacent "pair" training before the forward training, *A B, B C, C D.* Table 4.6 presents the three paradigms schematically.

Straub's subjects ultimately achieved a 70% success rate on the four-color sequences. Table 4.7 and 4.8 present the data from three sessions of each group of birds when they were responding at the 50% level (this level is chosen to be similar to the success rate of subjects in our original experiment). Despite the differences in training procedures, the response patterns are similar to those of the original experiment. In each case, forward and backward errors decrease and latencies increase as a function of distance from the correct response. Straub demonstrated further that the birds learned the

TABLE 4.7
Response Times (Sec) and Frequencies (in Brackets)
from Three Pigeons, Initially Given Forward Training[a]

	Response			
	A	B	C	D
Position or last key pecked				
Start	1.1 (83%)	2.2 (16%)	2.0 (< 1%)	0
A	0.2 (41%)	0.9 (53%)	1.6 (5%)	2.0 (2%)
B	1.0 (2%)	0.3 (61%)	1.0 (32%)	1.9 (5%)
C	0	1.5 (3%)	0.3 (56%)	1.3 (41%)

[a]From Straub (1979, Group 1; 50% level of accuracy;—about 2000 pecks).

TABLE 4.8
Response Times (Sec) and Frequencies (in Brackets) from Four Pigeons,
Given Initial Training on Sequence Pairs[a]

	Response			
	A	B	C	D
Position or last key pecked				
Start	1.1 (86%)	2.0 (11%)	1.8 (2%)	3.1 (< 1%)
A	0.2 (35%)	0.8 (53%)	1.2 (7%)	1.3 (4%)
B	1.1 (2%)	0.2 (69%)	0.9 (24%)	1.5 (6%)
C	0	0.8 (5%)	0.3 (47%)	0.9 (48%)

[a]From Straub (1979, Group 2; 50% level of accuracy—about 3000 pecks).

color sequence in two ways: He administered a generalization test with physically novel arrays and found virtually no performance decrement; he tested the birds on ordered pairs drawn from the full sequence *A B C D*, e.g., *A C, A D, B C, B D, C D.* He found an impressive, almost immediate transfer to these subsequences, demonstrating that the birds had acquired some representation of the separate ordinal relations among the colors.

We can tentatively conclude that the birds' mastering of the color sequence is not a matter of chance, although it remains to be seen how long such a chain can become without intermediate reinforcement. The establishment of a new paradigm in which serial behavior can be studied in animals is important for comparative psychology. We will be able to use it to study whether certain universals of language are also true of animal serial behavior. For example, the principles of "most-general-first" and "save-the-hardest-for-the-last" can be studied with expansions of the paradigm used in Straub et al. In this way, we can develop a true comparative study of the structural laws governing all serial behaviors. Part of this study involves a close examination of how animals might represent these complex performances—we turn to this in the next section.

What Is Learned?

Certain methodological difficulties force us to be cautious in claiming that we have conclusive proof that subjects mastered the color sequence, as opposed to memorizing the separate physical arrays. We *can* ask, however, what we will know about the mastery of sequences once the methodological limitations are overcome. There are two independent questions: At what physiological "level" is the chain represented? Is the representation ordered or unordered? The answers to the physiological question range from the "peripheral" to the "central"—at one extreme one could claim that the "representation" is encoded as a series of *sensorimotor-color-peck* pairs. The

alternative claim is that there is a central arrangement of *encoded-color-encoded-peck* pairs. It is important to remember that, however the physical question is answered, it does not determine whether the representation is itself of an integrated sequence or of a sequence of otherwise isolated responses. A complete solution to the problem of serial behavior may include an answer to the physiological question. But we will be in a better position to ask it intelligently if we have determined *what* is learned—how is the chain per se represented?

With respect to this question there are two extremes—on the one hand we could follow the implication of Lashley's considerations and claim that the chain is represented as an integrated response program. The alternative is the claim that the sequence is represented by uniquely encoded S–R complexes that can only be ordered in behavior in a single way. (See Wickelgren, (1969), for a presentation of such a model of sequencing in language.) The essentials of such a model rest on the attachment of mediating response–stimulus units, which bind the adjacent members of a sequence. For example, one could interpret the subsequence *A B* as composed of the following, unordered, set of learned behaviors:

1. At the start, peck *A*.
2. If *A* was just pecked, peck *B*.

Stated in this way, (1) and (2) are formally equivalent to a *sequence* representation. If we require that the representation account automatically for the order, the rules could be:

1. At the start, peck *A*; when pecking *A*, produce response "a."
2. If in bodily state "a," peck *B*....

In this way, the very manner of pecking *A* is itself the discriminative stimulus for pecking *B*; accordingly, "*A*" and "*B*" do not have to be represented as ordered—rather they are expressible only in the appropriate order, even though they are represented as unordered. At first, such a model appears to be compatible with an associative learning theory. For example, a bird might isolate the previously arbitrary distribution of body weight as the discriminative stimulus associated with each color-peck response:

1. At the start peck *A*; (when pecking *A*, shift weight to left claw).
2. If weight is on left claw, peck *B*.

There is a class of (peripheral) models in which no appeal to sequence-processing is necessary: those in which the discriminating mediator, "a," is produced following *A automatically* as a function of pecking *A*, rather than being actively isolated by the bird. For example:

1. At start, peck *A* (pecking involves approaching and withdrawing from a color).
2. If withdrawing from *A*, peck *B* . . . .

This class of models could be acquired without any explicit ordering of responses or processing of subsequences during acquisition.

Such a model can be extended to describe the four-color sequence, in such a way that the sequence itself is not explicitly represented. There is a corresponding nonperipheral model:

1. The starting configuration is the stimulus for pecking *A* . . . .
2. Having pecked *A* is the stimulus for pecking *B* . . . .

Both models appear to allow unordered statements to represent the ordered behavior. Now we come to two questions:

1. How does the organism isolate "a" as a possible discriminative stimulus—except by "noting" the sequence?
2. When isolated, how does the peripheral model differ from a nonperipheral sequence-representation model, except metaphysically?

The first question is crucial: Why should and how can an organism differentiate a response "a" that is uniquely associated with pecking *A* unless it is in response to the need to use it as a sequence mediator? To put it another way, how does the organism associate "a" as the mediator between *A* and *B* unless it *already* is processing what is being mediated, namely the subsequence "*A B*"? If the organism must first process the sequence in order to extract the mediators, then the mediator is hardly a formal replacement for sequential capacity: Rather, it is at best, a mnemonic device for the organism's representation of an already processed sequence.

It would seem that there is no associative model that easily accounts for the phenomena. However, the failure of a simple-minded associative theory is not a convincing argument that the birds learn a representation of the sequence. That is a negative argument. In the next section we show that the birds' behavior is efficiently represented by a computational model of how the response sequence is both represented and executed. This model also accounts in an intuitive way for the slight differences in the results from the three experiments. The model assumes the existence of a sequence representation; accordingly, the model's descriptive success can count as an empirical confirmation of the view that the birds acquire such a representation.

A Computational Model

The study of how representations are used is typical of research on human cognition and problem solving. For example, in the previous section, we presented an information-processing model of strategies that human subjects

use to search lists. Recently, such models have been applied to certain instances of animal behavior (e.g., Blough, 1977).

These models have varied interpretations concerning their "psychological reality." Indeed it can be argued that they merely simulate human performance rather than model human knowledge (cf. Tanenhaus, Carroll, & Bever, 1976). Such objections may have even more force when such models are applied to animal behavior, because we have no introspective evidence to aid our choice of a model. However, information-processing models have proven useful in organizing large amounts of data and in providing a precise basis for new experimental predictions. The orderliness of our data indicated that it might be correspondingly useful to apply such a model. As we outlined in the following section, we found a general model that deals with our result quite efficiently. This model presupposes both a representation of the sequence and a computational mechanism for the expression of that representation. We show that slight differences in three serial learning experiments with pigeons result in three similar models, each of which differs from the others in a way that is intuitively related to unique aspects of its experimental paradigm. This correspondence lends support to the appropriateness of such models for the description of animal behavior. Furthermore, the success of such models with our data may provide a start toward a new way of uniting the study of human and animal behavior, using such models as a common form of representation.

It was the error pattern of our data in Table 4.5 that first prompted us to apply computational modeling techniques. We noted previously that the probability of a forward or backward slip error decreased with the number of skipped colors. This suggests a probabilistic error function that iterates across the sequence. Suppose we postulate a model with two modes of operating—moving a pointer from the beginning to the end of a tape of the sequence and pecking the color that the pointer indicates. If the model corresponded with the errors, as in AVIAN in Fig. 4.3, it would always peck its way correctly through the sequence. If we now introduce error functions for the "peck" and "move" opeations, we can account better for the mean frequency of repeats and skips, as in Fig. 4.4.. The overall performance in these sessions is about 56%; if the errors occur equally frequently at each point, this requires that each individual transition be correct $\sqrt[4]{.56\%} = .86$. The frequency of repeat pecks (41%) is simply set empirically to match the overall mean of repeats. It is straightforward that, if after pecking, the device returns in a loop to peck again 41%, then 41% of the responses will be repeat pecks. Similarly, 14% of nonrepeat responses will skip at least 1 color, since the pointer moves to the right 14% of the time without pecking; $(14\%)^2$ of the nonrepeat pecks skips
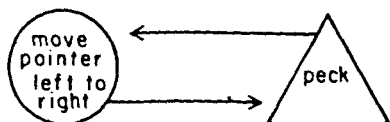

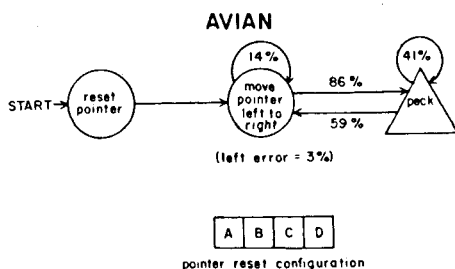FIG. 4.3.   Basic model of ordered responding in pigeons.

FIG. 4.4. AVIAN. Preliminary
model of serial pecking in pigeons
with initial backward training.

over at least two color positions, and so on. Finally, an assumption that the
pointer erroneously moves *backward* in 3% of the cases that it moves at all
generates the prediction that backward errors occur 3% of nonrepeat
responses, and two-step backward errors occur (3%)² of nonrepeat responses.
The second column in Table 4.9 presents the predicted frequency of the
different response categories as against the observed frequency presented in
the first column.

TABLE 4.9
Predicted and Observed Latencies and Frequencies for AVIAN

	AVIAN			
Correct	*Observed Frequency* %	*Predicted* 86% 41%	*Observed Latency*	*Predicted* m = .56 p = .38
A	86	86	1.5	1.5
B	54	51	1.0	.9
C	53	49	.9	.96
D	36	49	.9	.9
Repeats				
A	34	41	.5	.4
B	41	41	0.0	.4
C	63	41	.3	.4
Forward Skips				
Start—				
B	12	12	2.3	2.0
C	1.9	1.7	3.0	2.6
D	.1	.2	1.6	1.5
A-C	11.7	6.9	2.1	2.1
D	1.1	1.1	1.4	1.5
B-D	4.3	8.0		
Backward Skips				
B-A	1.7	1.5	—	—
C-B	1.1	1.5	—	—
C-A	0.0	.1	—	—
Correlation		.956		.859
Variance		91%		74%

The efficacy of an information-processing model such as AVIAN can be tested by examining how much of the variance in the actual data it accounts for (see Table 4.9). AVIAN accounts for 91% of the variance in the observed probabilities—this is supportive but not fully convincing. One way to gain additional support for AVIAN is to set temporal parameters that correspond to the "move" and "peck" operations: We set the move-pointer time at .56 sec and the peck time at .38 sec. The columns in Table 4.9 present the observed and predicted latency values for AVIAN (we do not compute predicted latency values for those response categories with less than 4% of the data because of the small number of responses in those categories). This analysis accounts for 73.8% of the variance in the latencies—again suggestive, but certainly not overwhelming confirmation of AVIAN.

Further consideration of the latencies stimulated us to develop a more sophisticated model, AVIAN *B*, presented in Fig. 4.5. It contains, like AVIAN, a move-pointer operation (on the left) and a pecking operation (on the right). This model allows us to take into account several systematic facts about the latencies. First, the repeat peck latencies decrease to colors later in the sequence. Second, the amount by which latency increases in forward skips decreases to colors later in the sequence. Finally, the latency to correct responses decreases to colors later in the sequence. AVIAN B captures this property by having a second pointer on the same tape, the "checker," that moves back from the end of the sequence to the color to be pecked. Only when the checker and pointer coincide can an actual peck be executed; the checker
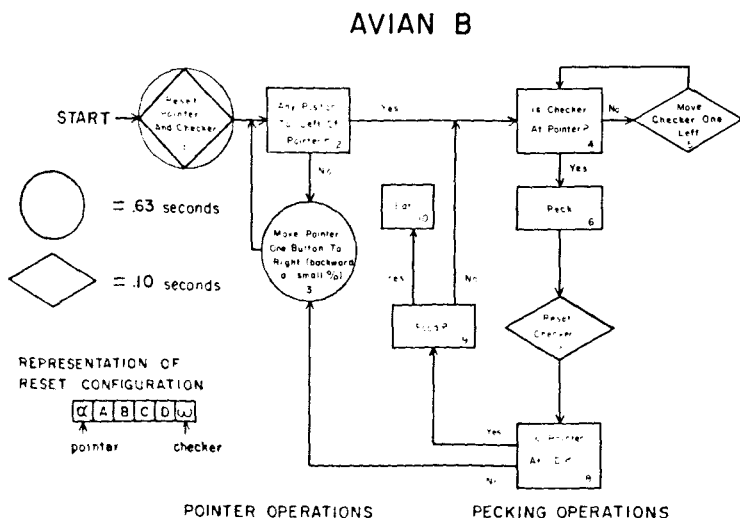

FIG. 4.5.   AVIAN B. Information-processing model model of serial pecking in pigeons with initial backward training.

TABLE 4.10
Predicted and Observed Latencies in the Three Experiments

	Backwards		Forward		Pair	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
Correct						
A	1.51	1.66	1.10	1.36	1.07	1.40
B	.96	1.03	.87	.93	.75	.85
C	.94	.93	.99	1.03	.91	.87
D	.91	.83	1.27	1.13	.93	.93
Repeats						
A	.51	.50	.19	.20	.22	.24
B	.38	.40	.29	.30	.19	.22
C	.33	.30	.34	.40	.24	.24
Forwards Errors						
St → B	2.32	2.19	2.21	2.09	1.84	2.01
St → C[a]	2.98	1.72	1.96	2.82	1.68	2.66
St → D[a]	.81	3.25		3.55	3.10	3.35
A → C	1.60	1.56	1.56	1.66	1.24	1.50
A → D[a]	2.07	2.09	1.89	2.39	1.29	2.19
B → D	1.40	1.46	1.87	1.76	1.47	1.56
Backwards Errors						
B → A[a]	.95	1.13	.99	.83	1.15	.87
C → B[a]	.73	1.03	1.53	.93	.84	.85

[a]Response categories that accounted for less than 2% of the data overall.

then resets to its end position. Because the early colors require more leftward moves of the checker, their latencies are predicted to be correspondingly longer. We assessed the adequacy of AVIAN B by postulating the move-pointer operation as requiring .63 sec and the move-checker operation as requiring 0.1 sec. The observed and predicted latencies are presented in the first two columns of Table 4.10, (as stated, only the 10 data points with more than 4% of the possible responses are tested for latency predictions—although the reader can satisfy himself that AVIAN B accounts quite well for all the latencies): The predictions account for 99% of the variance, which is well within accepted limits for confirmation of such a model. Furthermore, the model is a strong one in the sense that only two variables are needed to account for the 10 independent data points. (See Appendix for sample derivations).

AVIAN B can also account for the frequency pattern if we assume the same sort of error functions as in AVIAN. If the device erroneously answers "no" 14% of the time to the question "Is there a position to the left of the pointer?," then it will generate the same forward skip-error functions as AVIAN; 41% erroneous "yes" to the question "Is the pointer at D?" produces the same proportion of repeats; and an erroneous 3% leftward movement of the pointer

when it should be to the right produces the same pattern of backward skips. These functions could be repeated in AVIAN B and would account for the variance in frequencies in the same way as AVIAN. Accordingly, AVIAN B accounts for 98% of the variance in 10 latencies and 91% of the variance in 16 percentages with a total of five variables, applied to a single model.

The efficacy of this model and its ability to account simultaneously for the error pattern and the latency pattern are convincing features. However, unlike the case with humans, we have no independent evidence that the subjects (pigeons) ever "think" in terms of such devices as postulated by the model. These devices are themselves descriptively powerful, which raises the question of the ontological claims we make about their arrangement in the particular model. Is it a model of the birds' "knowledge"? Is it (only) a simulation of the birds' behavior?

We can attempt to resolve such questions in the usual way: by appealing to further data and showing that the model accounts for them in a revealing manner. If the models are "only" a simulation, then they cannot be expected to generalize to new paradigms. We found that a slight change in AVIAN B produces a new model that can account for the latency pattern of the birds in the "forward" training experiments, as shown in AVIAN F (Fig. 4.6). AVIAN F accounts for 97% of the variance in the latencies (see the second pair of columns in Table 4.10). This model is nearly identical to that for the original birds; most important, it uses the exact same two physical values (.63 sec for a pointer opertion, .1 sec for a checker). In fact, it has only one difference—*the "checker" moves from left to right rather than right to left*. This difference is necessary to account for the fact that the latency for repeat pecks goes *up* for
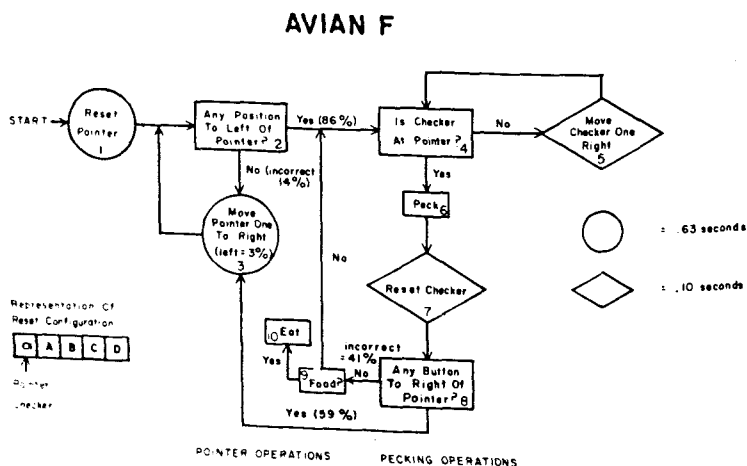
AVIAN F

FIG. 4.6. AVIAN F. Information-processing model of serial pecking in pigeons with initial forward training.
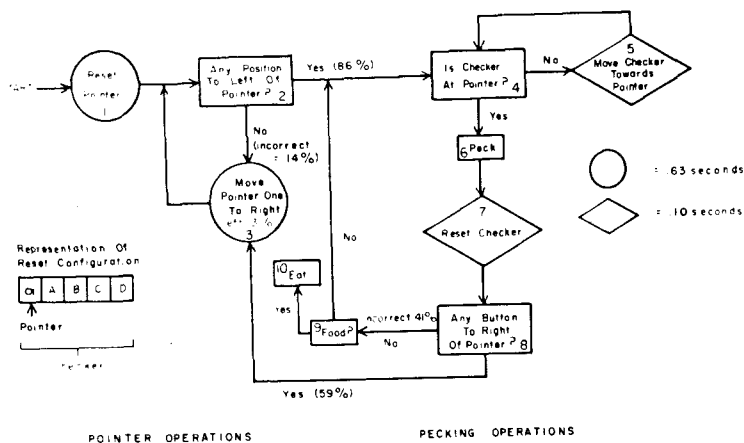
FIG. 4.7.   AVIAN P. Information-processing model of serial pecking in pigeons with initial pair training.

the later colors, as does the added time for an error of each size (recall that the opposite patterns held for the backward pretraining experiment). We do not discuss further the prediction of relative frequencies because the frequency patterns are similar in the three experiments, and all the models make the same frequency predictions.

It is a confirmation of our original model, AVIAN B, that it can account for the new data with the same constraints. Even more striking is that the one difference in the new model has an understandable basis in the different pretraining techniques. In the original experiment, birds were first trained extensively on the end of the sequence and then shifted to the beginning—it is those birds whose model assumes that the checker starts at the end of the sequence on each peck: The later birds were trained equally on all colors in isolation and then shifted to the beginning of the sequence. That is, the first presented pair in this experiment was *A B* rather than *C D*. This is reflected in the model by having the checker always reset back to the beginning.

A further modification in the checker-reset position yields a model that accounts for the latency data in a third, pair-pretraining experiment. AVIAN P (Fig. 4.7) is identical to the previous two, using the same configuration and the same physical variables *except that the checker resets randomly to each position*. This parallels the behavioral fact that there is no serially ordered increasing or decreasing trend in repeat and incremental error latencies, and the fact that overall, *all* the latencies are faster than in the other paradigms (see the last two columns in Table 4.10). Like AVIAN F, AVIAN P is also related to the pretraining procedure given the birds. They were exposed to isolated pairs *A B, B C, C D*, which can be understood as diffusing their

TABLE 4.11
Variance Accounted for by AVIAN Model for
All Response Catergories in Each Experiment

	Model		
Experiment	AVIAN B	AVIAN F	AVIAN P
Backwards Training	98%	88%	94%
Forward Training	79%	97%	65%
Pair Training	69%	97%	97%

attention evenly throughout the sequence. This diffusion is reflected in the fact that the checker in AVIAN P resets to each position equally frequently and randomly.

We have presented what we think are the best models for each of these separate experiments. Before interpreting the meaning of the differences in the models, it is necessary to make sure that they are empirically distinguishable—that is, that no single model designed for one experiment can predict the data from another experiment equally well. Table 4.11 presents the extent to which each model accounts for the variance in the latencies for each experiment. (For the purposes of this discussion, the same response frequencies are predicted by each model, so we can concentrate on the latencies.) AVIAN B, constructed for the backward experiments, does not strongly predict the other experiments and AVIAN P predicts the data from the pair experiment better than the other experiments. AVIAN F, however, originally designed to account for the forward experiment, accounts as well overall for the data from the pair experiment as does AVIAN P. This is mathematically due to the fact that the main qualitative difference predicted by the models is in the times for repeat pecks—but these latencies are extremely short compared with the other data points—thus any difference in the adequacy of predicting these points are obscured by the roughly equal ability of the models to predict the longer latency data points. We could have avoided this difficulty by calculating correlations between predicted and observed values, based on frequency-weighted latencies. We did not do this, however; we treated all reliable latencies equally to arrive at the best *qualitative* model.

It should be noted that the repeat pecks are a major component of the data in each experiment—comprising about one-half of all the pecks actually made. Accordingly, ceteris paribus, the relative ability of a model to predict these responses is decisive: By this criterion the model chosen for each experiment is the best. AVIAN B is clearly the most adequate for the repeats in the backward experiment, and close analysis shows that the AVIAN F is

best for the forward experiment repeats; AVIAN P remains the best for the repeats in the pair experiment. Furthermore, we have a separate way of conclusively demonstrating the superiority of each AVIAN model in accounting for its corresponding experiment. The models make exact quantitative predictions for each response category. For example, "repeat *A*" is predicted to take .50 and .20 by AVIANs B and F, respectively. We can note that this *relative* ordering is confirmed by the actual data on the observed repeat "*A*" pecks, .51 and .19. For the 10 response categories with at least 1% of the data in each experiment, the pair-by-pair directional predictions between AVIAN B and F are confirmed in all 10 cases; this is also true for AVIAN B and P; and for AVIAN F and P, the relative predictions are confirmed in nine cases (the reversal of .03 sec for correct *A* was also the smallest observed difference in the two experiments). (See Table 4.10.) In brief, the ambiguity left by the correlation test is resolved by careful nonparametric analysis: Each model is best for its corresponding experiment, and vice-versa.

To Sum Up. We have analyzed the performance of pigeons on three four-color serial experiments. *The exact same two quantitative variables* (.63 sec for a pointer operation; .1 sec for a checker operation) provide a convincing prediction of the latency data obtained in each experiment. The slight differences in the form of the predictive model for each experiment have a natural interpretation, based on the different pretraining procedures:

Backward Experiment: Subjects were pretrained on the final color alone. The final color is the checker reset position in the model for this experiment.

Forward Experiment: Subjects were pretrained on each color in isolation and then given initial color training alone. The initial color is the checker reset position in the model for this experiment.

Pair Experiment: Subjects were pretrained on paired subsequences, reinforcing each color as the member of a two-color chain. The checker resets randomly to any position, in the model for this experiment.

That is, according to the models, subjects "scan" the color sequence with the checker before each response, starting in each different condition at the position(s) on which they were pretrained. The intuitive nature of this interpretation is itself support for the models. Furthermore, the consistency of the quantitative variables across the experiments provides a strong basis for accepting the models: The models use two variables to predict 30 independent latency data points from three separate experiments.

Despite their success and intuitive consistency, the details of the models must be cautiously interpreted. For example, as the models are constructed, the time to execute a peck response is not separately represented—rather it is

embedded within the other times. This could be interpreted as claiming that each "peck" is a behavior that is inextricably linked to the decision process governing where to do it—certainly a possibility, but not one that we are likely to prove or disprove easily. Furthermore, the specific mechanics of the checker operations are constructed to generate the following generalization:

1. In experiment 1, focus on the end of the sequence.
2. In experiment 2, focus on the beginning of the sequence.
3. In experiment 3, attend equally to all positions.

These generalizations could be captured by formal devices other than those we have used.

Given these cautionary notes, we can still conclude from the models of how pigeons deal with serial order problems:

10a. Subjects encode a representation of the sequence.
10b. Subjects apply an orderly internal procedure to access the representation.
10c. The search procedure differs internally as a direct function of external variables.

The reader is invited to compare our conclusions in (10 a–c) to those made from the human studies, cited in (9 a–c), p. 66.

It is interesting to note that, the simplest model, AVIAN, could be interpreted as a model of two *physical* processes, "pecking" and "moving along in the sequence." In this sense, the model is consistent with a "peripheralist" interpretation of the representation of the sequence. An error is generated when the bird "skips over" a color, by "air-pecking" it: that is, by executing a response toward the color that is not sufficiently complete to close the recording circuit. This would account for the fact that downstream errors take additional time the further downstream they are. We pointed out previously that the nature of the physiological representation is important but orthogonal to the structural organization of the representation. The weakness of the original AVIAN does not involve its reducibility to physical terms but its inadequacy to predict the data. As we found models that are more adequate to the data empirically, we found them harder to interpret in sensorimotor terms. In particular, the checker and the various internal scanning mechanisms in the later three models are not easy to understand this way. Even if one interpreted the different patterns in the distinct experiments as due to a difference in focus (involving no checker at all), one would have to accept the concept of "focus" as a psychological entity in animals. Although such a notion is not unreasonable, given the manifest behavior of many wild and domestic animals, it certainly is not "peripheral."

We do not mean to suggest that no physiological representation can underlie the acquisition of mechanisms such as those we have isolated. Rather, there is no simple sensorimotor basis for these organized behaviors.

In our view, the integration of a sequence of originally isolated responses involves the emergence of an internal organization.

CONCLUSION—BACK AGAIN

We opened this chapter by raising the question of the explanation of serial behavior. We recalled that the existence of integrated subsequences of behavior, such as language, raises immediate conceptual problems for a response-by-response model of behavior. We reported on two attempts to reduce serial constraints in language to simpler terms: examining non-linguistic list search strategies that can explain certain properties of language and developing a paradigm for the study of serial behavior in nonlinguistic organisms.

In each case we have found that learning a serial behavior appears to force the subject to a complex organization. Our evidence suggests that humans and animals alike utilize sequence representations. Their behavior is efficiently modeled by scanning procedures that are similar and similarly dependent on environmental contingencies. This statement, of course, would not be startling to an S–R chaining theorist, who is committed to the belief that all behavior in humans and animals can be reduced to environmentally transparent processes. What should be startling to everyone, however, is that we have not succeeded in finding paradigms in which human behavior can be reduced to the simplicity of animal behavior. Rather, humans use intricate structures in serial behavior outside of language and animals spontaneously generate similar kinds of structural organizations for their serial behavior.

APPENDIX:
AN INTERPRETATION OF
INFORMATION-PROCESSING MODELS

The text in this chapter presents several information-processing models of behavior. It is important to understand how these models operate, because they make exact quantitative predictions that are crucial to the main argument of the paper. We present the following derivations of different kinds of responses produced by the models. The numbers indicate that operation is referred to in the corresponding model.

SEQUENCE MODEL
(as shown in Fig. 4.2)

This model basically executes a left–right serial search on the sequence representation (ordered in paid subsequences; randomized in unpaid sequences). As constructed, the model generates predictions for all correct responses. It could be adapted to predict the incorrect responses as well, but this

involves considerable complexity, and, consequently we have not included them.

Operation	Mode of Exit	Latency	Position of Pointer
1. Time to recognize "N" in example (6), (5 9 4 7 2 X B N R F), as Paid Sequence Item.				
Start	—	—	1
1	yes	—	1
4	no	—	1
5	yes	—	1
6	—	120	2
4	no	—	2
5	yes	—	2
6	—	120	3
4	yes	—	3
7	respond yes	1220	3
		1460(predicted latency)	
2. Time to recognize "F" as a Paid Sequence Item in the same sequence.				
a. Via Buffer				
Start	—	—	1
1	yes	—	1
3	yes	—	1
7	respond yes	1220	1
		1220(predicted latency)	
b. Via Pointer				
Start	—	—	1
3	no	—	1
4	no	—	1
5	yes	—	1
6	—	120	2
4	no	—	2
5	yes	—	2
6	—	120	3
4	no	—	3
5	yes	—	3
6	—	120	4
4	no	—	4
5	yes	—	4
6	—	120	5
4	yes	—	5
7	respond yes	1220	5
		1720(predicted latency)	

Mean latency predicted for sequence—final items = P_c = probability of an incorrect "no" on operation 3 or 4.

$(1 - P_c) (1220) + P_c (1720) = 1240$.

Operation	Mode of Exit	Latency	Position of Pointer
3. Time to recognize any Item as an Unpaid Sequence Item.			
Start			
1	no	—	
2	—	120	
—	—	—	
—	—	—	
—	—	—	

The number of cycles through 4, 5, 6, is the average number of pointer moves through the entire 5-item sequence ÷ 2 = 240 msec.

		240
7	respond yes	1220
		1580

4. Time to miss any paid item.
   Same as (2b).
5. Time to miss any unpaid item.
   Same as (2b) with an additional 120 msec for operation (2).

AVIAN MODELS

As presented, these models can predict the latency of every response category (although they are tested only on responses with at least 1% frequency). The models could also be adapted to predict the relative frequencies of responses. However, there is an extremely high correlation across the experiments of the relative frequencies of responses; the models make the same frequency predictions for each experiment. The latencies are less well-correlated across the experiments; the models make different predictions, due to the different reset configuration of the checker, and the corresponding differences in operation 5.

Each model had the following basic processes (numbers indicate specific operations in Figs. 4.4–4.6.):

1. Resetting pointer to position before the sequence representation.
2-3. Stepping the pointer through the sequence.
4-5. Stepping the checker toward the pointer until it coincides with the pointer.
6. Pecking at the coincident pointer/checker position.
7. Resetting the checker to its canonical position.
8. Checking if the sequence is finsihed (cycling to 3 if it is not).
9. Checking for food (cycling to 6 if there is not any).
10. Eating.

REPEAT RESPONSES AND ERRORS

Repeat responses and errors are generated in the following ways:

Repeats.   An incorrect "yes" to question 8 (i.e., "Is the sequence over?") generates a cycle back to 4-5-6, producing a peck without moving the pointer.

Forward Errors.   An incorrect "no" to question 2 (i.e., "Is the sequence at the beginning?") generates an extra pointer move (operation 3) before going to the pecking operations 4-6, thus creating a skip.

Backward Errors.   A small "jitter" function in the rightward pointer moving operation (operation 3) allows for erroneous backward movement of the pointer and a consequent backward peck.

AVIAN B

	Correct A			
	Exit Response	*Latency Increment*	*Pointer Position*	*Checker Position*
Start		—	—	—
1*		.63	α	w
2	no	—	α	w
3		.63	A	w
1	yes	—	A	w
4	no	—	A	w
5		.1	A	D
4	no	—	A	D
5		.1	A	C
4	no	—	A	C
5		.1	A	B
4	no	—	A	B
5		.1	A	A
4	yes	—	A	A
6	peck	—	A	A
		1.66 predicted latency		

*Note that the Start operations of resetting the pointer and checker are assumed to be parallel, thus adding only the longer latency of the pointer operations to the overall time.

		Correct B		
Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
6 (Peck A)	—	—	A	A
7	—	.1	A	w
8	no	—	A	w
3	—	.63	B	w
2	yes	—	B	w
4	no	—	B	w
5	—	.1	B	D
4	no	—	B	D
5	—	.1	B	C
4	no	—	B	C
5	—	.1	B	B
4	yes	—	B	B
6	Peck B			
		1.03 predicted latency		

		Repeat A		
Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
6 (Peck A)	—	—	A	A
7	—	.1	A	w
8	yes[a]	—	A	w
9	no	—	A	w
4	no	—	A	w
5	—	.1	A	D
4	no	—	A	D
5	—	.1	A	C
4	no	—	A	C
5	—	.1	A	B
4	no	—	A	B
5	—	.1	A	A
4	yes	—	A	A
6	Peck			
		.5 predicted latency		

[a]Incorrect operation.

Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
		Forward Error from A → C		
6 (Peck A)	—	—	A	A
7	—	.1	A	w
8	no	—	A	w
3	—	.63	B	w
2	no[a]	—	B	w
3	—	.63	C	w
1	yes	—	C	w
4	no	—	C	w
5	—	.1	C	D
4	no	—	C	D
5	—	.1	C	C
4	yes	—	C	C
6	Peck	—	C	C
		1.56 predicted latency		

Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
		Backward Error C → B		
6 (Peck C)	—	—	C	C
7	—	.1	C	w
8	no	—	C	w
3[a]	—	.63	B[a]	w
4	no	—	B	w
5	—	.1	B	D
4	no	—	B	D
5	—	.1	B	C
4	no	—	B	C
5	—	.1	B	B
4	yes	—	B	B
6	Peck			
		1.03 predicted latency		

[a]Incorrect operation.

AVIAN F

Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
		Correct A		
Start	—	—	—	—
1	—	.63	α	α
2	no	—	—	α
3	—	.63	—	α
2	yes	—	—	α
4	no	—	—	α
5	—	.1	A	A
4	yes	—	A	A
6	peck	—	A	A
		1.36 predicted latency		

Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
		Correct B		
6 (Peck A)	—	—	A	A
7	—	.1	A	α
8	no	—	A	α
3	—	.63	B	α
2	yes	—	B	α
4	no	—	B	α
5	—	.1	B	A
4	no	—	B	A
5	—	.1	B	B
4	yes	—	B	B
6	peck			
		.93 predicted latency		

Note: Other categories of AVIAN F responses are generated analogous to Avian B, except that the checker reset position is always α.

AVIAN P

(Essentially the same as AVIAN B, and AVIAN F, except that the checker
resets randomly to each position.)

Operation	Exit Response	Latency Increment	Pointer Position	Checker Position
		Correct A		
Start	—	—	—	$(\bar{\Sigma}=B)^a$
1	—	.63	—	α–D
2	no	—	—	α–D
3	—	.63	A	α–D
2	yes	—	—	α–D
4^a	—	—	A	α–D
5^a	—	$.14^a$	—	α–D
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
6	peck			
		1.4 predicted latency		

[a]If the checker reset varies evenly over the five representation positions, the average number of checker moves to A is:

From proportion weighted moves

$$\alpha\text{–}1 \times .2 = .2$$
$$A\text{–}0 \times .2 = 0$$
$$B\text{–}1 \times .2 = .2$$
$$C\text{–}2 \times .2 = .4$$
$$D\text{–}3 \times .2 = \underline{.6} \quad 1.4 \text{ moves} = .14 \text{ sec}$$

The checker moves in operations 4–5 for all the buttons are:

From	To A		To B		To C		To D	
α	1	.2	2	.4	3	.6	4	.8
A	0	0	1	.2	2	.4	3	.6
B	1	.2	0	0	1	.2	2	.4
C	2	.4	1	.2	0	0	1	.2
D	3	.6	2	.4	1	.2	0	0
moves	1.4		1.2		1.4		2.0	
Σ latency increment		.14		.12		.14		.20

Repeat and error responses are generated in the same way as AVIAN B and AVIAN F, except that the latency increments produced by operations 4–5 follow the above calculations corresponding to the actual pecked button.

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