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Effects of List Length on Short-Term Memory[1]

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A memory experiment has been performed with the following procedure. On each trial of the experiment a display of items was presented in a serial order. At the conclusion of each display S was tested for recall on one of the items. The length of the displays varied from 3 to 14 items. Plotted as serial position curves, the results showed an S-shaped recency effect and a smaller primacy effect. A specific version of a memory model formulated by Atkinson and Shiffrin (1965) was presented and applied to the data. The model assumes two memory states: a temporary storage state, called the buffer, from which retrieval is perfect; and a long-term storage state called LTS, from which retrieval is imperfect. Both response data and confidence ratings were accurately fit by the model.

A quantitative model for memory and learning has been recently proposed and applied successfully to serial-position curves from studies of free verbal recall (Atkinson and Shiffrin, 1965, 1967). It was found that variations in list length and presentation rate could be handled by the model with the use of only two parameters. It was then desired to extend the model to paired-associate learning; as a step toward this end, the present experiment was designed in which a paired-associate memory paradigm was used. On each trial of the experiment a new display of *d* items was presented sequentially to S. A display consisted of a random sequence of playing cards. The cards varied only in the color of a small patch on one side; four different colors were used. Following the presentation of the display, S was asked to recall the color of one of the cards. The S then gave a confidence rating, and the trial terminated with the experimenter informing S of the correct answer. Over trials the list length, *d*, took on values ranging from 3 to 14 cards. This procedure is similar to that reported by Atkinson, Hansen, and Bernbach (1964).

The model supposes two memory states: a temporary state called a buffer and a long-term storage state called LTS. The features of the buffer are similar in some respects to the short-term memory system proposed by Broadbent (1958, 1963). We postulate a limited and constant capacity for the buffer. Items enter the buffer successively until it is filled, and then each succeeding entering item causes exactly one of the items currently in the buffer to be lost. The constancy assumption holds when the items presented are reasonably homogeneous, as is usually the case for a given experiment. Since the size of the buffer (defined as the number of items that can be held simultaneously) depends on the nature of the items, a buffer size must be estimated for each experiment. We expect, however, that certain relations would hold from experiment to experi-

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ment; for example, the more complex the items, the smaller the estimated buffer size. Similarly, the assumption that a single item is lost when a new item enters the buffer depends on the homogeneity of the items; if the items are two-digit numbers and a four-digit number is suddenly presented, we might expect that two items currently in the buffer would be lost. In Broadbent's formulation items are postulated to decay quickly in a short-term state but may be "renewed" by recirculation through an attention channel. If it is assumed that a limited and fixed number of homogeneous items can be constantly renewed, then the two short-term systems are compatible.

We place upon the buffer the further requirement that a correct response occurs with probability one when the item tested is currently in the buffer. This point leads to the question, "What is stored in the buffer?" and "What is an item?" In terms of the preceding requirement (and in accord with the mathematical structure of the model) we may be satisfied with the definition, "an item is that amount of information that allows correct performance at the time of test." Because the model does not require a more precise statement than the above, it is not necessary for the present analysis to spell out the matter in detail. Nevertheless, in view of the work of Conrad (1964), Wickelgren (1965), and others on auditory confusions in short-term memory, we would be satisfied with the view that items in the buffer are acoustic mnemonics and are kept there via rehearsal, at least for experiments of a verbal character.

The remaining features of the buffer are presented in Fig. 1. The capacity of the buffer is r items. The newest item is in position r and the item which has been in the buffer for the longest time is in position 1. The items are temporally ordered because the buffer operates as a push-down list: when a new item is about to enter, the item in slot j of the buffer is lost with probability κ_j, the items above

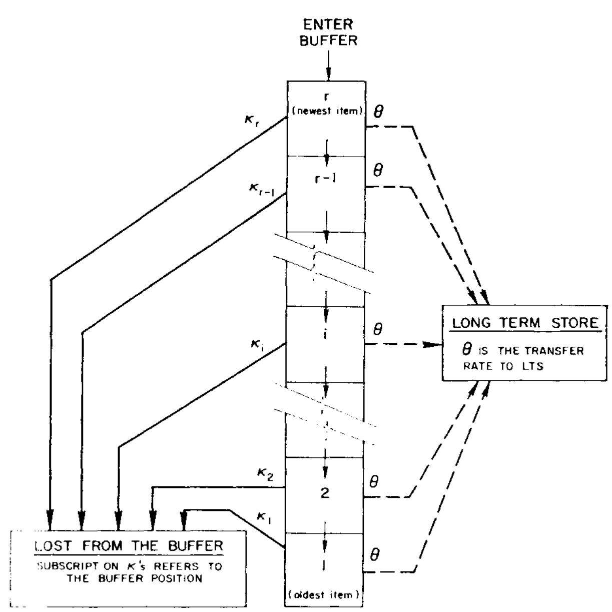

FIG. 1. A flow chart for the memory system.

slot j each move down one, and the new item is placed in slot r. Let us call the process by which an item is lost from the buffer the *knockout process*. It is assumed that this process can be characterized by the tendency for the older items to be knocked out first. A feature of the model which will be described later requires that information be transmitted to LTS during the period that an item resides in the buffer. Under these conditions it might seem natural that S would tend to eliminate the oldest items in the buffer, since these items have accumulated the greatest strength in LTS. It could be expected that the degree of this tendency would vary with experimental conditions and therefore must be estimated for each experiment. For this reason, suppose that the following process occurs when a new item enters a full buffer. The oldest item (in slot 1) is lost with probability δ; if this item is not lost then the item in slot 2 is lost with probability δ. This process continues until either an item is lost or slot r in the buffer is reached. If slot r is reached and no item has yet been lost, then the process cycles back to slot 1 and continues until an item is lost. Hence, the probability that the item in slot i is knocked out when a new item enters a full buffer is

$$\kappa_i = \frac{\delta(1-\delta)^{i-1}}{1-(1-\delta)^r}. \quad (1)$$

The larger the δ, the greater the tendency to lose the oldest item. When $\delta = 1$, the item in slot 1 is always lost. As δ approaches zero, the κ_i's all approach $1/r$. For the present experiment the assumption will be made that every item enters the buffer. It should be noted that this assumption will not be adequate in experiments run under conditions where S does not or cannot attend to every item presented.

We now consider the long-term store. LTS is viewed as a memory state in which information accumulates for each item. It is assumed that the information may enter LTS only during the period in which the item resides in the buffer. This conception is also in line with Broadbent's view that long-term storage occurs while the item is being processed through a filtering channel when in the short-term state. We postulate that the status of the item in the buffer is in no way affected by the transfer process to LTS. Whereas recall of an item from the buffer was assumed to be perfect, recall from LTS is not necessarily perfect and usually will not be. At the time of test, S gives the correct response if the item is in the buffer and searches LTS if the item is not in the buffer. This search of LTS is called the *retrieval process*. The first basic postulate concerning LTS states that retrieval of an item improves as the amount of information stored concerning that item increases. It should be noted that throughout this discussion the term information is used in an informal sense, referring to mnemonics, codes, mental images, or anything else S might store that would help him emit a correct response.

The second basic postulate concerning LTS states that the likelihood of retrieving a given item decreases as the amount of information stored for *other* items increases. Atkinson and Shiffrin (1967) have proposed several mechanisms whereby this can occur. For example, a limited search of LTS can be made, and the greater the total amount of information stored, the less the probability that any one item is found before the search ends. In the Discussion Section the details of LTS will be carefully spelled out as applicable to the present experiment, and a scheme will be proposed which can be interpreted as a quantification of proactive and retroactive interference effects.

To conclude the introduction we will specify the retrieval process more precisely. At the time of test it is assumed that S recalls an item correctly if the item is in the buffer. If the item is not in the buffer he searches LTS and retrieves the item correctly with a probability dependent upon the list length and the amount of time the item resided in the buffer. Thus we define $\omega_{ij}^{(d)}$ as the probability that item i in a list of length d stays in the buffer for exactly j interitem intervals. An interitem interval is the period from the presentation of one item to the presentation of the succeeding item. A display of size d is numbered so that item 1 designates the last item presented (the newest item), and item d designates the first item presented (the oldest item). The derivation of the ω's is straight-forward and is carried out in the appendix. We also define $\rho_{ij}^{(d)}$ as the probability of a correct retrieval from LTS of item i in a list of length d, given that the item stayed in the buffer for exactly j interitem intervals. The form of the ρ's will be specified in the discussion section. Now let $Pr\{C_i^{(d)}\}$ be the probability of a correct response to item i in a list of length d. Then

$$Pr\{C_i^{(d)}\} = \left[1 - \sum_{j=1}^{i-1} \omega_{ij}^{(d)}\right] + \left[\sum_{j=1}^{i-1} \omega_{ij}^{(d)} \rho_{ij}^{(d)}\right]. \quad (2)$$

The first bracketed term is the probability that the item is in the buffer at the time of test. The second bracket contains the probability of a correct retrieval from LTS. It is stated as a sum because it is conditionalized on the length of stay in the buffer.

Method

The Ss in this study were 20 females. They were drawn from a pool of Stanford University students who had expressed an interest in participating in psychological experiments, and were paid for their services. Each S participated in five sessions, each session lasting approximately 1 hr. The first session was a practice session, designed to familiarize S with procedure and to eliminate practice effects. Three display sizes ($d = 8$, 11, 14) were used in session 1; the next three sessions were also restricted to these three display sizes. The last session for each S employed five different display sizes ($d = 3$, 4, 5, 6, 7).

The experiment involved a long series of discrete trials. On each trial a display of d items was presented. A display consisted of a series of $2 \times 3\frac{1}{2}$-inch cards containing a $\frac{3}{4} \times 1\frac{1}{2}$-inch colored patch in the center. Four colors were used: black, white, blue, and green. The cards were presented to S at a rate of one card every 2 sec. The S named the color of each card as it was presented. A metronome was used to maintain a constant rate of presentation for each display. Once the color of the card had been named by S, it was turned face down on a display board so that the color was no longer visible, and the next card was presented. After presentation of the last card in a display, the cards were in a straight row on the display board: the card presented first was to S's left and the most recently presented card to her right. The trial terminated when the E pointed to one of the cards on the display board, and S attempted to recall the color of that card. The S was instructed to guess the color if uncertain and to qualify her response with a confidence rating. The confidence ratings were the numerals 1, 2, 3, and 4. The Ss were told to say 1 if they were positive, 2 if they were able to eliminate two of the four possible colors as correct, 3 if one of the four colors could be eliminated as correct, and 4 if they had no idea at all as to the correct response. These confidence ratings will be designated R_1, R_2, R_3, and R_4. Each display, regardless of size, ended at the same place on the display board; that is, displays began at different places on the display board and hence Ss knew, from the position of the first card, how long each display was to be.

Each S was given two complete blocks of displays in each of the first four sessions. A block consisted of one display for each serial position in each display size. Thus there were $(8 + 11 + 14) = 33$ displays per block, and a complete session involved the presentation of 66 displays. During the fifth day each S was given five complete blocks of displays. A complete block in the final session consisted of $(3 + 4 + 5 + 6 + 7) = 25$ displays; hence the total session involved the presentation of 125 displays. Each serial position of each display size was selected as the test position exactly once per block. The presentation order of displays (display size and test position) was randomized within each block; furthermore, the cards and their order were determined randomly for each display.

At the beginning of the second session Ss were told the proportion of correct responses that they had achieved for each of the four confidence ratings. They were reminded at that time that the "ideal" proportion correct was 100% for a confidence rating of R_1, 50% for R_2, 33% for R_3, and 25% for R_4. No further information feedback was given concerning the confidence ratings during subsequent sessions.

Results

The overall proportions of correct responses for Sessions 1 to 4 were .66, .72, .73, and .72, respectively; each point is based on 7920 observations. Since the proportion correct is reasonably stationary for the three sessions following the practice session, it is assumed that performance in Session 5 (involving different values of d) is comparable to that in the three preceding sessions. In subsequent analyses the data from Session 1, the practice session, will not be included.

Figure 2 presents the probability of a correct response plotted against serial position for list lengths $d = 5$, 6, 7, 8, 11, and 14. For list lengths 3 and 4 the probability correct was 1.0 at all positions. The circles in the figure are the observed points, the solid lines being the predicted curves which will be explained shortly. Serial position 1 denotes a test on the most recently presented item. Points on the curves for $d = 8$, 11, and 14 are based on 120 observations, whereas all other points are based on 100 observations. The most apparent features of the curves are a large s-shaped recency portion and a smaller, quite steep primacy portion.

Consider now the confidence ratings: if Ss were actually following the directions they were given, then the probability that they would give a correct response to an item to which they assigned a confidence rating of R_i should be $1/i$. This follows because the instructions asked S to assign confidence rating R_i if she were choosing her response from among i alternatives. The probability of a correct response given confidence ratings of 1, 2, 3, and 4 were respectively .97, .52, .38, and .28; if Ss were able to follow the instructions pre-

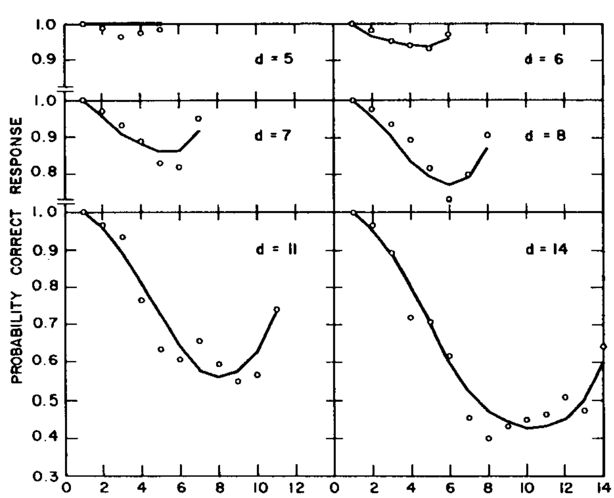

FIG. 2. Probability of a correct response as a function of list position and display size. Observed values are denoted by circles, and theoretical values by the solid lines. ($\chi^2 = 44.3$ based on 42 df.)

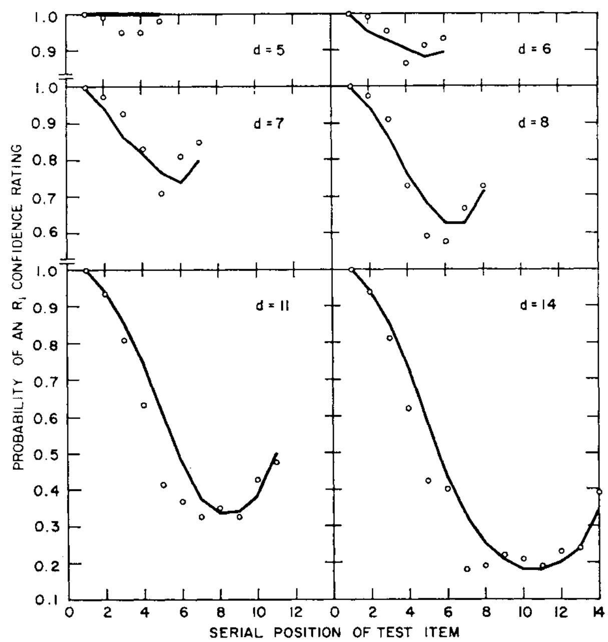

FIG. 3. Probability of a confidence rating R_1 as a function of list position and display size. Observed values are denoted by circles, and theoretical values by the solid lines. ($\chi^2 = 111.9$.)

cisely we would expect the values 1.00, .50, .33, and .25. It is beyond the scope of this paper to examine all the data on confidence ratings; we will consider only the serial position curves for confidence rating R_1. Figure 3 presents the probability of confidence rating R_1 at each list position. It can be seen that the observed points are similar to those for the probability of a correct response.

Discussion

In order to apply the model to the serial position curves for correct responses, we must calculate Eq. 2. Hence the $\rho_{ij}^{(d)}$ function must be specified and this requires a careful outline of the workings of LTS. The other function required is $\omega_{ij}^{(d)}$: the staying time distribution in the buffer. It should be noted that this distribution depends only on δ and the buffer size r, and is independent of LTS and the retrieval process. The $\omega_{ij}^{(d)}$ are defined recursively as difference equations in the appendix.

The first assumption we make regarding LTS is that information is transferred there from the buffer at a constant rate regardless of the number of items currently in the buffer. Let θ be the transfer rate of information per interitem interval. Then the total amount of information transferred for a list of length d will be $d\theta$. This assumption gains rough justification from recent studies showing a close relationship between learning and total presentation time (e.g., Waugh, 1963; Bugelski, 1962).

We now follow what is perhaps the strongest point made by Broadbent (1958) and state that information is transferred only while attention is fixed on an item, assuming that all items in the buffer share equally in the attention they receive. Hence if there are j items currently in the buffer, each will be attended to a proportion $1/j$ of the time. Now define $\mu_{ij}^{(d)}$ to be the attention time received by item i in a list of length d if the item stayed in the buffer exactly j interitem intervals. Then

$$\mu_{ij}^{(d)} = \begin{cases} \dfrac{j - i + d - r + 1}{r} + \displaystyle\sum_{k=d-i+1}^{r-1} \frac{1}{k} & \text{, for } i > d - r + 1 \\ \dfrac{j}{r} & \text{, for } i \leq d - r + 1. \end{cases} \quad (3)$$

Since θ is the transfer rate, the information accumulated in LTS for an item which remained in the buffer exactly j intervals is $\theta\mu_{ij}^{(d)}$. The θ parameter in Fig. 1 refers to the transfer rate just described.

Given an amount I of information stored for an item in LTS, it remains to specify the probability of a correct retrieval. Two conditions should be satisfied by any function we choose: first, the probability correct should be at the guessing level when $I = 0$; second, the probability correct should increase toward one as I increases. We choose the following function:

$$1 - (1 - g)e^{-I},$$

where g is the guessing level, which is ¼ in the present experiment. Thus, if no other items were stored, the probability of a correct response given a search in LTS would be: $1 - \frac{3}{4}\exp[-\theta\mu_{ij}^{(d)}]$. This function satisfies the first assumption stated in the introduction that the probability correct should increase as the stored information increases.

It remains now to examine the effect of storing information concerning items other than the one tested. We will assume that every other item stored causes an identical reduction in the effective strength of the information stored for the item to be tested. Let τ represent the proportional decrement; i.e., every other item causes the effective amount of information stored to be reduced by a proportion τ. If there are d items stored and the item tested had accumulated an amount of information I, then the effective amount of information found when LTS is searched is $I(\tau^{d-1})$. Thus

$$\rho_{ij}^{(d)} = 1 - \frac{3}{4}\exp[-\theta(\mu_{ij}^{(d)})(\tau^{d-1})]. \quad (4)$$

One view of the above decrementing process would interpret the reduction as actual physical destruction of the stored information. We prefer the view that no actual destruction occurs; rather, the value of the information stored is reduced. A brief example will help clarify this point. Suppose, in a paired-associate memory experiment the first item is GEX-5, and *S* stores "G__-5" in LTS. If tested now on GEX, *S* would give the correct response 5. Suppose now a second item GOZ-3 is presented and *S* stores "G__-3" in LTS. If he is now tested on either GEX or GOZ his probability of a correct response will drop to ½. This process could furthermore be viewed as a quantification of a simple form of interference theory. It is a simple form in that each item is postulated to have an identical interfering effect; in particular the proactive and retroactive effects are equal, that is, each preceding and each following item interferes to the same degree.

It is now possible to use Eq. 2 to fit our data. There are four parameters that must be estimated: r, δ, θ, and τ. For the purpose of estimating these parameters and evaluating the goodness-of-fit of data to theory, we define the following chi-square function:

$$\chi^2(d) = \sum_{i=2}^{d} \left[\frac{1}{NPr\{C_i^{(d)}\}} + \frac{1}{N - NPr\{C_i^{(d)}\}} \right] \left[NPr\{C_i^{(d)}\} - O_i^{(d)} \right]^2, \quad (5)$$

where $O_i^{(d)}$ is the observed number of correct responses for the ith item in a display of size d, and N is the total number of observations at each position of the display. (Recall that N was 120 for $d = 8$, 11, 14; and 100 for $d = 3$, 4, 5, 6, and 7.) The sum excludes item 1 because $Pr\{C_i^{(d)}\}$ is predicted to be one for all list lengths; this prediction is supported by the data.

Now define $\chi^2 = \chi^2(6) + \chi^2(7) + \chi^2(8) + \chi^2(11) + \chi^2(14)$, and observe that the value of χ^2 depends on the parameters r, δ, θ, and τ. We shall use as estimates of these parameters those values that minimize χ^2.[3] Successive sets of parameter values were generated, and for each set the predicted serial position curves were calculated on a high-speed computer. A grid of parameter values was examined which effectively covered the parameter space. Those parameters yielding the minimum χ^2 were: $r = 5$, $\delta = .38$, $\theta = 2.0$, and $\tau = .85$. The predicted serial position curves generated by these parameters are displayed as solid lines in Fig. 2. It should be noted that the model predicts that there will be no errors until the list length exceeds the buffer size. Since there were so few errors for list lengths of 5 and less, we are willing to assume that these were due to extraneous factors and thus have not included them in the χ^2. The minimum χ^2 was 44.3 and is based on 42 degrees of freedom. It should be apparent that the model simultaneously fits the various serial position curves with remarkable accuracy.

We shall now briefly consider the problem of confidence ratings. It should be clear that a model that postulates a distribution of strengths in LTS can handle the prediction of confidence ratings in any of several ways. For example, we could assume that there exist criterion points $c_0 = \infty$, c_1, c_2, c_3, and $c_4 = 0$, such that whenever the amount of information in LTS is between c_{i-1} and c_i, the confidence rating R_i will be given. A preliminary attempt to fit the confidence rating data in this manner did not prove fruitful, but it is possible that a more sophisticated version than we used could fit the data. The central question to be answered is whether, for small amounts of information in LTS, there is still some probability of giving a high confidence rating. The above approach holds that whenever the amount of information falls below a certain critical value, there is no chance of giving an R_1. We prefer the notion that given any amount of information in LTS, no matter how small, there exists some probability of giving an R_1 (this notion is easily generalized to the other confidence ratings). Nevertheless, we would place the following restrictions upon the process: the greater the amount of information, the higher the probability of giving R_1; when the amount of information stored is zero, the probability of an R_1 is zero. A function that satisfies these conditions is $1 - \exp(-c_1 I)$, where I represents amount of information.

It is now possible to fit the serial position curves for R_1 confidence ratings. It is assumed that an item in the buffer is always given confidence rating R_1. If LTS is searched and the item has strength I, the probability of an R_1 is $1 - \exp(-c_1 I)$. If $Pr\{R_{1,i}^{(d)}\}$ is defined as the probability of giving confidence rating R_1 to item i in a list of length d, then

$$Pr\{R_{1,i}^{(d)}\} = 1 - \sum_{j=1}^{i-1} \omega_{ij}^{(d)} + \sum_{j=1}^{i-1} \omega_{ij}^{(d)}\{1 - \exp[-c_1\theta\mu_{ij}^{(d)}\tau^{d-1}]\} . \quad (6)$$

Setting the values of the parameters r, δ, θ, and τ equal to those used to fit the correct response data, we then ran a minimum χ^2 grid search on the parameter c_1 in a fashion similar to the earlier fit. The minimum χ^2 value for the R_1 data was found when $c_1 = .66$ ($\chi^2 = 111.9$). The

[3] For a discussion of minimum χ^2 procedures for parameter estimation, see Atkinson, Bower, and Crothers (1965).

theoretical curves are shown as solid lines in Fig. 3. While the fit is not nearly as good as that in Fig. 2, it must be remembered that only a single parameter was estimated in fitting all five curves in Fig. 3. Since the predicted R_1 curves are consistently high in the recency portion, it is possible that the assumption that an R_1 is always given if an item is in the buffer needs modification. It is beyond the scope of this paper, however, to examine this possibility or any other features of the confidence ratings. It should be noted that our scheme for generating confidence ratings has not been spelled out in sufficient detail to calculate the probability of a correct response given an R_1. Since the data show this probability to be almost unity, it would be reasonable to assume that an R_1 is always accompanied by a correct response.

Appendix

Let $\omega_{ij}^{(d)}$ = probability that item i in a list of length d resides in the buffer for *exactly* j interitem intervals. In order to calculate the $\omega_{ij}^{(d)}$, we define the quantity β_{ij} = probability than an item currently in slot i of a full buffer is knocked out of the buffer at the moment the jth succeeding item is presented. Then

$$\begin{aligned}
\beta_{1,j} &= (1-\kappa_1)^{j-1}\kappa_1\\
\beta_{2,j} &= \kappa_1\beta_{1,j-1} + (\kappa_3+\kappa_4+\cdots+\kappa_r)\beta_{2,j-1}\\
&\vdots\\
\beta_{i,j} &= (\kappa_1+\kappa_2+\cdots+\kappa_{i-1})\beta_{i-1,j-1} + \\
&\qquad (\kappa_{i+1}+\kappa_{i+2}+\cdots+\kappa_r)\beta_{i,j-1}\\
&\vdots\\
\beta_{r-1,j} &= (\kappa_1+\kappa_2+\cdots+\kappa_{r-2})\beta_{r-2,j-1} + \kappa_r\beta_{r-1,j-1}\\
\beta_{r,j} &= (\kappa_1+\kappa_2+\cdots+\kappa_{r-1})\beta_{r-1,j-1}.
\end{aligned}$$

The initial conditions are $\beta_{i,1} = \kappa_i$. Hence

$$\omega_{ij}^{(d)} = \begin{cases}
1 - \sum_{j=1}^{i-1}\omega_{ij}^{(d)} & \text{, if } i = j\\
0 & \text{, if } i < j\\
\beta_{r,j} & \text{, if } i > j \text{ and } i \le d-r+1\\
\beta_{d-i+1,j-i+d-r+1} & \text{, if } i > j \text{ and } i > d-r+1 \text{ and } j > i-d+r-1\\
0 & \text{, if } i > j \text{ and } i > d-r+1 \text{ and } j \le i-d+r-1.
\end{cases}$$

For more details on this derivation see Atkinson and Shiffrin (1965).

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