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Less than expected variance in studies of serial position effects is not a sufficient reason for caution

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A number of reports of serial position effects have been criticized for displaying less than the variance that would be expected on the basis of the binomial theorem. The statistical evidence cited in support of this claim is reviewed and found to be far from conclusive. At least three problems with this statistical evidence are noted. First, typical patterns of variance in studies of serial position effects, which had not previously been established, are at odds with those predicted by the binomial theorem. Second, according to statistical theory, the variance observed in any particular study should not necessarily equal the variance predicted by the binomial theorem, and may do so only under a very limited number of conditions. Third, the assumptions underlying the binomial model have been violated in applications to data from experiments on serial position effects, causing severe and systematic error in the estimation of expected variance. Given that the burden of proof falls on those claiming that evidence from some experiments on nonhuman serial position performance is flawed, the doubts raised over their supporting evidence indicate that it would be prudent to suspend judgments regarding such claims pending further empirical data.

It has been suggested that inspection of the variance in data obtained from some studies of nonhuman memory for serially presented items can demonstrate the operation of processes other than those concerned with memory (e.g., E. A. Gaffan, 1992; E. A. Gaffan & D. Gaffan, 1992). This position is based on the fact that, in some studies, the variance reported in the data is low. This conclusion was arrived at by a comparison of the variance observed in the data of interest with that expected on the basis of the binomial theorem (see Hayes, 1988). In the present review, I do not deny that evidence regarding low variance may call into question the interpretation of data from studies on nonhuman memory. Rather, the present report is an examination of the *strength* of the evidence that supports the claim that low variance is likely to be a serious obstacle to the interpretation of data (see E. A. Gaffan, 1992; E. A. Gaffan & D. Gaffan, 1992; Rawlins, Deacon, Chih-Ta, & Aggleton, 1992).

It will be shown in the present article that the statistical evidence provided by E. A. Gaffan and D. Gaffan (1992; see also E. A. Gaffan, 1992), in support of their claims concerning some studies of serial position effects, is far from conclusive. To demonstrate this, a number of points with respect to the type of analysis performed in the abovementioned reports need elucidation. There are at least three major problems with the statistical evidence underlying the claim that low variance necessitates caution in interpreting effects in studies of memory for serially presented items. In the present article I will address the above points in three sections. First, it can be shown that typical patterns and levels of variance across the serial positions in the type of experiments examined by E. A. Gaffan and D. Gaffan (1992) were not established and, in fact, that these patterns cannot be predicted on the basis of the binomial theorem. Second, according to statistical theory (i.e., Lexis theory), the variance observed in any particular study does not have to equal the variance expected by the binomial theorem, and may only do so under a limited number of conditions. Third, whether such techniques are at all appropriate to apply in this context is open to doubt. In most cases in which the theorem has been applied to data from experiments on nonhuman serial position effects, the assumptions underlying the binomial model have been violated, causing severe and systematic error in the estimate of the expected variance.

The first two points are based on the assumption that the type of approach adopted by E. A. Gaffan and D. Gaffan (1992), among others, is potentially useful for examining studies in this field. However, if these points are accepted, they suggest that, at best, this particular statistical model has been presented in an oversimplified form that excludes information that is vital to a proper interpretation of the data. More damaging for the approach adopted by E. A. Gaffan and D. Gaffan (1992) and E. A. Gaffan (1992) is the final point, which draws into question the appropri-

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ateness of this type of exercise at all. Taken together, these considerations warrant substantial doubt about the strength of the evidence that is proposed as support for the claim that low variance necessitates caution in interpreting results.

Strength of Evidence Relating to Low Variance Drawn From the Binomial Theorem

Before any claims can be made regarding whether variance in a particular set of data is low, it is necessary to know the variance that is expected, given the experimental conditions. In the absence of a secure theoretical or empirical model concerning the expected probabilities of correct responses or variance at any serial position, one recourse is to examine the typical patterns of variance across the serial positions in the data that are obtained from studies of serial list learning. If it is appropriate to employ methods that are based on the binomial distribution to predict variance in experiments concerned with serial position effects, then it would be expected that patterns of variance across serial positions within an experiment must conform to those predicted by the binomial model. This model predicts that variance will increase with the number of trials conducted and—significantly for the present review—will also increase as the probability of a correct response approaches .50. To ascertain whether this pattern of variance held for studies of serial list learning, the data from a number of experiments were selected for analysis. In selecting these studies, it was determined that either all the data required to calculate probabilities of a correct response and the obtained variance were available in the published article, or the raw data had been made available for the calculation of these statistics. Of the 11 studies examined, several contained more than one experiment, so 22 experiments were scrutinized in all (5 with humans, 14 with nonhumans, and 3 that used nonhuman subjects to investigate serial order effects in relation to transitive inference). The studies are identified by letters (A–V) throughout the present report (see the Appendix for full details). These studies all had different numbers of trials and subjects, so direct comparison between them was difficult. To overcome this problem, the percentage of correct response scores was used, and the variance between subjects was calculated in terms of the percentage of correct choices made by each subject. The experiments selected for review all had different list lengths, so only the two end positions and the remaining serial position that generated the lowest probability of a correct response were examined.

Figure 1 displays the probability of a correct response and the levels of variance for the three serial positions examined in the 22 experiments studied. It should be noted that the levels of variance differed greatly from experiment to experiment, which is reflected in the different scales on the ordinate. Inspection of the figure reveals several patterns of variance across the three serial positions.

Seventeen of the studies appeared to show both primacy and recency effects. Of these 17 studies, 9 displayed a pattern of results in which variance was greatest at the ends of the list, where the probability of a correct response was greatest, and variance declined as the probability of a correct response declined in the center of the list (Experiments E, F, H, I, O, Q, T, U, V). Of the 8 remaining studies that demonstrated both primacy and recency effects, only 4 displayed a pattern of variance in that variance increased as the probability of a correct response declined between the two extreme serial positions in the list (Experiments C, D, J, S). This pattern of variance is consistent with the predictions of the binomial theorem (see Table 1); thus, the pattern of variance predicted by the binomial theorem was opposite to the patterns that were found in the majority of these studies.

The remaining five studies displayed either primacy or recency effects alone. According to the binomial theorem, if primacy alone is evident, then the obtained variance should be greatest at the end of the list. In contrast, if only recency is displayed, then the obtained variance should be greatest at the start of the list, where the probability of a correct response is lowest. In fact, in the studies that demonstrated either a primacy or a recency effect alone, there was no clear pattern to the obtained variance with respect to the probability of a correct response.

To facilitate examination of these data with respect to the predictions made on the basis of the binomial theorem, the pattern of variance predicted by this theorem can be compared with the patterns that were actually obtained. The 22 studies can be divided on the basis of whether the pattern across the serial positions is predicted by the binomial theorem, and they can also be divided in terms of whether both primacy and recency were noted or whether either alone was noted. These data are displayed in Table 1, which reveals that, in general, the binomial model does not predict the pattern of variance that was actually obtained.

The discrepancy between the obtained patterns of variance with respect to the probability of a correct response and those expected on the basis of the binomial theorem brings into question the appropriateness of the type of analysis commended by, inter alia, E. A. Gaffan (1992), E. A. Gaffan and D. Gaffan (1992), and Rawlins et al. (1992).

The present review also produced a novel finding that deserves comment. In studies in which a choice probe test was used and both primacy and recency effects were obtained (Experiments E, F, G, H, I, O, Q, T, V), vari-

Table 1
Studies in Which the Pattern of Variance Obtained Across the Serial Positions Conforms to That Predicted by the Binomial Theorem as a Function of Whether Both Primacy and Recency Effects Were Displayed or Whether Either was Displayed in Isolation

Effects	Predicted	Not Predicted
Both primacy and recency	C D J S	A E F G H I K O Q R T U V
Either primacy or recency	B L	M N P

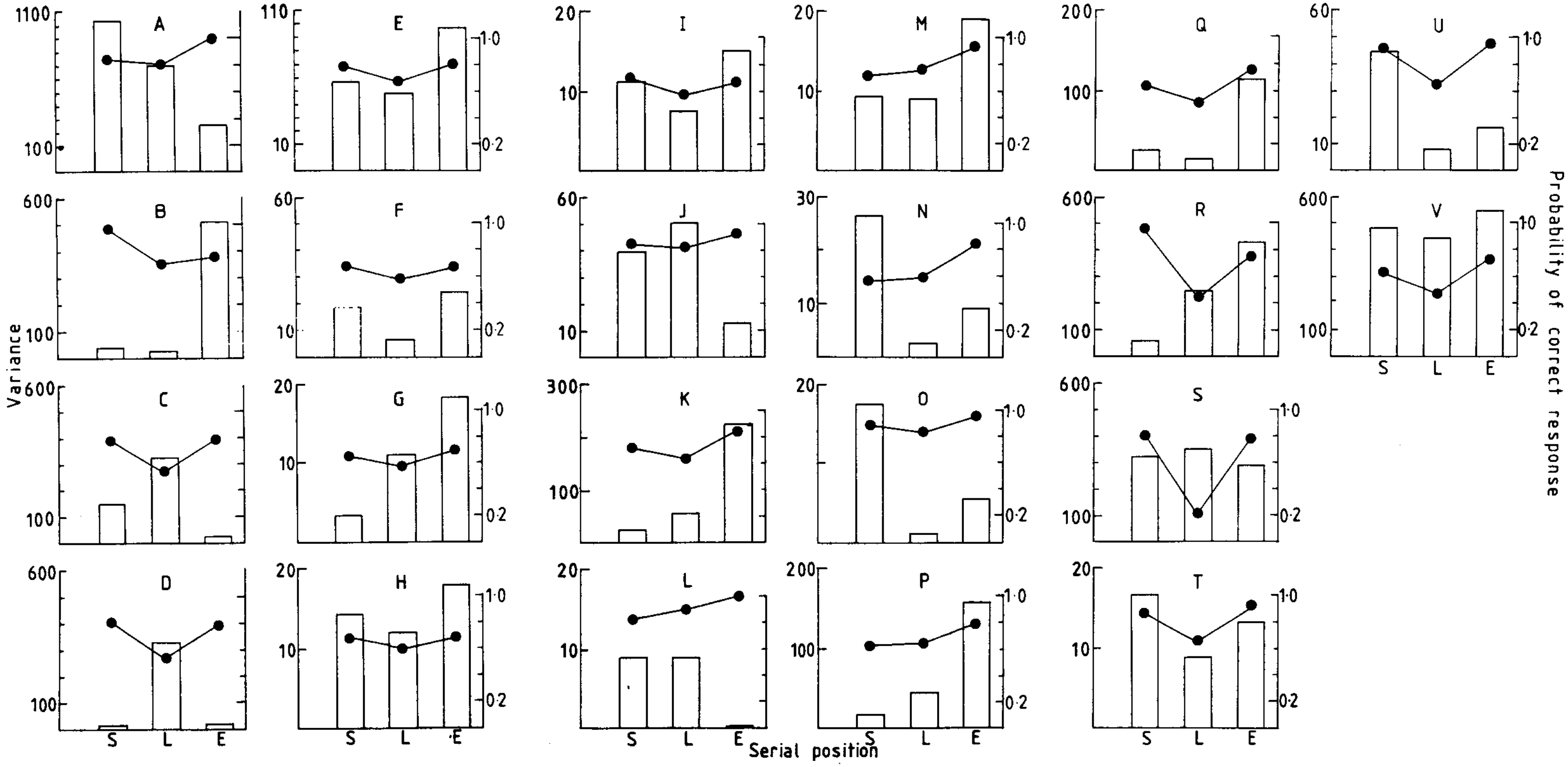

Figure 1. The lines and closed circles represent the probability of a correct response from the start (S), the end (E), and the remaining position that generated the lowest probability of a correct response (L) in the list. Probabilities are displayed on the right of the panels. The open bars show the amount of variance produced at each of the serial positions. Levels of variance are displayed on the left of the panels. The individual blocks A-V correspond to the studies that are detailed in the Appendix.

ance was lower for the central positions in the list than for the end positions. This pattern of variance across the serial positions was mirrored in the examination of the ratio of observed/expected levels of variance.

One hypothesis can explain this pattern of results. The subjects in these experiments might have performed either on the basis of memorial cues or according to a behavioral strategy. At the central positions of a list in which both a primacy and a recency effect are noted, it may have been that (in the limiting case) there were no memory cues available to the subjects to guide performance. If this was the case, then the subjects might have utilized a behavioral strategy when faced with a choice between two stimuli for which there were no memorial representations. If the subjects performed according to some behavioral strategy (e.g., a response to a particular spatial direction in a maze or conditioning chamber), then, in a two-choice situation in which the correct alternative is randomized across the two possible responses, they all would have performed with approximately 50% accuracy. In turn, variance in the data would have been reduced (see Reed, 1992, for an elaboration of this prediction, which assumes the behavioral strategy was win-shift/lose-stay).

This explanation of low variance at the central serial positions would only hold if the performance at those positions in the list was poor. It is conceivable that both primacy and recency effects occur, but that performance in the central position is much greater than chance, as in Experiment A. In such cases, performance at the central serial positions would still be based on memorial cues, and so the subject would not need to resort to the use of a behavioral strategy. Thus, variance would not necessarily be low at the central serial positions.

Alternative Accounts of Low Variance

According to statistical theory (see David, 1949), levels of obtained variance do not always have to equal the levels calculated by the equation $Tp(1-p)$. This point has not been stressed in reviews of the data concerned with serial position effects, in which it has been suggested that any low variance immediately draws the data into question. In fact, there are a number of possible alternative explanations of low variance in data, which allow insight into processes operating in these types of experiments. To understand these explanations, it is necessary to consider a general statistical model underlying the examination of variance (i.e., Lexis theory).

An examination of Lexis theory (David, 1949; Lexis, 1887; Mises, 1964) reveals that there are legitimate statistical reasons to expect variance to deviate from that expected on the basis of the binomial theorem. Lexis theory provides the potential to examine not only whether the observed variance is high or low compared with that expected on the basis of the binomial theorem, but also the manner in which the variance is produced.

If it is assumed that the probability of a correct response is independent across both subjects and trials, then the manner in which the probability of an event varies between subjects is critical in determining the ratio of observed to expected variance (the assumption regarding *independence* of observation is reviewed later). If the binomial theorem is applicable, it is necessary for the probability of a correct response to be the same for all subjects on any particular trial as well as the same throughout each of the independent sets of trials (see Mises, 1964). Such a series of trials is referred to as *Bernoulli*. From Lexis theory, if the series of trials is Bernoulli, then the ratio of the observed variance to the variance expected on the basis of the binomial theorem (i.e., the Lexis quotient) should be 1.

It is possible, and perhaps likely, that the probability of a correct response at a given serial position will not be constant across subjects; different subjects may well have different probabilities of a correct response. If the probability of a correct response differs from subject to subject, there are two ways in which the Lexis quotient could diverge from unity: it could be either higher or lower than unity. Lexis theory allows an analysis of the pattern of data that is likely to have caused such a divergence from expected variance that is found by using the binomial theorem.

If the probability of a correct response differs from subject to subject in an experiment, but differs in the same way for each subject across a number of trials, then *Lexis* trials are said to occur. With this type of data, the Lexis quotient (observed/expected variance on the basis of the binomial theorem) will be greater than unity (see David, 1949, pp. 152-160, for fuller discussion). Given the data discussed by E. A. Gaffan and D. Gaffan (1992), it is likely that this type of deviation in the probability of a correct response is observed moderately often in data that are obtained from studies of the serial position effect.

Alternatively, the probability of the occurrence of a correct response may be studied in several different subpopulations, each of which is internally homogeneous, over a number of trials. Thus, the different subgroups may have different probabilities of a correct response, but the probability of a correct response will be similar for subjects within each of the subgroups. Trials of this type result in *Poisson* variation. Poisson variation results in the Lexis quotient's being less than unity (David, 1949, p. 155; see also Mises, 1964). The fact that the existence of two distinct subgroups within the studied sample leads to lower-than-expected variance is counterintuitive, but it can be confirmed by a simple calculation. Say that a sample of 8 subjects has a mean probability of a correct response of .50, and 10 observations have been made on this sample. According to the binomial theorem, the expected variance is given by $Tp(1-p) = 10 \times .50\,(1-.50) = 2.50$. However, also assume that 4 of the subjects have a probability of .70 of a correct response and 4 have a probability of .30. Given the sample mean of .50, the sample variance given these two subgroups is .04—much lower than that predicted on the basis of the binomial theorem.

In the study of serial position effects, the question remains as to whether Poisson variance could, under some

Table 2
Between-Subject Variation in Serial Position Curves With Number of Subjects Showing Recency and/or Primacy Effects

	Effects			
Experiment	Recency	Primacy	Both	Neither
B	0	0	3	0
E	3	0	8	0
L	3	0	0	0
O	0	0	3	0
S	4	6	42	8
T	0	0	4	0
V	11	3	24	3

conditions, operate to produce less than expected variance. One possibility is that there could be different subgroups of subjects within the total number of subjects studied, so that each group would have a different probability of making a correct response on each trial at any particular serial position. This suggestion makes sense if it is assumed that some of the subjects will only display a primacy effect, some will only display a recency effect, and some will display both primacy and recency effects together.

In some of the studies of short-term memory, a variety of serial position curves were produced by the subjects. The number of subjects that displayed the different possible patterns of results in a number of such studies is shown in Table 2.

The fact that different animals may display different serial position curves has been noted in previous criticisms of studies purporting to show *both* primacy and recency effects in nonhumans. For example, in Experiments E, S, and V, most of the subjects produced both primacy and recency effects, but some displayed only one effect. To the extent that there are different subgroups of subjects, it is predicted that the Lexis ratio should be less than unity.

It should be noted, however, that Poisson variance may account for low variance only to a limited degree in studies of serial position effects. Two factors warrant such a statement. First, it has been claimed that Poisson variance is only rarely observed, and generally only accounts for a relatively small discrepancy between observed and expected variance (e.g., David, 1949; Geiringer, 1942). Second, some studies do not reveal different subgroups of subjects with respect to the probability of a correct response (e.g., Experiments B, L, O, T), yet variance is still lower than expected. It may well turn out to be the case that other factors, such as those discussed below, account for less than expected variance better than Poisson variation. Although it has not been definitively shown that the existence of different subgroups in the studies mentioned (i.e., Experiments E, S, V) contributed solely to the low observed variance, this possibility again raises doubts about the definitiveness of the claims that such low variance necessitates caution in interpreting results.

Misapplication of Statistical Techniques

There are a number of assumptions that must be satisfied prior to the utilization of the binomial theorem and Lexis theory. Violation of these assumptions necessitates revisions of both the amount of variance to be expected in any given set of conditions from that based on the binomial model, and the weight placed on arguments that use this model.

One of the most critical assumptions underlying the applicability of the binomial theorem is that successive observations must be independent. That is, over the course of a number of measurements, the outcome of one observation does not influence the outcome of subsequent observations; the events observed have to be proactively inert (e.g., tossing a coin). However, in studies conducted to investigate serial position effects in nonhumans, successive observations are generally carried out on the same subject, and it is unreasonable to suppose that such observations will be independent. The outcome that an animal experiences on one trial is likely to exert a proactive influence (possibly indeterminate) on performance on subsequent trials. The issues surrounding serial dependence in the analysis of dichotomous variables have recently received extensive treatment. A summary of these findings can be found in a review by Budescu (1985; see also Klotz, 1973). Budescu concludes that serial dependence can have a substantial effect on the outcome of predictions made on the basis of the binomial theorem, which cannot be dismissed or ignored (especially those predictions concerned with expected levels of variance). A similar point has been made regarding the effects of serial dependence on the results produced by repeated measures analyses of variance (see O'Brien & Kaiser, 1985).

The effects of violation of the assumption regarding independence of successive trials have been studied by several authors (e.g., Budescu, 1985; Geiringer, 1942; Klotz, 1973), whose analyses provide important insights into several possible explanations of low variance (see also Roberts, 1987). In the earliest account, Geiringer demonstrated that if successive trials are not independent, the observed variance can be either much higher or much lower than the expected variance on the basis of the binomial theorem (see also Budescu, 1985, pp. 557–559). If the probability of a correct response on one trial is positively correlated with the probability of a correct response on subsequent trials, then the observed variance will be greater than that expected on the basis of the binomial theorem. However, if the probability of a correct response on one trial is negatively correlated with the probability of a correct response on subsequent trials, then variance will be less than that expected on the basis of the theorem (see also Roberts, 1987). Because studies have been criticized on the grounds of less than expected variance, it is worth mentioning that, according to Geiringer, if a negative relationship between one trial and the next occurs, then variance would be expected to be very much lower than that expected on the basis of the binomial theorem—perhaps as low as one fourth that predicted by the theorem. This reduction in the observed variance is greater than that that would be accounted for on the basis of Poisson variation (see Geiringer, 1942) and, hence, may supply a better explanation of low variance.

Thus, if a priori reasons can be cited that would lead to the prediction that trials would either be positively or negatively proactively influential, then the manner in which variance should depart from that expected on the basis of the binomial theorem can be predicted. There are a number of possible causes of serial dependence of outcomes in successive trials in studies relating to serial position effects. E. A. Gaffan (1992) discusses some possibilities, one of which is experimenter expectation. Others include the effects of the behavioral strategy adopted by the subject, as discussed previously. However, it is not always possible to make a priori predictions about the effect of successive influence. For example, it is known that effects such as spontaneous alternation (e.g., Olton, 1982) or perseverative responding (e.g., Good, 1987) occur. Given the fact that proactive influence can affect the obtained variance, and given the myriad possibilities for such an influence to be either positive or negative, it is far from clear that *any* prediction can be made about the manner in which the variance should be expected to deviate from that predicted on the basis of the binomial theorem. Because no predictions about the expected variance can safely be made under these circumstances (which in practice might account for most of the experiments conducted in this area), the claim that low variance necessitates caution in interpreting results cannot be made with any degree of confidence.

Conclusions

In the present article I have sought to show that, on the basis of examination of variance in studies of serial position effects, there is no convincing evidence that would necessarily lead to treatment of the results with caution. It is not denied that effects other than those produced by memory processes may operate in some studies of serial position effects, but there is nothing in the examination of the variance in those studies that strongly supports such a claim. To restate the major points made in the analysis that led to this suggestion: (1) the binomial theorem cannot predict typical patterns of variance in studies of serial position effects, (2) it is not clear what level of variance should be expected, (3) greater or less than expected variance can be produced by different patterns of variation in subjects' probability of a correct response, and (4) the binomial theorem is not informative when studying proactive influential systems of indeterminate effect.

In the present analysis I have suggested some possible explanations for variance that deviates from that expected on the basis of the binomial theorem, assuming that the theorem is truly applicable. It is against this background that the variance reported in studies can be usefully examined and classifications of the situations that are likely to produce high or low variance can be made.

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APPENDIX
Key to Studies Used in the Present Review

Experiment	Report	Subjects	Technique
A	Bolhuis & van Kampen (1988; Experiment 1, 30-sec delay)	rats	radial maze
B	Gillan (1981; Experiment 1)	monkeys	serial order
C	Kesner & Novak (1982; no delay)	rats	radial maze
D	Kesner & Novak (1982; sham-lesioned subjects)	rats	radial maze
E	Reed et al. (1991; Experiment 1)	rats	Y-maze
F	Roberts & Kraemer (1981; Experiment 1, 3-item list)	monkeys	DMTS shapes
G	Roberts & Kraemer (1981; Experiment 1, 6-item list)	monkeys	DMTS shapes
H	Roberts & Kraemer (1981; Experiment 2, 3-item list)	monkeys	DMTS shapes
I	Roberts & Kraemer (1981; Experiment 2, 6-item list)	monkeys	DMTS shapes
J	Roberts & Kraemer (1981; Experiment 2, 3-item list)	humans	DMTS shapes
K	Roberts & Kraemer (1981; Experiment 1, 3-item list)	humans	DMTS shapes
L	Shimp (1976; short first item, 0.5-sec retention)	pigeons	DMTS colors
M	Shimp (1976; short first item, 2-sec retention)	pigeons	DMTS colors
N	Shimp (1976; short first item, 10-sec retention)	pigeons	DMTS colors
O	Shimp (1976; long first item, 0.5-sec retention)	pigeons	DMTS colors
P	Shimp (1976; short first item, 10-sec retention)	pigeons	DMTS colors
Q	Shimp (1976; long first item, 0.5-sec retention)	pigeons	DMTS colors
R	Smith & Stearns (1949)	humans	cued recall
S	Thomas & Reed (1993)	humans	free recall
T	von Fersen et al. (1991; Experiment 1)	pigeons	serial order
U	von Fersen et al. (1991; Experiment 2)	pigeons	serial order
V	Wright (1993)	humans	Olfactory recognition

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