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A Markov model for measuring storage loss and retrieval failure in retroactive inhibition

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Abstract

A Markov model is proposed to measure storage loss and retrieval failure in retroactive inhibition. This model generalizes Batchelder and Riefer's (1986) storage-retrieval model to account for retroactive inhibition. Storage loss is assumed to result in a disintegration of clustered items, while retrieval failure is assumed to prevent access to clustered items. The model is tested against data from three free recall experiments in which categorized item lists were presented to subjects. The kind of item categorization (conceptual vs. phonemic-orthographic) and the interlist similarity (different vs. identical categories) were manipulated across experiments. The model fits the data of all three experiments well, thus supporting the central inhibition concepts of the model. Based on these inhibition concepts and the parameter estimates of the model conclusions are drawn on the issue of whether retroactive inhibition is due to storage loss or retrieval failure in this experimental situation. In addition, rates of storage loss and retrieval failure are compared across the experiments. This latter analysis is discussed as an example of how the model reveals information about retroactive inhibition in ways that the storage-retrieval model cannot.

PsycINFO classification: 2240; 2343

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1. Introduction

Theories of retroactive inhibition often distinguish between two modes of forgetting: storage loss and retrieval failure. It is supposed that information stored in human memory may become unavailable as a result of interpolation and effectively lost, or that,

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although information remains stored in memory, it may become inaccessible. Indeed, much work, both experimental and theoretical, has concentrated on the question of whether retroactive inhibition is due to storage loss or retrieval failure (Crowder, 1976; Mensink and Raaijmakers, 1988; Postman and Underwood, 1973; Riefer and Batchelder, 1988; Tulving and Psotka, 1971).

While earlier theories emphasized the storage loss component, modern theories explain retroactive inhibition mainly in terms of retrieval failures (Baddeley, 1991; Estes, 1988). Despite the overwhelming evidence for an inhibition of retrieval processes in interpolation-induced forgetting, the question of whether storage loss can really be ignored when accounting for retroactive inhibition has not yet been solved (cf. Houston, 1991). A measurement tool which based on explicit inhibition concepts gave rise to direct measurements of storage loss and retrieval failure might help. Riefer and Batchelder (1988) propose such an approach. They apply their storage-retrieval model (Batchelder and Riefer, 1986) to retroactive inhibition in order to obtain measures of both storage loss and retrieval failure. This model, referred to as the SR-model, analyzes recall data in terms of storage and retrieval processes. For each level of interpolation a storage and a retrieval parameter are measured. This measurement indicates storage loss, if the storage parameter declines with the number of interpolated tasks, or retrieval failure, if the retrieval parameter declines with the number of interpolated tasks. In fact, when the SR-model was applied to data from free recall experiments, not only retrieval failure was found (Bäuml, 1991a,c; Riefer and Batchelder, 1988), but also storage loss (Bäuml, 1991a,b). This finding may point to the essential role of storage loss in retroactive inhibition, thus confirming conclusions already drawn in earlier studies (Earhard, 1976; Nelson and Brooks, 1974; Reynolds, 1977; Shuell, 1968; Sowder, 1973).

The SR-model is not itself a model of retroactive inhibition. Nonetheless, it has proven a useful tool for describing data from retroactive inhibition experiments. This fact together with the storage loss findings mentioned above motivates the generalization of the SR-model to a model of retroactive inhibition. This possibility arises, because the application of the SR-model to retroactive inhibition suggests concrete ideas about retrieval failure and storage loss processes. This generalization results in a more parsimoneous account of retroactive inhibition than the SR-model. Moreover, it has the potential to reveal information about retroactive inhibition in ways that the SR-model cannot.

The paper is organized in the following way. In Section 2, the ideas about storage and retrieval processes, which are incorporated in the SR-model, are made explicit. This results in concrete concepts of storage loss and retrieval failure. In Section 3, a Markov framework is chosen to formulate a model of retroactive inhibition, which reflects just these ideas. This model, referred to as the RI-model, can incorporate the SR-model as a special case when there is no interpolation. In Section 4, data from three free recall experiments are analyzed by means of this model and the experiments' data sets are interpreted in terms of the proposed inhibition concepts. Finally, rates of storage loss and retrieval failure are compared across the experiments. The rate of forgetting is also discussed as an example of how the RI-model reveals information about interpolation-induced forgetting in ways that the SR-model cannot.

2. An interpretation of the SR-model as it applies to retroactive inhibition

Batchelder and Riefer (1986) formulate a storage-retrieval model for the analysis of data from free recall experiments consisting of both categorizable item pairs and noncategorizable single items. They postulate three cognitive processes to explain recall data in this case: a storage process for pairs which reflects their clustering, a retrieval process for clustered pairs, and a storage-and-retrieval process for nonclustered pairs and single items. These processes are assumed to be dichotomous. Thus, after the presentation of an item list, an item pair is either stored as a cluster, or not. If it is stored as a cluster, it can either be retrievable, or not. If an item pair is not stored as a cluster, the two single items can be stored and retrieved, independently from each other. Analogously, a noncategorizable, single item is either stored and can be retrieved, or not.

The model has three parameters: a storage parameter for pairs (c) indicating the probability that a pair is clustered, a retrieval parameter for clustered pairs (r) denoting the probability for a clustered pair's successful retrieval, and a storage-and-retrieval parameter for single items (u) indicating the probability that a single item will be stored and can be retrieved. Thus, the model leads to separate measurements of a storage and a retrieval parameter. The following sample space describes the data for the recall of an item pair:

E_1 – both items of the pair are recalled, adjacently;
E_2 – both items of the pair are recalled, nonadjacently;
E_3 – one and only one item of the pair is recalled;
E_4 – neither item of the pair is recalled.

The following sample space describes the data for the recall of a single item:

F_1 – a single item is recalled;
F_2 – a single item is not recalled

(cf. Batchelder and Riefer, 1986).

When applying the SR-model to retroactive inhibition storage loss is related to a decline of the storage parameter c as a result of interpolation. This decline does not imply that a pair, which has been stored as a cluster, will be lost from memory store. Instead, following the ideas of the SR-model, a declining storage parameter means that there is a non-zero probability that a clustered pair may become disintegrated into its single items. This disintegration concept constitutes the central assumption of the model with respect to storage loss. Retrieval failure is related to a decline of the retrieval parameter r as a result of interpolation. This decline implies that there is a non-zero probability for a clustered pair to become inaccessible. This inaccessibility concept constitutes the central assumption of the model with respect to retrieval failure. Finally, another effect of interpolation within the SR-model could be a decline of the storage-retrieval parameter u for single items. This parameter covers single items that have not been clustered at all and items that have become disintegrated due to interpolation. A decline of this parameter implies that there is a non-zero probability for retrievable single items to become inaccessible, or even unavailable.

This interpretation of the SR-model for retroactive inhibition suggests three kinds of effects that interpolation can have on the fate of an item pair or single item. *First*, for a clustered and retrievable item pair interpolation can induce a retrieval failure, that is, access to a cluster's two items can be lost. *Second*, for a clustered item pair interpolation can lead to a disintegration of the item pair into its single items, that is, the items can become unclustered. *Third*, single items, disintegrated or not clustered from the start, that are stored and retrievable can become inaccessible. These three kinds of interpolation effects are at the heart of the following model of retroactive inhibition.

3. A Markov model (RI-model)

The SR-model indicates the following state spaces $Z_p = \{SR, S\bar{R}, \bar{S}C_2, \bar{S}C_1, \bar{S}C_0\}$ and $Z_S = \{U, \bar{U}\}$ for item pairs and single items:

SR	–	the item pair is stored as a cluster and is retrievable;
$S\bar{R}$	–	the item pair is stored as a cluster, however, it is not retrievable;
$\bar{S}C_2$	–	the item pair is not stored as a cluster, however, the two single items are stored and can be retrieved independently from each other;
$\bar{S}C_1$	–	the item pair is not stored as a cluster, and only one single item is stored and can be retrieved;
$\bar{S}C_0$	–	the item pair is not stored as a cluster, and neither of the two single items is stored and can be retrieved.
U	–	the single item is stored and can be retrieved;
$\bar{U}$	–	the single item is not retrievable.

Based on these state spaces, the above interpretation of the SR-model for retroactive inhibition suggests the following assumptions to describe the effect of an increasing number of interpolated tasks on item pairs and single items:

Assumption 1. If an item pair is stored as a cluster and is retrievable (SR), it can remain in this state; otherwise it either becomes non-retrievable ($S\bar{R}$), or a storage loss occurs ($\bar{S}C_2$ or $\bar{S}C_1$ or $\bar{S}C_0$). Let γ and β be the corresponding probabilities for a retrieval failure and a storage loss. If a storage loss occurs, one ($\bar{S}C_1$), two ($\bar{S}C_0$) or none ($\bar{S}C_2$) of the disintegrated items can become inaccessible. Let δ be the probability that a disintegrated item additionally becomes inaccessible.

Assumption 2. If an item pair is stored as a cluster but is not retrievable ($S\bar{R}$), it can remain in this state; otherwise a storage loss occurs ($\bar{S}C_2$ or $\bar{S}C_1$ or $\bar{S}C_0$). Let β be the probability for a storage loss. If a storage loss occurs, one ($\bar{S}C_1$), two ($\bar{S}C_0$) or none ($\bar{S}C_2$) of the disintegrated items can become inaccessible. Let δ be the probability that a disintegrated item also becomes inaccessible.

Assumption 3. Suppose that an item pair is not stored as a cluster. If the two single items are retrievable ($\bar{S}C_2$), the item pair can remain in this state; otherwise one ($\bar{S}C_1$) or two ($\bar{S}C_0$) of the single items can become inaccessible. Let ϵ be the probability that a single item becomes inaccessible. If only one single item is retrievable ($\bar{S}C_1$), it can remain in this state; otherwise the single item becomes inaccessible ($\bar{S}C_0$). Here, too, ϵ represents the probability of a single item becoming inaccessible. If none of the single items is retrievable ($\bar{S}C_0$) the item pair remains in this state.

Assumption 4. If a noncategorizable single item is stored and retrievable (U), it can remain in this state; otherwise it becomes unretrievable ($\bar{U}$). Let ϵ be the probability for this retrieval failure. If a single item is not retrievable ($\bar{U}$), it remains in this state.

Assumptions 1–3 lead to the following state space operator that specifies the state transitions of an item pair when a new task is interpolated (see Wickens, 1982, for technical details):

	SR	$S\bar{R}$	$\bar{S}C_2$	$\bar{S}C_1$	$\bar{S}C_0$
SR	$(1-\beta)(1-\gamma)$	$(1-\beta)\gamma$	$\beta(1-\delta)^2$	$2\beta\delta(1-\delta)$	$\beta\delta^2$
$S\bar{R}$	0	$1-\beta$	$\beta(1-\delta)^2$	$2\beta\delta(1-\delta)$	$\beta\delta^2$
$\bar{S}C_2$	0	0	$(1-\epsilon)^2$	$2\epsilon(1-\epsilon)$	ϵ^2
$\bar{S}C_1$	0	0	0	$1-\epsilon$	ϵ
$\bar{S}C_0$	0	0	0	0	1

Assumption 4 induces the following state space operator that specifies for a single item how its state may change by incrementing the number of interpolated tasks:

	U	$\bar{U}$
U	$1-\epsilon$	ϵ
$\bar{U}$	0	1

No assumptions are yet made to handle the initial conditions for an item pair, or single item, without interpolation. The initial conditions for an item pair (single item) are specified by a multinomial (binomial) distribution:

Assumption 5. There are probabilities $\alpha_{P,i}$ ($i = 1,2,3,4$) which specify the tendency that an item pair is in state SR, $S\bar{R}$, $\bar{S}C_2$, or $\bar{S}C_1$ at the start; as a result, the probability $1 - \alpha_{P,1} - \alpha_{P,2} - \alpha_{P,3} - \alpha_{P,4}$ specifies the tendency that an item pair will be in state $\bar{S}C_0$. Finally, there is a probability α_S that, at the start, a single item is in state U; with probability $1 - \alpha_S$ it will be in state $\bar{U}$.

Two very general characteristics of these assumptions may be stressed. *First*, the defined state space operator assumes stationary forgetting. The rules of interpolation-induced forgetting do not change as a function of the interpolation level, with respect to both storage loss and retrieval failure. *Second*, the individual states of the state space are linearly ordered. Interpolation can induce an item pair's transition from higher states like SR or $S\bar{R}$ to lower states like $\bar{S}C_1$, while it cannot induce transitions from lower states like $\bar{S}C_0$ or $\bar{S}C_2$ to a higher state like $S\bar{R}$. Consequently, $\bar{S}C_0$ is assumed to be an absorbing state. Similarly, interpolation can induce a single item's transition from the higher state U to the lower state $\bar{U}$, while it cannot induce the transition from the lower state $\bar{U}$ to the higher state U. $\bar{U}$ is assumed to be an absorbing state (see Wickens, 1982, for similar classes of models).

The data for the recall of an item pair or single item are described by the same sample space as the one in the SR-model (see above):

Assumption 6. If an item pair is stored as a cluster and is retrievable (SR), both items will be recalled adjacently (E_1). If an item pair is stored as a cluster but is not retrievable ($S\bar{R}$), neither of the items will be recalled (E_4). If an item pair is not clustered ($\bar{S}C_2$ or $\bar{S}C_1$ or $\bar{S}C_0$), either both items will be recalled nonadjacently (E_2), or one and only one item will be recalled (E_3), or none of the items will be recalled (E_4), respectively. If a single item is stored and is retrievable, the item will be recalled (F_1). Otherwise it will not be recalled (F_2).

Notice that this assumption, like the SR-model, contains a simplification: the possibility that an item pair that is in state $\bar{S}C_2$ will be recalled adjacently (E_1) by chance is ignored. Assumption 6 leads to the following response operator, which handles the mapping of the possible states of an item pair into observable response categories and the mapping of the possible states of a single item into observable response categories:

state	SR	$S\bar{R}$	$\bar{S}C_2$	$\bar{S}C_1$	$\bar{S}C_0$	U	$\bar{U}$
response	E_1	E_4	E_2	E_3	E_4	F_1	F_2

The model has nine parameters with parameter space $\Omega = \{\beta, \gamma, \delta, \epsilon, \alpha_{P,1}, \alpha_{P,2}, \alpha_{P,3}, \alpha_{P,4}, \alpha_S | 0 \leq \beta, \gamma, \delta, \epsilon, \alpha_{P,1}, \alpha_{P,2}, \alpha_{P,3}, \alpha_{P,4}, \alpha_S \leq 1\}$. While five of these parameters ($\alpha_{P,1}, \alpha_{P,2}, \alpha_{P,3}, \alpha_{P,4}, \alpha_S$) characterize the initial storage and retrieval conditions for an item pair and single item without interpolation, the remaining four parameters ($\beta, \gamma, \delta, \epsilon$) relate to forgetting with respect to storage loss and retrieval failure. The following analyses will show whether this model can fit experimental data, and whether based on this model storage loss or retrieval failure is indicated with interpolation.

4. Experiments

Bäuml (1991a,b,c) reports three free recall experiments on retroactive inhibition manipulating the kind of item categorization and the interlist similarity. In the first experiment lists of conceptually categorizable item pairs and single items were presented to subjects. The categories were different both within and across lists. The second experiment was identical to the first one, except that phonemic-orthographic categories were used instead of conceptual ones. Finally, in the third experiment conceptual categories were used again that were different within lists but, contrary to the first experiment, replicated across lists. For convenience, I will shortly summarize these experiments here.

4.1. Method

4.1.1. Subjects

Fifty psychology students at the University of Regensburg participated in each of the three experiments. In each experiment the subjects were randomly assigned to the five interpolation levels. The subjects were not paid for their participation, but received credit for fulfilling a degree requirement.

4.1.2. Material

In all three experiments the item material consisted of 125 items, 50 pairs of categorially related items and 25 single items. These 125 items were randomly assigned to five lists with the restriction that in every list there were 10 pairs and 5 singles. Thus, every list consisted of 25 items.

In *Experiment 1*, the item pairs were conceptually related, but each pair came from a different conceptual category (for example, translated into English: apple–pear, rain–snow, cello–trombone, etc.). The so-called singles were items that were not related in any obvious manner. That is, they were not related mutually or with regard to the pairs, and were not conceptually or phonemic-orthographically related, either. The pairs and the singles were largely taken from the categories of Battig and Montague (1969), although some categories not found in Battig and Montague were also included in the lists (Scheithe and Bäuml, 1995). For every category and for both item pairs and single items, prominent categorial words were used. The pairs were therefore highly associated.

In *Experiment 2*, the item pairs were phonemic-orthographically categorizable, but each pair came from a different phonemic-orthographic category (for example, in German, Rose–Hose, Hand–Wand, Leder–Feder etc.). The two items in each pair were similar both phonemically and orthographically and shared the same letters except for at the most two different initial letters. Every effort was made to minimize conceptual categorizability both within and across pairs. In many cases one item of a pair and the singles were taken from the categories of Battig and Montague (1969), or Scheithe and Bäuml (1995). Very prominent categorial words were used. The second item of a pair was selected to provide an obvious rhyme with the first item in order to induce high rates of association. The singles were not categorizable in any obvious manner, not mutually or with regard to the pairs, and not phonemic-orthographically or conceptually.

In *Experiment 3*, the item pairs were selected from ten different conceptual categories, and five item pairs were taken from each category. These categories were taken from the 50 categories used in Experiment 1. Again very prominent categorial words were used. The singles were taken from the same categories as in Experiment 1. The 125 items were randomly assigned to five lists with the restriction that in every list all ten categories were represented by one pair of items.

4.1.3. Procedure

In each experiment the interpolation level varied from one presented list (no interpolation) to five presented lists (four interpolated lists). At the beginning of each experimental session the items within a list were mixed randomly with the restriction that the pairs were presented with no intervening items (massed mode). The items were presented on a computer screen one at a time with an exposure rate of 5 sec per item. After the presentation of a complete list subjects were given 90 sec to write down the items from this list. After this recall period, and a break of 60 sec, the session continued with the next list. After all of the lists were presented, a final free recall test was given, in which subjects attempted to recall the items from all of the previous lists. Subjects were given up to 5 minutes for this final written recall (for details see Bäuml, 1991a).

4.1.4. Data analysis

For all three experiments the *first list* final recall was analyzed. The RI-model was fitted to the data of each individual experiment. The goodness-of-fit of the model was compared with the goodness-of-fit of a statistical baseline model. For each experiment, the data of an interpolation level were described by a joint distribution resulting from the product of a multinomial distribution and a binomial distribution. The multinomial distribution served as a statistical model to describe an item pair's probabilities $p(E_i)$ $(i = 1, 2, 3, 4)$ to fall into the four response categories E_i $(i = 1, 2, 3, 4)$. The binomial distribution served as a statistical model to describe a single item's probabilities $q(F_j)$ $(j = 1, 2)$ to fall into the two response categories F_j $(j = 1, 2)$ (see Riefer and Batchelder, 1988). The product of these joint distributions over the five interpolation levels was used as the statistical baseline model to describe an experiment's whole data set. This model includes 20 (5×4) free parameters. A likelihood-ratio test (Lindgren, 1976) was used to compare the goodness-of-fit of the RI-model with the (perfect) goodness-of-fit of the statistical baseline model.

Given the model described the experiments' data sets well, a number of hypotheses were tested on these data. One line of hypotheses addressed the issue of storage loss and retrieval failure in retroactive inhibition by testing appropriate parameter restrictions on the model, *separately* for the individual experiments. These tests indicate whether interpolation-induced forgetting in the present experiments was due to storage loss or retrieval failure, or both. The other line of hypotheses addressed the issue of rates of forgetting by testing appropriate parameter restrictions on the model *across* several experimental data sets. These tests indicate whether the rate of retrieval failure and the rate of storage loss depended on the kind of item categorization and on the interlist similarity in the present experiment.

In detail, each experiment was examined for evidence of an interpolation-induced disintegration of clusters in the data. Storage loss is reflected in parameter β of the model. Accordingly, whether β differed reliably from 0 was tested. Based on the result of this test, the data were examined to determine if they suggested a retrieval failure for clusters. This was done by testing whether parameter γ of the model deviated significantly from 0. By testing the restrictions $\delta = 0$ and $\epsilon = 0$ the question of whether interpolation caused the forgetting of single items was finally investigated. In fact, these two parameters reflect the forgetting of single items within an experiment's data set, where δ represents the forgetting that occurs directly after a disintegration of clusters and ϵ represents the forgetting of single items in all other aspects of the experiment. This first line of hypotheses was completed by testing whether δ and ϵ differed reliably from each other, thus addressing the issue of whether a prior disintegration affects the forgetting of single items.

Table 1
Recall probabilities (relative frequencies) for the response categories E_i ($i = 1, 2, 3, 4$) and F_j ($j = 1, 2$) for the three experiments' five interpolation levels. The order of the probabilities within each cell reflects the order of the experiments (Experiment 1/Experiment 2/Experiment 3).

NIL	$p(E_1)$	$p(E_2)$	$p(E_3)$	$p(E_4)$
0	0.69/0.46/0.74	0.02/0.05/0.05	0.05/0.18/0.05	0.24/0.31/0.16
1	0.58/0.32/0.58	0.04/0.07/0.04	0.06/0.18/0.14	0.32/0.43/0.24
2	0.55/0.19/0.42	0.01/0.04/0.03	0.03/0.18/0.28	0.41/0.59/0.27
3	0.48/0.17/0.28	0.02/0.03/0.03	0.03/0.13/0.33	0.47/0.67/0.36
4	0.39/0.14/0.21	0.03/0.02/0.01	0.06/0.11/0.27	0.52/0.73/0.51

NIL	$q(F_1)$	$q(F_2)$
0	0.62/0.60/0.66	0.38/0.40/0.34
1	0.50/0.34/0.42	0.50/0.66/0.58
2	0.60/0.26/0.32	0.40/0.74/0.68
3	0.48/0.20/0.22	0.52/0.80/0.78
4	0.44/0.18/0.16	0.56/0.82/0.84

NIL = Number of Interpolated Lists.

With respect to the second line of hypotheses, the kind of item categorization and the interlist similarity were examined to determine whether they influenced the rate of storage loss and the rate of retrieval failure. To achieve this parameter β, or parameter γ, were tested to see if they differed reliably across experiments. This was done by fitting the RI-model to the data of two experiments, imposing the restriction that β, or γ, is constant across the two data sets. Similarly, the rates of forgetting for the single items were examined to determine if they varied as a function of the experimental variables, i. e. whether parameter δ, or parameter ϵ, depended on the item categorization and the interlist similarity.

All these tests were conducted by performing likelihood-ratio tests comparing a version of the model in which some restriction is imposed on the parameter values with the general version of the model in which the parameters vary freely. In all cases the parameters of the model were estimated by numerical optimizations using PRAXIS (Gegenfurtner, 1992), as well as using a one-dimensional hill-climbing procedure (Wickens, 1982). The likelihood functions were optimized with the restriction that the parameters fall within the real interval $[0, 1]$. The results did not depend on the procedure used.

4.2. Results

Table 1 shows the relative frequencies for each response category for the three experiments. As the number of interpolated lists increases, for all three experiments the data show a decline in the probability that a pair will be recalled with no intervening items ($p(E_1)$) and an increase in the probability that a pair will not be recalled at all ($p(E_4)$). Moreover, there is hardly any difference between the experiments in the

Table 2
Estimates of the parameters of the model and χ^2-values from the likelihood-ratio tests, which compare, separately for all three experiments, the goodness-of-fit of the model with the goodness-of-fit of a statistical baseline model

	Experiment 1	Experiment 2	Experiment 3
β	0.00	0.04	0.27
γ	0.12	0.24	0.00
δ	0.00	0.30	0.62
ϵ	0.07	0.28	0.28
$\alpha_{P,1}$	0.69	0.44	0.74
$\alpha_{P,2}$	0.22	0.21	0.18
$\alpha_{P,3}$	0.02	0.07	0.03
$\alpha_{P,4}$	0.05	0.19	0.05
α_S	0.60	0.56	0.63
$\chi^2(11)$	6.71	5.31	13.12

probability that the members of a pair are recalled non-adjacently ($p(E_2)$); this probability is very small and fairly constant across the respective interpolation levels. However, the three experiments differ strongly with respect to the probability for the recall of just one word of a pair ($p(E_3)$). While this probability remains fairly constant for Experiment 1, for Experiment 2 it *decreases* somewhat with interpolation level, and for Experiment 3 it *increases* strongly with interpolation level. Finally, as the number of interpolated lists increases, all three data sets show a decline in the probability that a single item will be recalled ($q(F_1)$) and, correspondingly, an increase in the probability that a single item will not be recalled ($q(F_2)$). This decline, or incline, is quite strong in the data sets of Experiments 2 and 3, and moderate in the data set of Experiment 1. These differences in recall probabilities between Experiment 1, on the one hand, and Experiments 2 and 3, on the other hand, demonstrate effects of the two manipulated factors (kind of categorization, interlist similarity) on retroactive inhibition in the present experiment.

4.2.1. *Goodness-of-fit of the model*

Table 2 shows the parameter estimates that I found when fitting the model to the three data sets. In addition, Table 2 shows the χ^2-values from the likelihood-ratio tests, comparing the goodness-of-fit of the model with the (perfect) goodness-of-fit of the joint multinomial model for all three experiments. The RI-model has nine parameters and describes twenty independent data points. Thus, the test is conducted with eleven degrees of freedom. As can be seen, the fit of the model is good for all three experiments, with none of the data sets leading to a rejection of the model.

Figs. 1–3 show graphically the relative frequencies for the response categories and the respective probabilities that are predicted by means of the RI-model and its parameter estimates, both for item pairs and for single items. These graphics reflect how well the model fits the data of all three experiments. In the following, the fit between the model and the data is used to test certain hypotheses about parameter values.

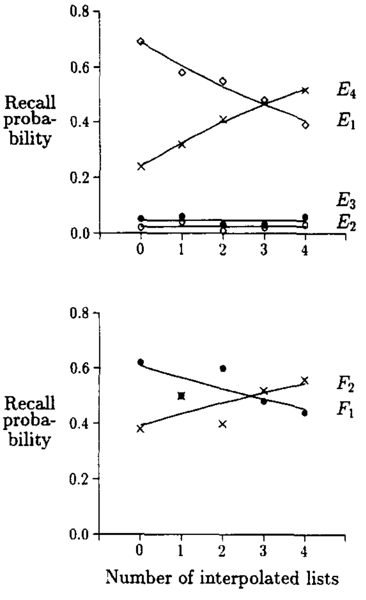

Fig. 1. *Experiment 1 (conceptual, different)*: Graphical representation of the recall probabilities and the model's fits for the response categories E_i ($i = 1, 2, 3, 4$) and F_j ($j = 1, 2$) as a function of the number of interpolated lists. Notice that since the probabilities for the four (two) response categories E_i (F_j) sum to one, the four (two) curves of the graph are not independent.

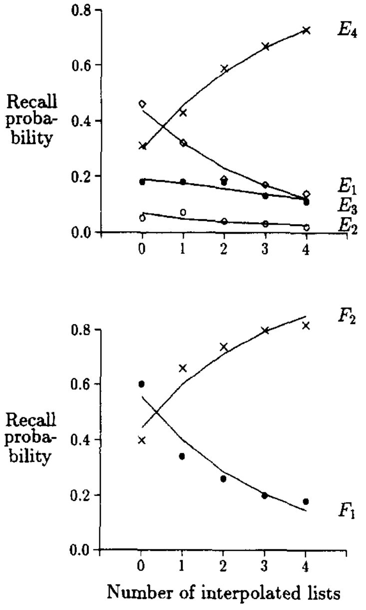

Fig. 2. *Experiment 2 (phonemic-orthographic, different)*: Graphical representation of the recall probabilities and the model's fits for the response categories E_i ($i = 1, 2, 3, 4$) and F_j ($j = 1, 2$) as a function of the number of interpolated lists (see Fig. 1).

4.2.2. Hypothesis testing

4.2.2.1. Parameter restrictions within an experimental data set. I started out by testing, separately for the data of each individual experiment, whether the storage loss parameter β differs reliably from 0. While for Experiment 1 and Experiment 2 the restriction $\beta = 0$ did not deteriorate the fit of the model in any significant way ($\chi^2(1) = 0.48$, $\chi^2(1) = 3.42$), the restriction deteriorated the fit for Experiment 3 ($\chi^2(1) = 60.50$). Based on this result, I tested whether the retrieval failure parameter γ differs reliably from 0. While I found the null hypothesis $\gamma = 0$ to be acceptable for Experiment 3 ($\chi^2(1) < 0.01$), it had to be rejected both for Experiment 1 and for Experiment 2 ($\chi^2(1) = 21.71$, $\chi^2(1) = 33.31$).

Next I tested for each data set whether the parameters which reflect the forgetting of disintegrated and single items (δ, ϵ) deviate from 0. While the hypothesis $\delta = 0$ did not reduce the fit of the model in a significant way for Experiments 1 and 2 ($\chi^2(1) < 0.01$, $\chi^2(1) = 0.66$), it did reduce the fit for Experiment 3 ($\chi^2(1) = 60.47$). With respect to parameter ϵ I found no reliable deviation from 0 for Experiment 1 ($\chi^2(1) = 2.88$), but highly reliable deviations for Experiments 2 and 3 ($\chi^2(1) = 29.67$, $\chi^2(1) = 63.66$). The experiments also differed in whether these two parameters can be assumed to be equal. While for Experiments 1 and 2 I found the hypothesis $\delta = \epsilon$ to be acceptable ($\chi^2(1) = 0.05$, $\chi^2(1) = 0.01$), the two parameters differed significantly from each other for Experiment 3 ($\chi^2(1) = 20.02$).

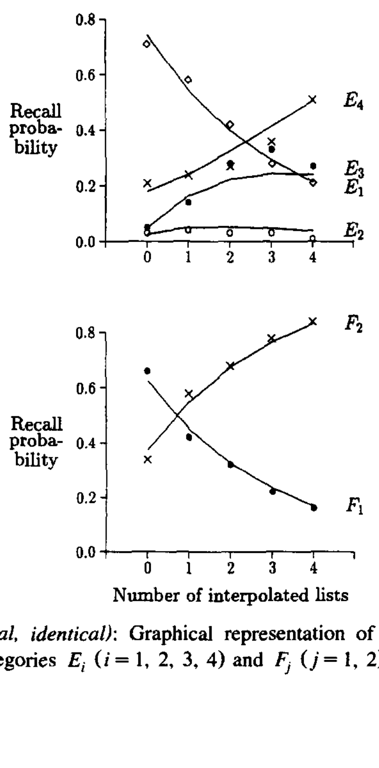

Fig. 3. *Experiment 3 (conceptual, identical)*: Graphical representation of the recall probabilities and the model's fits for the response categories E_i ($i = 1, 2, 3, 4$) and F_j ($j = 1, 2$) as a function of the number of interpolated lists (see Fig. 1).

4.2.2.2. Parameter restrictions across the experimental data sets. I tested whether the storage loss parameter β varies reliably between Experiments 1 and 2, and Experiments 1 and 3. While I found a significant variation of the parameter between Experiments 1 and 3 ($\chi^2(1) = 15.33$), the assumption of the constancy of the parameter did not deteriorate the fit of the model for the data from Experiments 1 and 2 ($\chi^2(1) = 0.10$). Similarly, I tested whether the retrieval failure parameter γ varied reliably across experiments. I found a significant variation both between Experiments 1 and 2 ($\chi^2(1) = 10.84$) and between Experiments 1 and 3 ($\chi^2(1) = 9.73$).

Next I tested the constancy of the forgetting parameter ϵ across experiments. I found this parameter to vary significantly both between Experiments 1 and 2 ($\chi^2(1) = 10.47$) and between Experiments 1 and 3 ($\chi^2(1) = 14.88$). Quite a different pattern arose for the forgetting parameter δ. There was neither a significant variation between Experiments 1 and 2 ($\chi^2(1) = 0.02$) nor between Experiments 1 and 3 ($\chi^2(1) = 0.11$). Obviously, there is not enough statistical power to find differences with respect to parameter δ across experiments. This is due to the fact that δ is a conditional probability that depends on the value of β. β, however, was found to be very small for Experiments 1 and 2, thus preventing a reliable estimation of δ in these cases.

4.2.3. Incorporating the SR-model into the RI-model

In the above form of the model the initial conditions of an item pair and single item are described by means of a multinomial and binomial distribution with five parameters (see above). A more parsimoneous account of these initial conditions might be achieved by using the SR-model to describe them. Indeed, the SR-model describes an item pair's five initial states and a single item's two initial states by means of only three parameters c, r, u (see above), thus reducing the number of parameters of the RI-model by two.

Table 3 shows the parameter estimates for this version of the RI-model that I found when fitting this model to the three data sets. The table also shows the χ^2-values from the likelihood-ratio tests, comparing the goodness-of-fit of this model with the (perfect) goodness-of-fit of the joint multinomial model for all three experiments. The RI-model has seven parameters and describes twenty independent data points. Thus, the test is

Table 3
Estimates of the parameters of the model when including Batchelder and Riefer's storage-retrieval model to describe the initial conditions. The χ^2-values from the likelihood-ratio tests, which compare the goodness-of-fit of this version of the model with the goodness-of-fit of a statistical baseline model, are also shown

	Experiment 1	Experiment 2	Experiment 3
β	0.00	0.03	0.27
γ	0.12	0.25	0.00
δ	0.00	0.35	0.62
ϵ	0.06	0.26	0.28
c	0.91	0.66	0.91
r	0.75	0.66	0.82
u	0.59	0.52	0.62
$\chi^2(13)$	7.15	6.67	13.96

conducted with thirteen degrees of freedom. As can be seen the model provides a good fit to the three data sets.

The version of the RI-model that includes the SR-model and the more general version of the model are nested. As a result, the more restrictive version fits the data worse than the less restrictive one (compare Tables 2 and 3). I examined each individual data set to determine whether the more restricted version fits the data significantly worse than the more general one. I conducted likelihood-ratio tests to examine this issue. The tests were conducted with two degrees of freedom. For all three data sets, the restriction of using the SR-model to describe the initial conditions instead of the more general multinomial and binomial distributions did not deteriorate the fit of the model in a significant way ($\chi^2(2) = 0.44$, $\chi^2(2) = 3.29$, $\chi^2(2) = 0.84$).

5. Discussion

The RI-model fits the data of all three free recall experiments well. This finding provides empirical support for the central inhibition concepts of the model, which are the storage loss concept and the retrieval failure concept. Interpolation can be assumed, first, to disintegrate clustered items into single items (storage loss), second, to prevent access to clustered pairs (retrieval failure), and, third, to prevent access to single items. Thus, the model has proven successful in separately measuring storage loss and retrieval failure in retroactive inhibition.

The RI-model generalizes Batchelder and Riefer's (1986) storage-retrieval model into a model of retroactive inhibition. Based on the same ideas of storage loss and retrieval failure as were used within the SR-model, the latter model is extended by incorporating state-to-state forgetting parameters. In this way, the RI-model accounts for the same data sets with fewer parameters, and hence more degrees of freedom than the SR-model. Because of this it is a more parsimoneous and a more accurate method for measuring storage and retrieval processes than the SR-model. As a side result, which is indicated above, the SR-model can be incorporated into the RI-model to account for initial free recall of item pairs and single items. In this sense, the SR-model represents a special case of the RI-model, handling the cases where there is no interpolation.

5.1. Storage loss or retrieval failure

Based on the model's inhibition concepts the estimates of the forgetting parameters of the model can be used to analyze the effect of interpolation on storage and retrieval processes. This was done for the data of three free recall experiments. In Experiment 1 conceptual categories were used with different categories both within and across lists. No storage loss was found. In fact, the respective likelihood-ratio test showed no reliable deviation of the storage loss parameter from zero. The same was not true for the retrieval parameter which differed significantly from zero. This result suggests a retrieval failure. So, with conceptually categorizable items and different categories across lists the model indicates that interpolation leads to a retrieval failure without storage loss. This result agrees with the conclusions of Tulving and Psotka (1971) and

Riefer and Batchelder (1988), and is in accordance with retrieval-based theories of retroactive inhibition.

Experiment 2 differed from Experiment 1 in that phonemic-orthographic categories were used instead of conceptual ones. The results of this experiment, however, were quite similar to those of Experiment 1. No reliable deviation of the storage parameter from zero was found, while the retrieval parameter differed significantly from zero. This finding suggests a retrieval failure without storage loss for phonemic-orthographic categories as well. Nelson and Brooks (1974) conducted a quite similar experiment. They found retrieval failure with slight storage loss. So the present result agrees only approximately with the conclusions of Nelson and Brooks, and instead, is in agreement with retrieval-based theories.

Experiment 3 differed from Experiment 1 in that identical categories were used across lists instead of different ones, thus manipulating the interlist similarity. This experimental manipulation induced drastic changes in the results compared to those from Experiments 1 and 2. No deviation of the retrieval parameter from zero was found, suggesting that no retrieval failure occurs with a high interlist similarity. While this result disagrees with an earlier finding of Shuell (1968), it is consistent with a finding of Strand (1971). In fact, Strand found no inhibition of recall of categories if the categories were identical across lists, however, strong inhibition if the categories were different across lists. The storage parameter differed strongly from zero. This finding suggests that interpolation leads to a disintegration of clustered items into single items. Moreover, parameter δ also deviated from zero, suggesting that aside from causing a disintegration, an increasing interpolation level can make one or even two of the disintegrated items inaccessible. This result differs fundamentally from the view that retroactive inhibition is only retrieval-based (Estes, 1988; Tulving and Psotka, 1971). On the other hand, it is in agreement with similar conclusions drawn by Shuell (1968), Sowder (1973), or Reynolds (1977).

These findings point to the following conclusions. *First*, if the similarity between the interpolation task and the learning task is low, retroactive inhibition induces a retrieval failure without storage loss. This is true both for conceptual and for phonemic-orthographic categories. *Second*, if the similarity between the interpolation task and the learning task is high, retroactive inhibition induces a storage loss without retrieval failure. Thus, the two levels of similarity lead to quite opposite patterns of results. The findings concerning storage loss suggest that interpolated items can disintegrate clustered items if they are related to the clustered items, while there is no disintegration if they are not related to the clustered items. The findings concerning retrieval failure provided evidence that the presentation of different categories makes preceeding categories inaccessible, while a repeated presentation of the same categories prevents stored clusters from being blocked.

Notice that these conclusions parallel those that result when we apply the SR-model to the same data sets. Indeed, I analyzed the data sets by means of the SR-model in some previous work (Bäuml, 1991a,b,c). For Experiments 1 and 2, I found the storage parameter c not to depend on the number of interpolated lists, while the retrieval parameter r declined with interpolation. This suggests a retrieval failure without storage loss for a low interlist similarity. For Experiment 3, I found the retrieval parameter r not to depend on the number of interpolated lists, while the storage parameter c declined with interpolation. This points to a storage loss without retrieval failure if interlist similarity is high.

5.2. Rates of forgetting

The comparison of the forgetting parameters of the model across the three experiments reveals the extent to which rates of forgetting, i. e. rates of storage loss and rates of retrieval failure, varied as a function of the kind of item categorization and of the interlist similarity. The kind of item categorization (Experiment 1 vs. Experiment 2) did not affect the storage loss parameter, suggesting that rate of storage loss does not depend on this variable. Indeed, the likelihood-ratio tests showed no reliable variation of the storage parameter across the two experiments. The same was not true for the retrieval failure parameter, which varied reliably across the experiments. The analyses indicate a higher rate of retrieval failure for phonemic-orthographically clustered pairs than for conceptually clustered pairs. The forgetting parameter for single items also showed variation across the two experiments. This points to a higher rate of interpolation-induced forgetting for single items in the context of phonemic-orthographic clusters than in the context of conceptual clusters.

The similarity between the learning task and the interpolation task (Experiment 1 vs. Experiment 3) influenced both the storage loss parameter and the retrieval failure parameter. This suggests that both the rate of storage loss and the rate of retrieval failure depend on the similarity between the learning task and the interpolation task. In fact, the analyses indicate that a higher similarity induces a higher rate of storage loss but a lower rate of retrieval failure, than a lower similarity does. The forgetting parameter for the single items also varied across the two experiments, suggesting a higher rate of forgetting for single items in the context of a high interlist similarity, than in the context of a low interlist similarity.

These findings point to the following conclusions. *First*, the rate of storage loss does not depend on the kind of item categorization but is influenced by the interlist similarity (see above). *Second*, when presenting lists of equally related item pairs the retrieval of phonemic-orthographically coded clusters is less robust against interpolation than is the retrieval of conceptually coded clusters. When interpreted in terms of the levels-of-processing approach (Baddeley, 1991; Craik and Lockhart, 1972; Craik and Tulving, 1975) these results indicate that a lower level of processing induces a higher rate of retrieval failure than a higher level of processing does, while the rate of storage loss does not depend on the level of processing. *Third*, the interpolation-induced forgetting of single items is affected by certain features of the item lists, like the kind of clustering of the item pairs and the similarity of the item pairs across lists. As the data show, while the retrieval of singles is not severely influenced by these two variables when there is no interpolation, this independence no longer holds when there is interpolation. This pattern suggests that the retrieval fate of a single item does not only depend on the single items that have been learned but also depends on the item pairs that have been learned, which points to considerable interactions between the items pairs of a list, on the one hand, and the single items of a list, on the other hand.

The comparison of rates of forgetting across experiments was conducted by testing whether the appropriate parameters of the RI-model varied reliably across experiments. The model explicitly incorporates forgetting parameters, so the tests could be done in a straightforward and fairly simple way. This would not have been possible with the same ease had the SR-model been used. The reason is that the SR-model does not include forgetting processes and, thus, does not include a criterion for equal rates of forgetting. Indeed, as is also pointed out by Estes (1988), when analyses of interpolation-induced forgetting are not based on models that include specific forgetting processes, answers to questions of rates of forgetting must remain, to a certain degree, arbitrary. (This arbitrariness is at the core of the controversy between Slamecka (1985) and Loftus (1985), on the issue of finding the 'right' definition of equal rates of forgetting.) Thus, when comparing the potential of the RI-model to reveal information about retroactive inhibition with that of the SR-model, the issue of rates of forgetting provides a nice example of how the RI-model reveals information about retroactive inhibition in ways that the SR-model cannot. This holds true even though the two models tend to come to the same conclusions on the issue of whether retroactive inhibition is due to storage loss or retrieval failure.

5.3. *Qualitative rules to describe interpolation-induced forgetting*

The above analyses confirm the inhibition concepts used within the RI-model. The good account of the model, however, also confirms some more general assumptions on which the RI-model is based. First, the analyses indicate that the model's theoretical states were linearly ordered in this experimental situation. That is, increasing the interpolation level did neither make unretrievable clusters retrievable, nor did it induce the clustering of unclustered item pairs, nor did it make forgotten single items accessible. [1] Second, the effect of incrementing the number of interpolated lists did not vary as a function of the interpolation level, which is consistent with a stationarity rule. Third, the effect of incrementing the number of interpolated lists did only depend on the theoretical state at the given interpolation level but not on any states at earlier interpolation levels, which is consistent with a Markovian rule. These suggestions reflect some simple qualitative rules along which the dynamics of interpolation-induced forgetting may be described in the present experimental situation.

Of course, these simple qualitative rules will not hold in general. Their approximate validity in the present experimental situation, instead, benefited from the use of a theoretical approach that, first, focuses on the number of recalled items of a list as the basic data, and on interpolation-induced changes in these numbers as the basic phe-

[1] I also fitted a more general version of the RI-model to the data of the three experiments, in which the theoretical states were not restricted to be linearly ordered. In fact, I incorporated three additional parameters into the model which reflect the possibility that incrementing the number of interpolated lists may, first, induce the clustering of nonclustered item pairs, second, make unretrievable clusters retrievable, and, third, make forgotten single items accessible. However, as might have been expected from the good fits of the original version of the model, none of these parameters contributed significantly to the description of the data, thus indicating that the theoretical states can in fact be assumed to be linearly ordered in this experimental situation.

nomenon to be explained, and that, second, uses recall data of different groups of subjects for the different interpolation levels of an experiment. This approach, which is widely used in studies on retroactive inhibition (Müller and Pilzecker, 1900; Tulving and Psotka, 1971; Riefer and Batchelder, 1988; cf. Crowder, 1976), ignores at least two properties of our retrieval system: the property that different items from a list may be retrieved on successive recalls (Brown, 1923; McGeoch, 1932; Tulving, 1974), and the property that retrieval of an item may affect later retrieval of this item and of other items (Anderson et al., 1994; Bäuml, 1996; Hogan and Kintsch, 1971). These properties are common phenomena of our retrieval system. Though they occur also in interpolation situations, they are not caused, possibly not even affected, by interpolation. Since the main emphasis of the present study is on interpolation effects, these properties are therefore neglected in this first approximation to the problem.

5.4. *Alternative frameworks*

The conclusions of the present study regarding the source of retroactive inhibition were based on the inhibition concepts that are incorporated in the RI-model, on the retrieval failure concept, and on the storage loss concept. Indeed, the use of these concepts was motivated by the results of several previous studies (Bäuml, 1991a,b; Jones, 1976; Reynolds, 1977; Riefer and Batchelder, 1988; Shuell, 1968; Sowder, 1973), and the good fit of the RI-model to the present data further supports this view. Nonetheless, other models using different inhibition concepts might have come up with different conclusions regarding the source of retroactive inhibition.

One prominent alternative framework that incorporates different inhibition concepts is the SAM theory by Raaijmakers and Shiffrin (1980, 1981). Raaijmakers and Shiffrin (1980) presented a version of SAM that adequately handles the recall of categorized item lists without interpolation. SAM is a cue-dependent retrieval theory. For this experimental situation SAM assumes two kinds of cues to retrieve items from the memory store, a context cue and a category cue. These cues are based on context and category information that are supposed to be stored in memory together with the item information during presentation of the items for study. SAM provides two basic reasons why in this experimental situation an item may be retrieved easier before interpolation than after interpolation. First, contextual fluctuations that result from a change of context over interpolation levels may lead to a decrease in the retrieval strength of the context cue (Estes, 1955; Mensink and Raaijmakers, 1988). Second, the number of other items associated with the category cue may be greater after interpolation than before interpolation, thus reducing the retrieval strength of the category cue to an item (Mueller and Watkins, 1979; Shiffrin, 1970).

Thus, SAM theory incorporates two retrieval failure mechanisms that may account for interpolation-induced forgetting, one reflecting the failure of the context cue and the other reflecting the failure of the category cue to retrieve associated items. The RI-model, on the other hand, incorporates one retrieval failure mechanism, quantified through the retrieval failure parameter γ, and one disintegration mechanism, quantified through the storage loss parameter β. While the retrieval failure concept used in the RI-model may be related to the failure of the context cue that is proposed in SAM, the storage loss concept used in the RI-model is fairly different from the failure of the category cue that is proposed in SAM. This conceptual difference between the two frameworks represents just one of the different views that still exist in the literature on the source of retroactive inhibition (cf. Houston, 1991).

Instead of presenting a complete, general theory of free recall like SAM theory, the goal of the present approach has been to formulate a simple model of interpolation-induced forgetting that embodies some basic ideas about retrieval failure and storage loss, and that provides a useful approximation of interpolation-induced forgetting in free recall of categorized item lists. In a similar way the concepts incorporated in SAM might be used to formulate a comparable simple model of interpolation-induced forgetting as the RI-model is (see Wickens, 1982, for the discussion of possible advantages that result from this approach). If such a model accounted equally well for the data as the RI-model did, this result would indicate that the data cannot distinguish between the different inhibition concepts of the two frameworks. In this case, the question of whether the inhibition in the present data is purely retrieval-based or whether there is some additional storage loss would remain unsolved. However, if such a model did worse than the RI-model, then this result would provide support for the inhibition concepts that are incorporated in the RI-model.

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