Memory & Cognition
1975, Vol. 3 (2), 210-215

Structural and transient components of memory

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The decomposition of free recall serial position curves into permanent and transient components (primary and secondary memory, Waugh & Norman, 1965) is widely accepted. In this paper, a hypothesis is proposed directly relating the permanent memory component to a vector quantity which reflects sequential allocation of attention during encoding. In conjunction with a previously published model for encoding and retrieval in free recall (Hogan, 1975), the hypothesis is shown to break down predicted serial position curves into permanent and transient components, in a manner analogous to but in various ways less restrictive than the decomposition proposed by Waugh and Norman.

In immediate memory for sequences of letters, digits, or words, one can usually recall the most recent item, but retention of earlier items declines systematically and quickly. Waugh and Norman (1965) focused attention on this regularity and proposed a way of decomposing serial position curves into their permanent and short-lived memory components. They suggested that R(i), the probability of recalling an item followed by i subsequent items; P(i), the probability of the item's presence in primary memory; and S(i), the probability of its presence in secondary memory, are related by

$$R(i) = P(i) + S(i) - P(i)S(i) .$$

The quantity P(i) has transient characteristics, made explicit in the assumptions that P(i) is a monotonically decreasing function of i and that $\lim_{i \to \infty} P(i) = 0$. S(i), by contrast, does not vary in the tasks under consideration; Waugh and Norman restrict their discussion to cases where $S(i) > 0$ and S(i) is independent of i.

Waugh and Norman's decomposition has demonstrated value, but its use has been limited in two ways. The above quantities have been estimated from serial position data rather than predicted on the basis of specific assumptions about encoding and retrieval. Also, for an item presented in serial position j and recalled on draw q of a retrieval sequence, an expression for R(i) must be the limiting case of a potentially more informative expression for R(j,q).

Serial position phenomena with explicit dependence on j and q have been predicted from assumptions about encoding and retrieval in a recent paper concerned with free verbal recall. From a hypothesis relating patterns of encoding to sequential decisions during retrieval, Hogan (1975) developed the following expression for R(j,q), the mean probability of retrieving the j^{th} item on the q^{th} draw of a verbal recall retrieval sequence:

$$R(j,q) = (\vec{\pi} P^q)_j \quad (1)$$

This research was supported by USPHS Grant GM01789 and by Grant MH23878.

where $\vec{\pi}$ refers to a normalized n vector of "search initiation positions" over subjects and lists, and P corresponds to a normalized n by n "search decision matrix" defined in terms of sequential encoding patterns of the same subjects on the same lists.

No attempt was made to decompose serial position curves as Waugh and Norman had done. However, Equation 1 was tested using encoding patterns obtained from overt rehearsal data to evaluate P; analysis of rehearsal data revealed several points relevant to the possibility of a decomposition into permanent and transient components.

1. The matrix P was regular (Kemeny & Snell, 1961) and would probably be regular under a wide range of conditions on sequential encoding. This fact could be valuable because any regular matrix has a unique limiting vector or "equilibrium distribution." In the present case, the matrix P, which reflects the result of temporal constraints on encoding, has a unique equilibrium distribution $\vec{\delta}$.

2. The limiting vector obtained from rehearsal data showed a strong primacy component and a "negative recency" region. This is highly suggestive, as neither primacy nor negative recency were taken into consideration in the original Waugh-Norman formulation.

3. When the quantities $(\vec{\pi} P^q)_j$ were plotted for individual draws, q (see Figure 1 of Hogan, 1975), they appeared to show properties like those we associate with primary and secondary memory. There appeared to be "transient" components of the distributions, which caused earlier ones to deviate systematically from the limiting vector, $\vec{\delta}$, and which became relatively less important as position in the response sequence increased.

The present paper is concerned with elaborating on Point 3, by suggesting a system by which the predicted curves may be broken into permanent and transient components. The first section proposes a hypothesis relating secondary memory to the vector $\vec{\delta}$. The relationship defines a "structural component" of the predicted serial position curve; a "transient component" is introduced as the complement of the structural component. The second section demonstrates that structural and transient components on any particular draw q are predictable from specifics of encoding plus knowledge of search initiation points. The third section shows, under conditions less restrictive than those originally considered by Waugh and Norman, that formal properties of the transient component analogous to properties of P(i) follow from the hypothesis for a broad range of matrices P. A General Discussion then follows, enumerating ways in which the transient and structural components resemble and differ from prior conceptions of short- and long-term memory.

DEFINITION OF STRUCTURAL AND TRANSIENT COMPONENTS

Perhaps the simplest plausible hypothesis relating the secondary memory component of the serial position curve to specific patterns of encoding is the following: The distribution, over serial position, of items retrieved from secondary memory on any draw is governed by the structural distribution $\vec{\delta}$, but the likelihood of retrieval being from secondary memory may vary with q. One would, accordingly, write $S(j,q) = a_q\delta_j$, where S(j,q) is the probability of the j^{th} item presented being retrieved from secondary memory and a_q is the proportion of retrievals governed by the structural distribution on draw q. We shall refer to $a_q\vec{\delta}$ as the structural component of the generic serial position curve $\vec{\pi}P^q$.

In these terms the law of total probability can be written

$$R(j,q) = a_q\delta_j + (1 - a_q)\tau_{qj}, \tag{2}$$

where $\vec{\tau}_q$ is a probability vector defined implicitly by a_q and $\vec{\delta}$, $a_q \neq 1$. We shall refer to $(1 - a_q)\vec{\tau}_q$ as the "transient component" of the generic serial position curve $\vec{\pi}P^q$. The quantity $(1 - a_q)$ is clearly the proportion of retrievals *not* governed by the structural distribution on draw q. $\vec{\tau}_q$ may be thought of as the probability distribution governing retrieval when retrieval is not from secondary memory on draw q.

It might seem natural to assume that, if item j is retrieved, it is retrieved from either primary or secondary memory, and to associate the quantities $\vec{\tau}_q$ and $(1 - a_q)$ with primary memory; we do not wish to make this assumption, however, in view of certain differences between primary memory and the transient component which will be discussed later.

ALGORITHM FOR COMPUTING STRUCTURAL AND TRANSIENT COMPONENTS

Equation 2 can be used under conditions less restrictive than those of Waugh and Norman to determine the form and relative proportion of structural and transient components on any draw q. Waugh and Norman restricted their discussion to situations in which they could estimate S(i) from the "average proportion of items recalled from the middle of a long list," i.e., situations in which P(i) = 0 for serial positions in the middle of a long list. A similar purpose is served, for a list of any length, by the following less restrictive assumption: For the serial position curve $\vec{\pi}P^q$ associated with a given q, $\tau_{qj} = 0$ for at least one serial position $j = j'$. Waugh and Norman also required that S(i) > 0 and that S(i) not vary with i; here we require only that $\delta_{j'} > 0$, a requirement always met for regular matrices since, if P is regular, all δ_j's > 0.

These restrictions are sufficient to determine every a_q and $\vec{\tau}_q$, q less than some positive integer, in terms of P and $\vec{\pi}$. From Equation 2 we get

$$a_q\delta_{j'} = (\vec{\pi}P^q)_{j'}$$

and because $\delta_{j'} \neq 0$,

$$a_q = \frac{(\vec{\pi}P^q)_{j'}}{\delta_{j'}},$$

which may be computed by finding the smallest element of the set

$$\left| \frac{(\vec{\pi}P^q)_1}{\delta_1}, \ldots, \frac{(\vec{\pi}P^q)_n}{\delta_n} \right|,$$

since

$$\frac{(\vec{\pi}P^q)_j}{a_q\delta_j} \geq 1,$$

with equality holding at $j = j'$. Now if $a_q = 1$, there is no transient component and τ_{qj} is undefined. If $a_q \neq 1$, then

$$\tau_{qj} = \frac{(\vec{\pi}P^q)_j - a_q\delta_j}{1 - a_q}.$$

Stated less formally, the crucial point is that the vector $\vec{S}_q$, of which S(j,q) is one element, must touch $\vec{R}_q$ at at least one point but not necessarily over an entire plateau. Figure 1 shows that, of the class of vectors proportional to $\vec{\delta}$, there is only one, $a_q\vec{\delta}$, which subtends the maximum area below $\vec{\pi}P^q$ without exceeding $\vec{\pi}P^q$ at any serial position. Finding this vector determines a_q, the proportion of retrievals wholly governed by structural factors on draw q. Once a_q is known, the vector $(1 - a_q)\vec{\tau}_q$ may be found, since its elements correspond to heights in the shaded area of Figure 1.

This algorithm has been applied to overt rehearsal and search initiation point data previously reported by

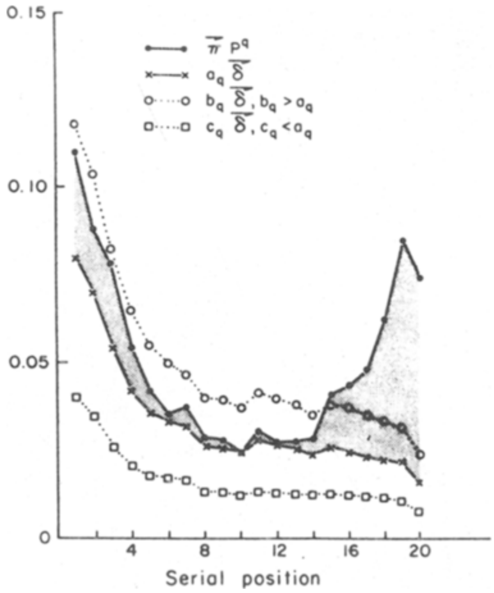

Figure 1. The generic serial position curve $\vec{\pi}P^q$, its structural component $a_q\vec{\delta}$, and two inadequate candidates for structural component, $b_q\vec{\delta}$ and $c_q\vec{\delta}$.

Hogan (1975). That study was designed to vary the vector $\vec{\pi}$ while holding the encoding matrix P constant over experimental conditions. Figure 2 shows the quantities $(1 - a_q)$ computed by means of the above algorithm for three experimental conditions with quite different distributions of search initiation points. Figure 2 illustrates the intuitively reasonable result that the proportions are predicted to be exponentially decaying functions of q, though their rates of decay appear to vary with initiation point vector $\vec{\pi}$.

The vectors $\vec{\tau}_q$ differ for the same three conditions, in ways that are to be expected in view of the differing initial vectors. Figure 3 shows the transient component of the cumulative serial position curve, computed for each of the three conditions by summing $(1 - a_q)\vec{\tau}_q$ from q = 0 to q = 12. (The observed number of draws was approximately 12 in each experimental condition.) The panels show that the transient components for the three conditions differ. They also illustrate that the transient component is *not* limited to list's end.

Figure 3 also shows the structural component for each of the three conditions, computed by summing $a_q\vec{\delta}$ from q = 0 to q = 12. It is clear that the structural component changed very little with experimental condition.[1]

PROPERTIES OF THE TRANSIENT COMPONENT

Properties analogous to those attributed by Waugh and Norman to primary memory follow from the present model. We proceed to prove that (1) $\lim_{q\to\infty}(1 - a_q)\tau_{qj} = 0$, for every j, in analogy with Waugh and Norman's assumption that $\lim_{i\to\infty} P(i) = 0$; and (2) for P with all nonzero elements p_{ij} and $a_q \neq 1$, the "area" of $\vec{R}_q$ associated with transient factors is a monotonically decreasing function of q. In other words, the transient component of the serial position curve on draw q becomes less important with increasing q. This is a partial analogue of Waugh and Norman's assumption that P(i) is a monotonically decreasing function of i.

1.
$$a_q = \min\left|\frac{(\vec{\pi}P^q)_j}{\delta_j}\right|$$

$$\lim_{q\to\infty} a_q = \lim_{q\to\infty}\min\left|\frac{(\vec{\pi}P^q)_j}{\delta_j}\right|$$

$$= \min\left|\lim_{q\to\infty}\frac{(\vec{\pi}P^q)_j}{\delta_j}\right|$$

$$= \min\left|\frac{1}{\delta_j}\lim_{q\to\infty}(\vec{\pi}P^q)_j\right| .$$

But

$$\lim_{q\to\infty}(\vec{\pi}P^q)_j = \delta_j .$$

Therefore

$$\lim_{q\to\infty} a_q = \min\left|\frac{1}{\delta_j}\cdot\delta_j\right| = 1 ,$$

so

$$\lim_{q\to\infty}(1 - a_q) = 0 ,$$

and finally

$$\lim_{q\to\infty}(1 - a_q)\tau_{qj} = 0 .$$

2. The vectors $\vec{\pi}P^q$ and $\vec{\delta}$ are discrete probability distributions, so the shaded "area" in Figure 1 corresponding to transient factors is

$$\sum_{j=1}^{n}(\vec{\pi}P^q)_j - \sum_{j=1}^{n}a_q\delta_j = 1 - a_q\sum_{j=1}^{n}\delta_j = 1 - a_q .$$

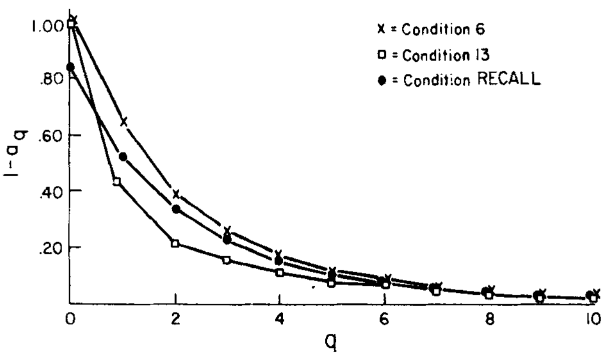

Figure 2. Proportion of retrievals not governed by the structural distribution as functions of q and experimental condition.

Consider the case where $a_q \neq 1$, and $p_{ij} > 0$ for all i and j. If $\vec{\tau}_q$ is a probability vector, then

$$(\vec{\tau}_q P)_j = \sum_{i=1}^{n} \tau_{qi} p_{ij} > 0$$

because

$$\sum_{i=1}^{n} \tau_{qi} p_{ij} = 0$$

implies that $\tau_{qi} = 0$ for all i.

Also, by Equation 2

$$\vec{\pi} P^{q+1} = a_{q+1} \vec{\delta} + (1 - a_{q+1}) \vec{\tau}_{q+1} .$$

But

$$(\vec{\pi} P^{q+1}) = (\vec{\pi} P^q) P = [a_q \vec{\delta} + (1 - a_q) \vec{\tau}_q] P$$
$$= a_q \vec{\delta} + (1 - a_q)(\vec{\tau}_q P)$$

since vectors proportional to $\vec{\delta}$ are not changed when operated on by P. In order to solve for a_{q+1}, we have required that $\tau_{q+1\,j} = 0$ for some $j = j'$. Taking the j'^{th} component of the previous equation,

$$a_{q+1} \delta_{j'} = a_q \delta_{j'} + (1 - a_q)(\vec{\tau}_q P)_{j'} .$$

But for $a_q \neq 1$, the inequality presented above implies that $a_{q+1} > a_q$, so, finally, $1 - a_{q+1} < 1 - a_q$.

A slightly weaker property holds for any regular matrix P, since $p_{ij} \geqslant 0$ for all i and j leads to $a_{q+1} \geqslant a_q$. The "area" $1 - a_q$ is then a nonincreasing function of q.

GENERAL DISCUSSION

The proofs show how arguments, similar in spirit to Waugh and Norman's original decomposition of the serial position curve, can be applied to theoretical curves stemming from hypothetical processes of encoding and retrieval. In particular, properties analogous to those of P(i) and S(i) have been shown to follow from a model for "interitem encoding and directed search" (Hogan, 1975), under a hypothesis relating the stable component of the serial position curve to an equilibrium distribution characteristic of sequential encoding. We shall now summarize ways in which the transient and structural components resemble and differ from prior ways of viewing short- and long-term memory.

1. Waugh and Norman were concerned with systematizing known empirical regularities, while the present model attempts to go beyond these regularities to characterize underlying processes of encoding and retrieval in free recall.

Encoding

Waugh and Norman neither made nor needed an explicit assumption about the nature of encoding. However, the present model relates serial position phenomena to a cognitive structure which is sensitive to specific sequential operations of encoding. For this reason, it is sensitive to encoding strategies, to clustering and subjective organization, to degree of relationship between list items, in short, to those variables which have seemed most interesting to investigators of verbal recall.

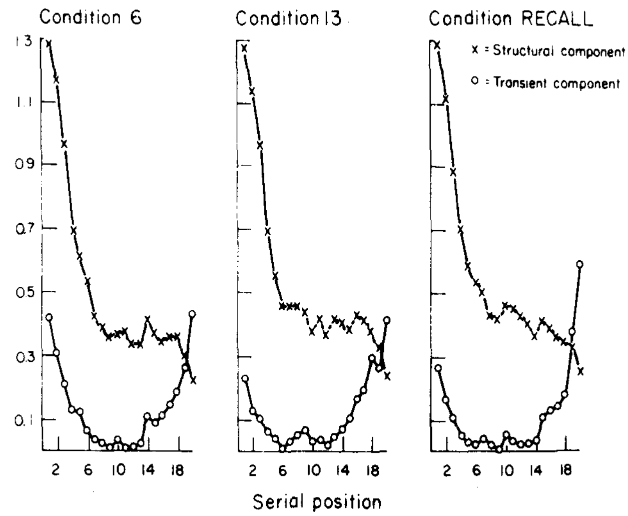

Figure 3. Cumulative structural and transient components as functions of experimental condition.

Retrieval

A model for retrieval in free recall requires an explicit decision about whether draws are made with or without replacement. It seems more plausible that draws be made with replacement. However, models such as Waugh and Norman's are not explicit about the number of draws during the retrieval sequence which actually produce repetitions (draws of an item already retrieved). Such an assumption is clearly necessary for any model which is to be regarded as characterizing the retrieval process rather than the serial position curve.

Under conditions in which subjects were instructed to report all items retrieved, even those that were repetitions, Hogan found that repetitions constituted at least 40% of all items reported, and was able to predict the distribution of repetitions over serial positions with reasonable success. Equation 1 gives an expression uncorrected for the "editing" of repetitions.

2. The form of the equilibrium distribution is completely determined by patterns of encoding. Exploiting this fact, the form and relative proportions of structural and transient components are *predicted* on the basis of specifics of encoding plus search initiation point data, rather than evaluated after the fact.

3. The present formulation deals well with primacy and negative recency (see Hogan, 1975), though these phenomena were not addressed by Waugh and Norman. Atkinson and Shiffrin (1968) have also presented a model in which processes of encoding are jointly consistent with a "recency" component in immediate recall, primacy, and negative recency. Two basic differences between Atkinson and Shiffrin's model and

the present one are that (a) encoding, here, means changes in a network of relationships between items, rather than a strengthening of the representations of particular items, and (b) the present model, by using overt rehearsal data to reflect processes of encoding, requires no ad hoc search for best-fit parameters.

4. In order to break serial position curves down into their structural and transient components, we require that $\overline{S}_q$ touch $\overline{R}_q$ at at least one point but not (as in Waugh & Norman) necessarily over a whole plateau. The assumption of a broad central plateau in the immediate recall serial position curve is not generally valid; it is usually violated with relatively short lists, and its validity with longer lists is rarely certain.

Of course, the reason we can apply the present formulation in cases where no flat asymptotic section can be found is that we can predict an asymptotic component from encoding.

5. As Figures 1 and 3 make evident, the transient component in this formulation is not necessarily limited to list's end. See Cohen (1970) or Hogan (1975) for data which suggest the influence of a transient component over early serial positions.

6. In this formulation, the analogues of certain properties which had merely been assumed [$\lim_{i \to \infty} P(i) = 0$, P(i) being a monotonically decreasing function of i] follow logically from prior assumptions about encoding.

7. The structural and transient components are *different* parts of the serial position curve, but follow from the *same* assumptions about encoding and retrieval. We have made no assumption which requires that they be assigned to separate mechanisms of storage.

Waugh and Norman (1965) and Glanzer (1972) both assume that the different properties of primary and secondary memory (short-term storage and long-term storage) reflect separate mechanisms of storage. However, Tulving (1968) argued that such an assignment is premature without better understanding of the retrieval mechanisms involved. The present formulation is consistent with Tulving's view, i.e., the transient component follows from a more explicit characterization of the retrieval process.

8. Structural and transient components, being of recent theoretical origin, have received little experimental scrutiny in comparison with their analogues in earlier formulations.

Long-Term Storage and the Structural Component

It remains to be shown that variables such as rate of presentation, word frequency, or mnemonic relatedness of list items differentially influence the structural but not the transient component, though these relationships are documented for LTS and STS (Glanzer, 1972). However, the variables mentioned influence encoding, and encoding patterns determine $\overline{\delta}$, so one would expect the variables to influence primarily the structural component.

In one instance, the model has had excellent success in predicting the primacy component of immediate recall curves, and both primacy and negative recency components of final recall curves (Hogan, 1975). These results also suggest that the structural component is closely related to LTS (or secondary memory).

Short-Term Storage and the Transient Component

Short-term storage is not sensitive to the above variables or others known to influence long-term storage (Glanzer, 1972); the influence of these variables on the transient component remains to be experimentally examined.

The only variable known to influence an item's presence in STS is the number of interfering items which follow it. Here the STS and transient components differ in two ways:

1. An additional variable can influence the shape and extent of the transient component. In tasks which require a sequence of responses, part of the predicted recency component may be "transferred" to earlier serial positions by postlist cuing of search initiation points. Theoretical discussions of PM or STS make it clear that their influence is restricted to list's end, so this property suggests an experimental program for distinguishing between the two components.

2. Investigators have generally accepted (without direct test) Waugh and Norman's assumption of the equivalence of "response-produced" and "stimulus-produced" interference. We have shown that a monotonically decreasing property characterizes the transient component's dependence on the response index q but, as Figure 3 makes clear, the height of the transient component is not necessarily a monotonic function of the stimulus index j.

In addition, evidence reported by Hogan (1975) suggests that the predicted transient component at final serial positions may be appreciably smaller than the observed recency effect (the PM or STS component is equal to the recency effect by definition).

In summary, then, the transient component may not be related to STS in as simple a way as the structural component is related to LTS.

In seeking the relationship between transient component and STS, we should not assume that the latter is completely understood. Investigators have been tempted to attribute properties other than a decrement with interfering items to the "recency store;" however, arguments based on coding, on capacity, and on decay characteristics have not been compelling (Craik & Lockhart, 1972). Further, "modality effects" (e.g., Murdock & Walker, 1969) have been found of the same general extent and form as free recall recency, although they had not been anticipated in the formulations of Waugh and Norman or Atkinson and Shiffrin. The relationship between "echoic" memory, thought to underlie modality effects, and STS is an unresolved question. It therefore seems that PM or STS may be less well understood than SM or LTS in terms of our ability to predict its precise form or in terms of the number of variables with which we can manipulate it. Viewed in this light, the transient component's underpredicting the recency effect may not be a serious drawback. The transient component, rather than being set equivalent to PM or STS, might be used in conjunction with contributions from other sources (e.g., echoic memory) to predict the PM component.

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NOTE

1. The quantities plotted in Figure 3 may exceed 1.0 since they correspond to the possibility of repetitions, as well as first recall, of particular items. One may compute the "area" associated with the transient component for each of the three conditions to get a predicted "capacity." This area ranges from 2.4 to 2.8 items; however, comparison with other estimates of short-term store capacity is indirect for many reasons.

(Received for publication November 21, 1974; accepted January 8, 1975.)