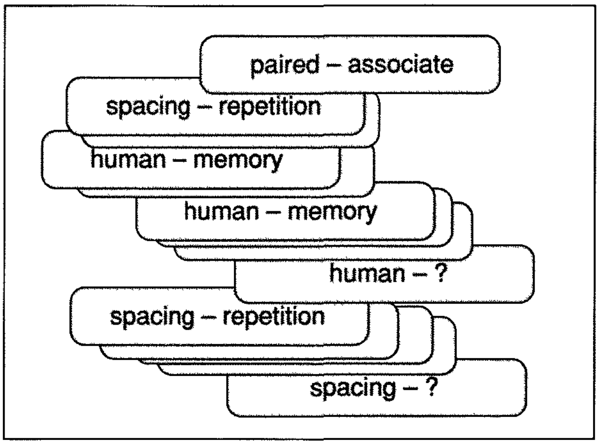
Spacing and Repetition Effects in Human Memory



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SPACING AND REPETITION EFFECTS IN HUMAN MEMORY

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op het gebied van de sociale wetenschappen,
in het bijzonder de psychologie

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VOORWOORD

Op deze plaats wil ik iedereen, ook degenen die ik hieronder niet met name noem, met wie ik tijdens mijn aanstelling bij de vakgroep Mathematische psychologie heb samengewerkt, koffiegedronken en geleuterd, bedanken.

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CONTENTS

1. INTRODUCTION

In this introduction the effects of spacing of repetitions and the theories to explain these effects will be discussed. In the first section, an overview is given of the effects of repetition and of the spacing of these repetitions. Repetition effects and the effects of spacing of repetitions are not dependent on the type of task; in nearly all memory tasks with repetition these effects are found. In the second section, a summary is given of two kind of theories, the consolidation and rehearsal theories, and the encoding variability theories, that are often used to explain spacing and repetition effects. The Component-Levels theory of Glenberg (1979), a special case of encoding variability, will also be described. The Search of Associative Memory (SAM) theory, where aspects of both the rehearsal and the encoding variability theory are incorporated, is discussed in the third section. The SAM theory is a probabilistic cue-dependent search theory that describes retrieval processes in long-term memory. Storage of information and retrieval of information through sampling and recovery will be discussed. In the fourth section, the experiments that are used to test the models are briefly described. In the last section, some aspects of mathematical modelling are discussed, along with what is involved in constructing a model and how the model is evaluated. Some further remarks will be made on the psychological interpretation of mathematical models, and on the psychological reality and the psychological plausibility in relation to mathematical models.

1.1. SPACING AND REPETITION EFFECTS

It is a truism that repetition improves performance. The more often things are presented, the better they are remembered. The so-called repetition effect is found when successful recall of repeated items is compared with successful recall of items presented only once. Moreover, for knowledge that must be retained for a very long period, it is best to time space the repetitions. Massed repetitions (repetitions that rapidly follow each other) lead to less durable storage than spaced repetitions.

Massed presentations are preferred only for things that must be remembered for a short while and may be forgotten soon thereafter. If both the number of presentations and the total study time are equal, spaced repetitions lead to better performance than massed repetitions. For example: When you phone someone five times on one particular day there is little chance that you can remember that number after a month. However, when you phone the same person once a day on five successive days only, there is a greater chance that you can remember the number.

The distribution effect:

The difference in recall between items with massed presentations and items with spaced presentations is called the *distribution effect* (or massed - distributed effect). Here the term "distribution effect" refers only to the difference between massed and spaced presentations. This difference can be either positive or negative. Also, nothing is said about presentations with moderate inter-presentation intervals. The difference between spaced and massed presentations can also be observed in various experimental designs: In paired-associate, free recall and recognition experiments, where two presentations of a stimulus are followed by a test a distribution effect is found. In free recall tasks it is found that, when the spacing between the two presentations (the spacing time or spacing interval) increases, the performance becomes better.

The lag effect:

When at least some other items separate the repetition, performance steadily improves as a function of how many intervening items there are. This pattern of results is known as the *lag effect* (or *Melton effect*, Melton, 1970). In most experiments where the lag effect is observed (see also Toppino and Gracen, 1985) there is, because the whole list of stimuli is presented prior to testing, a relatively large interval between the presentations and the testing. D'Agostino and DeRemer (1973) have shown that some distinction between the lag and the distribution effects is valid. They found that long lag effects (as obtained by Melton) are specific for free recall, whereas the massed versus distributed effect is obtained with both free recall and cued recall.

The spacing effect:

In a continuous paired-associate (CPA) paradigm it is possible to present stimuli and also test these stimuli within the same list. The time, between the presentations and between the presentations and test may then be varied independently. The time between two successive presentation is called the spacing (interval) or lag, and the time between the last presentation and the test is called retention (interval). In the paired-associate paradigm an interaction is found between the lag or spacing interval and the retention interval (e.g. Glenberg, 1976). This interaction is called the *spacing effect.* With a small retention interval performance decreases when the spacing becomes larger. In that case, massed presentations are better than spaced presentations. With a larger retention interval performance increases as the spacing increases. The results with large retention intervals are comparable with the lag effect found in free recall experiments.

More than two presentations lead to still better performance. After each additional presentation the performance increases until retention reaches an asymptotic level. Here also the difference between massed and spaced presentations is found. In general, it is found that long spacing intervals between the presentations lead to better performance than short spacings (Rumelhart, 1967).

In many experiments with repeated presentations, the findings violate the, otherwise useful, principle in human memory called the *total time law* (Bugelski, 1962; Cooper & Pantle, 1967). The *total time law*, within certain limits, states that the degree to which an item can be recalled is a direct function of the total study time, independent of how that study time is distributed among short, frequent exposures or long, infrequent exposures. Therefore, one presentation with a duration of four seconds would lead to performance comparable to that of two presentations of two seconds study time each. This law predicts also that every spacing interval between two presentations with equal duration leads to about equal retention. Both the spacing and the lag effect do not follow the total time law; the total time law predicts the same effect independent of the spacing of the presentations: it merely considers the sum of the presentation times (Underwood, 1970).

Waugh (1963) has attempted to give a rational formula to predict the recall of repeated items from the performance of once-presented stimuli. Sometimes, the subject can remember both occurrences of a repeated item, but, in the score for recalling, no distinction can be made whether the first, the second or both occurrences are remembered. The *independence baseline principle* states that both occurrences are seen as totally independent experiences and the probability of recalling at least one of such independent events is then: $P(E_1) + P(E_2) - P(E_1)\ P(E_2)$, where: $P(E_1)$ is the probability of recalling the first event and $P(E_2)$ is the probability of recalling the second event. This independence baseline principle predicts the same probability of a correct answer for all events repeated twice, however, both the distribution and the spacing effect show that this principle is incorrect. Application of this independence baseline principle to experimental data shows that massed practice is worse than predicted by independence and that distributed practice is better (Glenberg, 1974). In Glenberg's case the single-presentation recall probability from the Melton-Madigan study (1969, 1970) is taken as overall estimate of memory for single presentation events, and used to predict the recall probability of repeated events.

In the preceding description of the effects of repetition and of spacing of repetitions, the nature of the stimulus material and the type of retention test was not specified. Either the spacing effect or the lag effect appears to occur in nearly all memory tasks with repeated presentations. Either the spacing effect or the lag effect has been found in paired-associate learning (e.g., Peterson, Hillner & Saltzman, 1962a; Greeno, 1964; Glenberg, 1976), in free recall (e.g., Melton, Reicher, & Shulman, 1966; McFarland, Rhodes & Frey, 1979; Zechmeister & Shaughnessy, 1980), in recognition memory (e.g., Hintzman & Block, 1970; Kintsch, 1966; Nairne, 1983), and in the distractor paradigm (e.g., Peterson, 1963; Dannenbring & MacKenzie, 1981). Not only the probability of recall or recognition but also recognition latency (Hintzman, 1969a; Johnston & Uhl, 1976) and judged frequency (Hintzman, 1969b; Underwood, 1969; Hockley, 1984; Leicht & Overton, 1987) have been dependent variables. In addition when the presentations are all visual, all auditory (Melton, 1970) or both visual and auditory in a mixture in the same list (Hintzman, Block, & Summers, 1973) a spacing effect or a lag effect is found. Nonsense syllables (e.g., Kintsch, 1966), words (e.g., Melton, 1967; Rose, 1984), sentences (e.g., Underwood, 1970; Postman & Knecht, 1983) and pictures (Hintzman & Rogers, 1973, von Wright, 1976) have been used as materials. A wide range of presentation rates has been used (Melton, 1970) and the spacing effect or the lag effect occurs regardless of whether levels of spacing are manipulated within a list or between lists (Underwood, 1969).

Sometimes the lag effect is not found. In a series of nine experiments, Toppino and Gracen (1985) were unable to replicate the usual monotonically increasing lag effect by using lists and procedures similar to that used by Glenberg (1977, experiments I and II). It remains unclear why they failed to replicate Glenberg's findings. In some experiments of Toppino and Gracen the presentation rate and/or the modality of the presentations differed from those of Glenberg. The lag effect has, however, been found under many different circumstances. Toppino and Gracen concluded that the monotonically increasing lag effect in free recall does not invariably occur and is limited by, as yet undetermined, boundary conditions. Hall and Buckolz (1982) investigated whether repetition and lag improve the recognition of movement patterns. They tested recognition memory for single presentations, massed repetitions, and spaced repetitions immediately after the presentations and again following a two day delay. They found that a distribution effect failed to be demonstrated in movement repetition. There was a significant decrease in recognition memory when the retention interval was increased, but this appeared unrelated to the spacing interval between the presentations. Despite the fact that it remains unclear why a lag or spacing effect is not always found, some theories explaining the effects of repetition and of spacing of repetitions are described in the next section.

1.2. THEORIES EXPLAINING THE SPACING AND REPETITION EFFECT

In the psychological literature on learning and memory many explanations have been presented to account for both the effects of repetition and the differences between massed and spaced presentations (see Crowder, 1976; Hintzman, 1974, 1976 for detailed reviews). For the free recall paradigm, Melton (1970) distinguished three major classes of ideas. Firstly, inattention theories that propose a decrement in the processing of the second occurrence when it comes immediately after the first occurrence. The inattention theories will not be described further. Secondly, consolidation theories that assume the first occurrence is longer processed resulting in a higher strength when plenty of time is allowed before the second presentation. Thirdly, encoding variability theories that propose spaced repetition is more enable to lead to two different encoding contexts for an item and consequently to better recall than massed repetition. One encoding variability theory, namely the Component-Levels theory of Glenberg (1979) is described in the present section in more detail. Some theories are combinations of the consolidation idea with the encoding variability principles. The most important aspects of these theories will be reviewed below, but only the explanations of effects of repetition and of spacing of repetitions will be discussed. (For detailed descriptions and other aspects of the theories the reader is referred to Crowder (1976) or to the references given below.)

1.2.1. Consolidation and Rehearsal Theories

The principles of the consolidation process in memory have a long tradition. Müller and Pilzecker described this process in 1900. The general principles of these theories is that learning is not complete at the time that the practice is discontinued, but learning continues for some period of time during which the consequences of learning persist, and therefore remain active. During this persistence the memory trace is more securely fixed or consolidated, resulting in a better performance on later memory tests. There are two assumptions made. First: After stimulus presentation, there is a phase of active persistence, and secondly persistence promotes a stronger memory trace than is possible without persistence. The persistence process can be destroyed or interrupted by interpolated tasks (retroactive inhibition), thereby preventing consolidation. In figure 1.1 the consolidation after an interruption by a task of moderate difficulty of, respectively, an easy and a difficult task is shown. The trace strength, which is defined to be proportional to the area under the curve showing short-term decay, is greater after an easy than after a difficult task. Evidence for this kind of consolidation process is also found in the fact that after *mental inactivity* such as sleep the

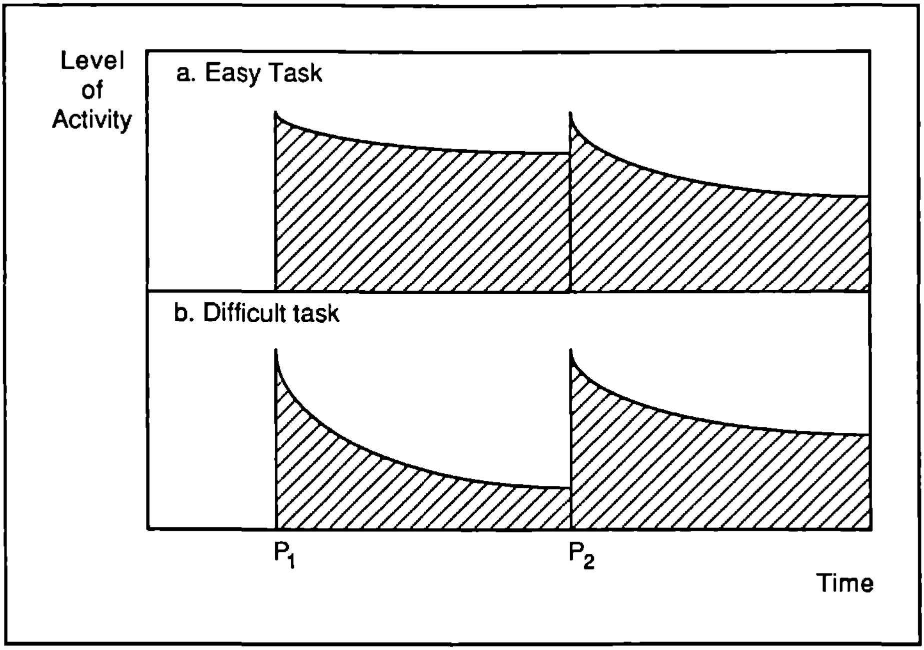

Figure 1.1. Predictions of the consolidation theory for an easy and a difficult task after P_1. (Fig 9.16 from Crowder, 1976) Shaded area represents the total amount of permanent (long-term) memory resulting from the two presentations P_1 and P_2. In (a) the task between P_1 and P_2 is easy, resulting in more total consolidatory activity then in (b) when the inter-presentation task is difficult. The task following P_2 is of moderate difficulty.

performance on memory tasks is greater than after a similar period of waking activity (McGeoch, 1942).

In more recent years, the consolidation theory has been elaborated in different manners. Landauer's (1967) main assumption is that the first process, neural reverberation (Hebb, 1949) decays steadily and that the amount of consolidation into long-term (permanent) memory is proportional to the integral of the decay curve – the area under the curve showing short-term decay. This is illustrated in figure 1.2 and is applied there to a single presentation and two presentations with short and long

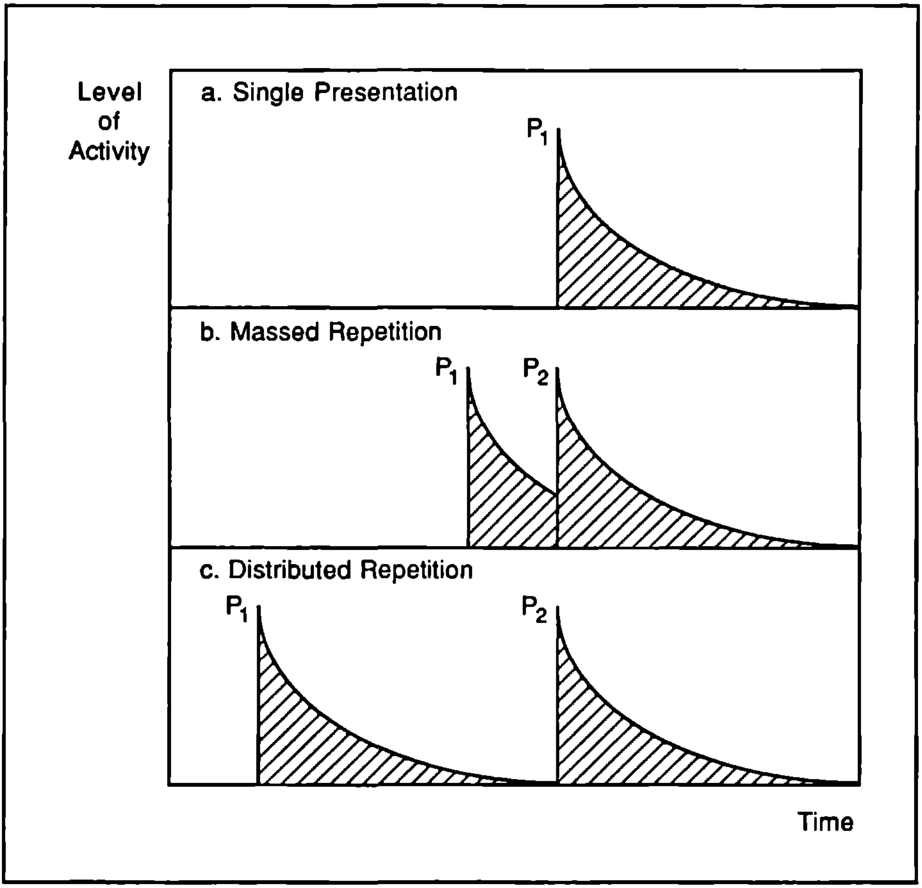

Figure 1.2. The consolidation theory of memory as applied to repetition - spacing effects. The strength of the trace in memory is proportional to the shaded area under the curves (Fig. 9.5 from Crowder, 1976)

lags. Although the momentary strength of the consolidation is the same whatever the spacing interval, adding a second presentation merely restores the process to the same maximum. That is, whenever the second presentation occurs it simply resets the consolidation process as if it were a first presentation. This being the case, there is more total consolidation activity for distributed than for massed repetition. However, note here that the effects of the second occurrence of the repeated item are constant, independent of lag, and that it is the differential effectiveness of the first occurrence that determines the lag effect, exactly the opposite to what is held by the inattention theories.

The traditional consolidation processes are assumed to be involuntary processes. A number of important theories in the course of time can be seen as examples of the consolidation theory (Bjork & Allen, 1970). The trace-consolidation theory of Landauer (1969) and the multi-trace strength theory proposed by Wickelgren (1970) are two theories where the *consolidation* is conceived as an involuntary process. In the rehearsal-buffer theory proposed by Atkinson and Shiffrin (1968) however *consolidation* is conceived as a voluntary process.

According to the *rehearsal theory* of Atkinson and Shiffrin (1968, 1971) items enter primary memory and are actively rehearsed for some time. The results of this rehearsal process are comparable to those of the consolidation theory. There is a continuing processing of information in absence of a stimulus. The difference is in the control of this processing, voluntary in case of rehearsal or involuntary in case of consolidation. While rehearsing the item in the primary memory the information is transferred to a permanent, secondary memory. There is a positive relationship between the total time rehearsing and the information transfer to secondary memory. Atkinson and Shiffrin (1968) assumed that a small number of items (the so-called rehearsal set) is rehearsed in the primary memory (later called the rehearsal buffer, part of the short-term memory) concurrently. Rehearsal can increase the amount of information about the item that is transferred to long-term memory by prolonging the stay of the item in rehearsal buffer.

The spacing effect is explained by two additional assumptions. Firstly, the probability that the trace of the first presentation, P_1, which is a member of the rehearsal set, decreases with time since P_1. Secondly, that the subject will not hold concurrently two copies of the same item in the rehearsal set. Therefore, the total amount of rehearsal given to an item (and also the total long-term trace strength) will be greater if the second presentation, P_2, occurs when P_1 is no longer in the buffer than when P_2 comes shortly after P_1. The maximal rehearsal time of two presentations is twice the total rehearsal time of once presented items.

Rundus (1971) has shown in a investigation of rehearsal patterns that the general ideas of the rehearsal theory are realistic. Subjects were instructed to rehearse aloud during presentation of free recall lists with word repetitions that were variably spaced. With short spacing intervals the words were rehearsed fewer times than with longer spacing intervals. Much of the differential rehearsal (Rundus's data show) took place during the spacing interval. The general idea of the rehearsal theory is one of the aspects of the Search of Associative Memory (SAM) model presented in this dissertation. Another crucial aspect used in the SAM model presented here is the variable encoding principle described in the next paragraph.

1.2.2. Variable Encoding Theories

Variable encoding is most widely used to explain the spacing and repetition effects. A great number of theories assume that the encoding of an item is in principle not always exactly the same. Which aspect of the item that is varyingly encoded depends on the specific theory.

An elaboration of variable encoding, which Martin (1968, 1972) has developed for verbal learning, was applied to lag effects by Melton (1970), Madigan (1969) and Bower (1972). It assumes that items can be encoded in different ways and that the representation of a word depends on the cognitive context in which it occurs. Crucial here is the context operating at time of retrieval. It is assumed that some context cues available at presentation are reproduced at retrieval. The chance of retrieval is higher when the context at presentation and testing is similar. For items presented twice the chance of retrieval is higher if the item has been presented in two different contexts. It assumes, further, that a greater spacing of presentations leads to more diversity in the encoding context, implying that, at test, there are more ways to retrieve the stimuli.

A great number of these theories assume that encoding varies along semantic dimensions. Therefore, presentations in different contexts lead to different interpretations. Madigan (1969) used forced encoding variability to directly control the encoding process by presenting nouns with more than one semantic interpretation in contexts indicating one or the other meaning. But by assuming only semantic features responsible for variable encoding a lot of spacing or lag effects found experimentally cannot be explained. Nonsense syllables (Hintzman, 1976) or abstract pictures (von

Wright, 1976) are usually not encoded with semantic features. However, a lag effect is found for this kind of stimuli as well.

In other theories the encoding variability is assumed to occur along more subtle and important dimensions. Anderson and Bower (1972) assume that, when an item is encoded in memory, its meaning becomes associated with a bundle of context elements. These context elements represent the state of the subject's stream of consciousness. At every occurrence a new bundle of context elements can be associated with the meaning of the word. The associations of meaning and context are crucial information for accurate performance on most memory tasks. When more different appropriate associations with the context are retrieved there is more evidence for deciding that it occurred in the experimental context, it is, therefore, more likely that the item is reproduced on a recall test or is recognized. It is important to note that traces of items with the same meaning can differ because the context elements stored vary. A plausible assumption for this kind of encoding variability is that in immediate repetitions more of the same context elements are sampled, while more different context elements are stored with longer spacings. The temporal parameter of the spacing effect depends on the rate of turnover of context elements in consciousness (Bower, 1972). A problem with this hypothesis is that the nature of the context elements involved is not specified so that the hypothesis is difficult to assess.

Johnston and Uhl (1976) derive encoding variability from the principles of encoding specificity of Tulving and Thomson (1971). Their primary assumption is that the retention of an item positively correlates with the degree to which it has been processed in different cognitive environments. At the first presentation a particular cognitive environment is assumed. Further, it is assumed that the probability and magnitude of the change in the individual's environment increase with the length of the spacing intervals. The definition of cognitive environment is comparable to that of the cognitive context. In both definitions the context or the environment determines how a particular item is encoded.

All kinds of possible variations in encoding are used to explain the spacing and repetition effects with greater or lesser success. In some theories it is explicitly assumed that for every presentation of the item a new trace is formed, implying a kind of multiple trace theory, while in other theories only one trace is formed and with every repetition new features or elements are added to the trace.

In exactly the same way as the variable encoding theory predicts a spacing or lag effect for two presentations of the same item, Ross and Landauer (1978) arrive at a prediction of this effect for two presentations of any item, whether the same or different. They distinguish three different kinds of encoding variability theories to test their *independence hypothesis*. All theories predict that the probability of remembering at least one of two different items should increase as the spacing between them increases. They assume that all traces of presented items are more or less correlated with each other. The different theories suppose that there are different features of storage that vary in correlation with spacing. In variable learning rate theories there are variations in the likelihood or effectiveness of registration on individual learning presentations. The effectiveness of registration can be influenced by a nonconstant feature such as, for example, fluctuations in attention. Due to waxing and waning of attention there are alternating periods with more or with less attention. It is more likely that massed presentations occur in one attention state. Other nonconstant influences with the same effects on learning are, for example, fluctuations in ambient noise, or rapidly increasing fatigue. In variable encoding theories per se the variability is due to varying context elements, variable cognitive context or different cognitive environments as described above. The third distinguished theory is the variable storage locus theory of Landauer (1975), which assumes that individual trials produce separate records and that the place in memory where the record is stored drifts with time. The records of two events directly following each other are more adjacent in memory (in place) than records of items spaced in time. Records of items spaced in time are more widely distributed in memory (in place). At a given time only a limited region of memory can be accessed and the probability of finding at least one of two records will be greater for widely distributed records in memory than for records more closely located. In a number of experiments Ross and Landauer (1978) found a lag effect only in cases of repeated items and not in cases of two different items each presented once. A theory that assumes that for repeated presentations two independent traces are always formed, cannot explain this difference. However, theories (such as the Component-Levels theory of Glenberg, 1979 and the SAM model presented in this dissertation) that assume that new information is added to an existing trace at the second presentation can explain this difference (See chapters 2 and 8 for more details).

A difficulty with the encoding variability theories is that only a small number of possible context variations can be measured directly. Many attempts to determine the spacing or lag effect experimentally have failed to directly measure the presumed processing underpinnings of the effect. In the following section (1.2.2.1) the Component-Levels theory of Glenberg (1979) will be presented which proposes that spacing and lag effects are due to variable encoding of any or all of three types of informational components. Variability of encoding can reside in the semantic interpretation (Bower, 1972; Madigan, 1969), in the context in which the events are encoded, and in the subjective organization in which the events are embedded (Melton, 1970). These three notions of variable encoding are combined in the Component-Levels theory.

1.2.2.1. Component-Levels Theory (Glenberg)

The *Component-Levels theory* of Glenberg (1979) was designed to explain the effects of spacing and repetitions in the continuous paired-associate paradigm. It incorporates as a basic principle the assumption of encoding variability. The theory assumes that a stimulus is represented by a multicomponent episodic trace. Which components are included in a trace is determined by such factors as the stimulus being processed, the nature of the processing task, the subject's strategies and the context in which the stimulus is presented. Three types of components are distinguished: context[1], structural and descriptive elements. Context components, representing the context in which the item is presented, are encoded automatically. Context includes such information as the characteristics of the physical environment, the time of learning and the learner's cognitive and affective state. A repetition is effective when different information is stored at the two presentations of the repeated event. The conditions under which new information is stored at P_2 depends upon the components already stored. Since context information is automatically encoded, new context information is stored simply as a function of the change in context. Different aspects of the context

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[1] Glenberg uses the term contextual instead of context.

typically have different rates of change. Glenberg makes a distinction between global and local context elements. Local elements change rapidly in the course of the experiment, i.e. these elements fluctuate between two successive presentations. Global context information on the other hand changes very slowly; these elements are very general and can be assumed to remain constant during an experimental session. Therefore for repeated items, only the amount of change in the local context is important. The lag between the items is directly related to the change in local context elements. *Differential storage* then refers to the positive correlation between the repetition lag and the number of different components stored in the trace.

Structural components are less general than the context elements. The structural components represent the structure that the subjects impose on the items, i.e. which items are associated, grouped, categorized or chunked together. This storage is not automatic and depends on control processes used by the subject. The nature of the task, the task instructions, and the motivation of the subject, for example, influence these control processes. The local context determines which structural elements are encoded and stored in the trace. Aspects of the context such as the other items currently being processed affect the encoded structure of a set of items. Associations are made only between items that are simultaneously processed. Whether or not a repetition is effective for storage of new structural components depends on the context and on the encoding and storage processes used by the subject. New structural components are added to the trace at the repetition only when the structure assigned to the stimuli (induced by the context) is changed. The structural components are also characterized by differential storage, because the change in structural components depends on the changes in local context components. The more the context changes, the more structural components are encoded and stored in the trace.

The third kind of components are the descriptive components. These are the most specific pieces of information that are encoded, and include information such as the orthography, articulation and the meaning of a stimulus. The descriptive components are copied from the semantic memory representation of the stimulus. Which specific descriptive components are copied depends on the local context in which the stimulus is presented. For example, the interpretation of a stimulus depends upon the surrounding stimuli (e.g., the word "table" preceded by "figure" or by "chair"). Variability in specific descriptive components encoded at the two presentations of a repeated stimulus, is a function of control processes and the local context. Different contexts on two presentations may lead to encoding of different aspects of the stimulus on the two occurrences. Therefore, the level of descriptive components is also characterized by differential storage.

Remembering a specific stimulus requires retrieval of the memory trace representing the stimulus. Cues at the time of remembering are necessary for retrieval. The local context at the time of retrieval is one important cue. The greater the similarity of the context at the time of testing to the context elements stored in the memory trace, the stronger the activation of that trace and the higher the probability of retrieval. Specific cues, containing many specific components, are very effective in the activation of a small number of traces that have these elements in common, and often only one trace will be activated strongly enough to be retrieved. For free recall, less specific cue information will be used for retrieval than for paired-associate testing and recognition. The cues for paired-associates and especially recognition consist of a larger number of structural and descriptive components than the cues for free recall.

At P_2 of a stimulus, additional elements will be stored in the memory trace. Depending on the variation of the context, new context and sometimes new structural and descriptive elements will be stored in the trace. The more the context has fluctuated, the more additional elements there will be stored. Sometimes the context will have changed so much that another meaning is given to the stimulus. In that case a new set of descriptive and structural elements is stored. It follows that the more distributed the presentations of the same stimulus, the more likely it is that the context has been changed and the more different storages there will be. Spaced presentations are better than massed presentations (except when tested immediately) because more components are stored and can be activated by the retrieval cues. Only for short retention times will massed presentations be superior to spaced presentations because, only in that case, will the similarity between the context at test and the stored memory trace be greater for massed presentations.

The Component-Levels theory is not mathematically elaborated. It is not possible to give exact predictions for the probability of a correct answer for different combinations of spacing and retention intervals. The global ideas of the Component-Levels theory will be incorporated in the SAM theory of Raaijmakers and Shiffrin (1981a), see chapter 2. In the next section the SAM theory elaborated with the context fluctuation model will be presented.

1.3. THE SAM THEORY WITH THE CONTEXT FLUCTUATION MODEL

In this dissertation, we will elaborate a model intended to explain the basic findings concerning spacing and repetition effects, findings that have been shown in many experiments to be relatively robust and reliable. The model is based on the general Search of Associative Memory (SAM) theory (Raaijmakers & Shiffrin, 1981a) but incorporates a model describing context fluctuation processes (Mensink & Raaijmakers, 1988). In this section, we will use the description of the SAM theory by Mensink and Raaijmakers (1988, 1989) and adjust this description to effects of repetition and of spacing of repetitions.

The SAM theory (Raaijmakers & Shiffrin; 1980, 1981a; Raaijmakers, 1979) can be seen as an elaboration of the rehearsal-buffer model of Atkinson and Shiffrin (1971). The storage in permanent memory takes place during rehearsal of information in a rehearsal buffer, which is part of the short-term store, just as in the rehearsal-buffer model. However, the SAM theory is not a theory for storage of information, but a theory for retrieval of information from memory.

The SAM theory is a probabilistic cue-dependent search theory that describes retrieval processes in long-term memory. The retrieval of information is assumed to be a two-stage process of sampling and recovery. Retrieval cues such as specific items and context, are used in the sampling phase to select an image in memory (or a memory trace) as a candidate for recall or recognition. After successful sampling the retrieval cues are used in the recovery phase to assemble and articulate the information into an answer. As has been documented in previous papers (Raaijmakers & Shiffrin, 1980, 1981a, 1981b), the SAM theory is capable of predicting a considerable number of findings that have been reported in the literature. Memory phenomena such as serial position effects, response latency, output interference, list-length effects, cued and non-cued recall of categorized lists, and the interference phenomena have been successfully predicted. In addition, Gillund and Shiffrin (1984) developed an extension of the SAM theory that handles recognition data and the relation between recognition and recall. However, as yet, the theory has not been tested for the effects of repetition and of spacing of repetitions. Since effects of repetition and of spacing of repetitions are found in many situations (see before), a general theory of memory such as SAM should be able to handle such phenomena.

Previously versions of SAM (e.g., Raaijmakers & Shiffrin, 1981b) would be able to explain some of the effects of repetition and of spacing of repetitions by means of the rehearsal buffer. The theory is not yet equipped to handle specific phenomena such as the spacing effect. For explanation of such phenomena some aspect of SAM has to be turned into a time-dependent variable. We will incorporate a model for context fluctuation to account for these time-dependent changes. Context fluctuation is assumed to cause the interdependence between memory performance and retention time (Bower, 1972; Estes, 1955; Raaijmakers & Shiffrin, 1981a). The context strength, i.e. the associative strength between the context cue at test and the stored memory images, is determined by the context fluctuation model, and is therefore a function of time. A full account of the mathematical details of this development has been presented by Mensink and Raaijmakers (1989). Through the context fluctuation model the encoding variability ideas are mathematically implemented in the SAM theory.

It is assumed that the associative strength between the context cue at time of testing and a particular memory image (which is related to the probability of retrieving that image; see below) is determined by the overlap between the context at the time of storage and the test context. In the general SAM theory (Raaijmakers & Shiffrin, 1981a) the duration of the stay in the rehearsal buffer can be used to explain some of the repetition effects. In order to explain spacing and repetition effects over a wider range we will make use of the concept of context fluctuation in modelling the enrichment or stengthening of the memory trace on successive presentations.

In this section, we will present the general SAM theory in relation to paired-associate modelling (often used to test the spacing and repetition effects). First, we will discuss the storage of paired-associates in memory and the associative strengths between possible retrieval cues and the stored episodic images. Two kinds of associative strength will be used for paired-associates, namely inter-item and context strength. The context fluctuation model will be used to describe the context strength. In the second paragraph, we discuss how the information is retrieved from memory. For a full description of the basic concepts in SAM see Raaijmakers and Shiffrin (1981a). In chapter 2 the more specific mathematical details to explain spacing and repetition effects will be presented.

1.3.1. Storage

When a paired-associate (a-b) is presented, it enters the short-term store (STS). In STS processing operations are carried out on the presented information, such as elaborative rehearsal. The amount and kind of information stored in memory is determined by the nature of these processes. It is assumed that the amount of elaborative rehearsal will be proportional to the length of time that an item is studied (rehearsed) in STS. This rehearsal process is modelled by a limited capacity buffer. Items that are simultaneously present in this buffer build up inter-item associative strength. For free recall tasks, an item will be associated to previously or subsequently presented items, to the extent that they are simultaneously in the buffer. In such studies, all items in STS are assumed to be part of the rehearsal buffer. There is, however, evidence (Raaijmakers & Shiffrin, 1981b) that the rehearsal process is somewhat different in paired-associate paradigms. In that case, the buffer and STS do not coincide. That is, the two members of a pair are associated only to each other and not to members of other pairs, still present in STS. This is demonstrated by the absence of a primacy effect, indicating the absence of cumulative rehearsal. However, since previous items may still be in STS (although not actively rehearsed), a recency effect may still be observed (Murdock, 1974). Further, it can be noted that in most paired-associate experiments the subjects are explicitly instructed to attend to only the shown paired-associate and not to rehearse other pairs at the same time. Hence, it is assumed that at anyone time the buffer is occupied only by a single paired-associate and that the next pair always replaces the previous one (Raaijmakers & Shiffrin, 1981b).

In SAM, it is assumed that during the stay in the buffer, information in STS about the items to be learned is added to long-term store (LTS). The stored information is called a memory image. An image (or episode) may be considered as the unit of episodic memory, the memory trace corresponding to a specific event in a particular spatio-temporal context. In paired-associate paradigms, the images are assumed to consist of information corresponding to the presented pairs. Hence, a single image includes both stimulus, response, and context information as well as associative information[2] (information about how the stimulus and the response can be associated with each other). It should perhaps be mentioned that the assumptions that a pair constitutes a single image differs somewhat from previous applications of SAM to free recall paradigms where the image corresponded to individual words. However, if we think of what is stored as an episodic event consisting of a (single) set of features (a quite common assumption in current theories), then the above assumption makes perfect sense. Moreover, it may be shown that the choice between the two ways of representing a pair of words is in fact a matter of preference, since the two versions make equivalent predictions (see Raaijmakers & Shiffrin, 1981b).

It is assumed that the amount of information (i.e. the number of encoded features) is proportional to the length of stay in the buffer. If, as we assume, each paired-associate is replaced immediately by the following pair, the length of stay in the buffer will be equal to the presentation time. As discussed in previous papers (see Raaijmakers & Shiffrin, 1981a), the memory structure is represented by a retrieval structure expressed by the associative strengths between possible retrieval cues and the stored episodic images. These associative strengths are a function of the overlap between the set of features contained in the cue and the set of features contained in the image.

In the present elaboration, two types of retrieval cues are involved: item cues corresponding to the stimulus member of a pair and context

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[2] Note that the assumptions that item and associative information are both stored in the same image does not imply that item information may not be retrieved separately. That would only be true if recovery was assumed to be an all-or-none process (which it is not).

cues. Although the encoding of the stimulus may be variable (stochastic), it is assumed that this is not a function of the time between presentations. That is, the stimulus does not have to be encoded in exactly the same way on two occasions A and B. But the similarity of these two encodings does not depend on the temporal distance between A and B. Hence, the associative strength of the stimulus item to the stored image (henceforth called the inter-item strength) is assumed not to depend on the length of the retention interval, but it does depend on the number of presentations. We will denote the inter-item strength of the stimulus to the corresponding image as I [3]. The inter-item strength will depend on the presentation time and the amount of associative information transferred per second, but this strength is independent on the temporal distance t between A and B. However, the presentation time is equal for all presented paired-associates in one experimental setting, so that only the amount of information transferred per presentation is determining the inter-item strength. The amount of information transferred from STS to LTS is not constant but depends on such factors as pre-experimental associative strengths, the imagibility, and the encoding strategy. For the experiments discussed in this dissertation, these factors are assumed to be held constant, so that the inter-item strength is assumed to be a constant when one presentation followed by a test is considered. The inter-item strength for more than one presentation of the same pair is assumed to be determined by the number of presentations and the amount of associative information transferred for a single presentation.

Next, we have to discuss the context associative strengths. In a model for interference and forgetting (Mensink & Raaijmakers, 1988, 1989) this aspect is for the first time changed with respect to previous applications of the SAM theory. This context associative strength is assumed to depend on the overlap between the context at time of storage and the context at time of testing. Hence, this strength should be a function not only of the number of presentations and the presentation time, but also of the retention interval and the inter-presentation intervals. In order to

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[3] Later we will use t to indicate the time (-interval) of presentation(s) and/or test(s). Since the inter-item associative strength is a function of the number of presentations and since the context associative strength is a function of the elapsed time, we will write, in the sequel, all associative strengths as a function of t, e.g. $I(t_m)$, where t_m denotes the time interval between presentation(s) and/or test(s).

accomplish this, Mensink and Raaijmakers (1989) have developed a context fluctuation model based on the stimulus sampling theory. A full account is given by Mensink and Raaijmakers (1988, 1989). For our purposes, the context fluctuation model will be adjusted to account for repeated presentations in a continuous paired-associate paradigm.

Context (internal as well as external) is represented as a set of context elements (following: Estes, 1955, and Bower, 1972). Context elements can be in an *active* or *inactive state.* Active context elements are those which are perceived by the subject at a given moment of time. These are also denoted as the current context. All other context elements, not perceived elements, are called inactive. We assume that at any moment only a fixed proportion s of the elements are in the active state. Hence, the proportion of inactive elements always equals $1 - s$. With the passage of time the current context changes due to a fluctuation process: inactive elements may become active and active elements will become inactive (see figure 1.3).

We will now apply these ideas to a paired-associate paradigm with repetitions (a - b , ... , a - b , ...). Imagine that a subject is given a study trial on a stimulus-response pair (a - b) and some time later an

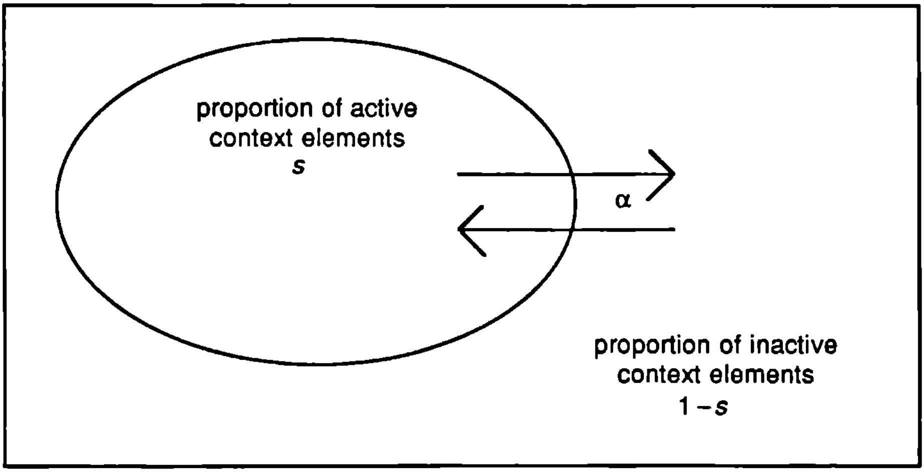

Figure 1.3. A graphic representation of the context fluctuation process assumed in the context model. During the time interval Δt there exists a probability α that two elements, one active and one inactive, are exchanged between states.

additional study trial of the same pair. This particular situation is illustrated in the following scheme:

$$a - b \;\overset{t_1}{\text{————————}}\; a - b \;\overset{t_2}{\text{————————}}\; \text{test}$$

where t_1 and t_2 represent the lag or spacing interval, and the retention interval, respectively.

When the a - b pair is presented for study, any active context element may be encoded in the item's image. It is assumed that only active elements can be stored in the episodic image. During the spacing interval t_1 the fluctuation process causes a new sample of context elements to be active when the a - b pair is presented for the second time. This active set will contain both encoded and unencoded elements. Some of the active elements that were not encoded before, will be added to the a - b image. At the end of the retention interval t_2 the active set will contain encoded and unencoded elements due to the fluctuation process. These elements constitute the context cue that is used to retrieve images from memory. Its associative strength to an image is assumed to be proportional to the number of active and encoded elements at the time of testing, i.e., to the overlap of the set of elements stored in the image and the set of elements active at the time of testing. One can distinguish the following four classes (or types) of context elements:

1. active and encoded,
2. active, but not encoded,
3. inactive and encoded,
4. inactive and not encoded.

Mensink and Raaijmakers (1989) have made some simplifying assumptions in order to keep the model mathematically tractable. They assume that during a learning trial the context state remains fixed, i.e., active elements remain active and, similarly, inactive elements remain inactive.

In addition, they made some decisions concerning the relationship between the elements encoded on a given trial in the images corresponding to different items. It seems unlikely that the same subset of active elements is encoded in all images. It will therefore be assumed that the encoding of active elements in a memory image is governed by a stochastic process and that the subsets of active elements that are encoded in the image of different items are independent samples from the set of elements that constitutes the current active context. In this dissertation, we will assume that only a proportion w of the active elements are stored during the presentation of a paired-associate. Only active elements that are not already been encoded in the image can be stored during a study trial.

As mentioned above, the associative strength of the test context to the stored image is assumed to be proportional to the overlap ($O(t)$) between the context elements stored in the image and the set of context elements active at time of testing. The context strength ($C(t)$) is given by:

$$C(t) = a\,O(t), \tag{1.1}$$

where a is a scale parameter.

The context fluctuation model enables us to calculate the expected proportion of elements of each type at each time. This is based on the following formula which gives the expected proportion of elements of a certain class, which are active following t seconds of fluctuation, given that the state at time $t = 0$ is known (see Mensink & Raaijmakers,1989). Let $O(t)$ represent the proportion of active elements stored at the first presentation and active after t seconds of fluctuation:

$$O(t) = A(0)\,\mathrm{e}^{-\alpha t} + K(0)\,s\,(1 - \mathrm{e}^{-\alpha t}). \tag{1.2}$$

In this equation s stands for the equilibrium value of the proportion of elements that is active, and α[4] is the parameter that gives the rate of fluctuation between the active and the non-active states. The context fluctuation process was illustrated in figure 1.3. In general, $A(...)$ will represent the proportion of stored elements that were active at the last presentation, and $K(...)$ will be the total proportion of stored elements,

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[4] In the elaboration of the SAM model of Mensink and Raaijmakers (1988, 1989) there are also fluctuation and storage parameters used, namely γ the rate at which an inactive element becomes active and β the rate at which an active element becomes inactive. The parameters s and α are transformations of these parameters, namely $s=\gamma/(\gamma+\beta)$ and $\alpha=\gamma+\beta$.

both active and non-active, at the last presentation. In equation 1.2 the overlap after a single presentation is given. Immediately after a single presentation, at time $t = 0$, $A(0)$ and $K(0)$ will be equal, because all encoded elements are also active at this single presentation. There are no encoded elements that are not active at time $t = 0$. Both proportions are given by:

$$A(0) = K(0) = w\,s, \tag{1.3}$$

where w is the probability of encoding an active element. Therefore, it follows that:

$$O(t) = w\,s\,\mathrm{e}^{-\alpha t} + w\,s^2\,(1 - \mathrm{e}^{-\alpha t}). \tag{1.4}$$

With more than one presentation followed by a test the situation is more complicated. In the following, the spacing time is denoted by t_1, and the retention interval is denoted by t_2. For reasons of simplicity, it is assumed that fluctuation occurs only between consecutive study trials and not within a study trial. When the item is recognized at P_2, additional elements of the current active context will be stored in the existing image. If not recognized a new trace is formed. It is assumed that a given element can be stored only once in a particular image. In general we denote the proportion elements of a certain kind at time $t_1 + t_2 + \ldots + t_n$ as $A(t_1,t_2,\ldots,t_n)$, where t_m is the time interval between presentations m and m+1, and t_n is the time elapsed since the nth presentation. The proportion of stored elements that are active at P_2 is given by:

$$A(t_1,0) = O(t_1) + w\,(s - O(t_1)). \tag{1.5}$$

The total proportion of stored elements after P_2 is:

$$K(t_1,0) = K(0) + w\,(s - O(t_1)). \tag{1.6}$$

The overlap of the enriched image and the active context at test, T, is given by:

$$O(t_1,t_2) = A(t_1,0)\, e^{-\alpha t_2} + K(t_1,0)\, s\, (1 - e^{-\alpha t_2}). \tag{1.7}$$

For more than two presentations the proportion of stored elements active at P_m is:

$$A(t_1,\ldots,t_{m-1},0) = O(t_1,\ldots,t_{m-1}) + w\,(s - O(t_1,\ldots,t_{m-1})), \tag{1.8}$$

in which t_m is the interval between P_m and P_{m+1} and the total proportion of stored elements after m presentations is:

$$K(t_1,\ldots,t_{m-1},0) = K(t_1,\ldots,t_{m-2},0) + w\,(s - O(t_1,\ldots,t_{m-1})). \tag{1.9}$$

The overlap of the enriched image and the active context at the m+1th trial is:

$$O(t_1,\ldots,t_m) = A(t_1,\ldots,t_{m-1},0)\, e^{-\alpha t_m} + K(t_1,\ldots,t_{m-1},0)\, s\, (1 - e^{-\alpha t_m}). \tag{1.10}$$

Using equation 1.4 it becomes possible to calculate at each moment in time the expected proportion of active elements of each type after a single presentation. (The relevant difference equations can be found in Mensink & Raaijmakers, 1989.) The expected proportion of active elements of each type after multiple presentations can be calculated with equation 1.10.

Note that a result of our fluctuation model is that the context associative strengths will depend not only on the number of presentations but also on the inter-presentation and the retention intervals. This enables us to predict a number of time-dependent spacing and repetition effects.

1.3.2. Retrieval

In the general SAM theory, the retrieval of information is a two-stage process of sampling and recovery. Retrieval cues such as specific items and context, are used in the sampling stage to select (activate) an image (trace) in memory as a candidate for recall or recognition. Such memory images may be assumed to consist of a large number of elements. Specific information such as the orthography, articulation and the meaning of a stimulus is encoded in so-called purely descriptive elements, other encoded elements are structural or context (terminology of Glenberg, 1979). The retrieval cues used in sampling are based on information given in the test question and on information retrieved on previous memory searches. This is to a large extent a strategy-dependent process. However, the set of cues also includes context information based on the momentary external (environmental) and internal context. The search process itself is an automatic process. The retrieval cues will activate a number of different images that all have some aspects in common with these cues. The degree to which images are activated depends on how strongly they are associated to the retrieval cues. To recall the first item in a free recall task only the context is used as cue, next, both that specific item together with the context are used. For paired-associates always one of the items of the pair and the context will be used. The probability of sampling (P_{SAM}) a particular image of a paired-associate after t seconds is a function of the associative strength between the cues used and that image, relative to other images and is given by:

$$P_{SAM}(t) = \frac{I(t)\ C(t)}{I(t)\ C(t) + Z}, \qquad (1.11)$$

in which $I(t)$ is the inter-item associative strength, $C(t)$ is the context strength and Z is the residual strength of other images retrieved by the cues. Note that in equation 1.11 the sampling probability of a paired-associate presented once and tested after t seconds is given. This sampling probability depends on the retention interval between presentation and test. After more than one presentation the sampling probability will depend on all inter-presentation intervals and on the retention interval.

Sampling of an image is not sufficient for successful reproduction. For example, in recall tasks sufficient information must be activated from the image to enable the reconstruction of the name of the item on the basis of the encoded information (this explains the "tip of the tongue" phenomenon: the image is sampled but is insufficient to reconstruct the name we are trying to find). This process is termed *recovery.* It is assumed that the probability of successful recovery is a function of the associative strengths. In SAM, the probability of recovery (P_{REC}) is given by:

$$P_{REC}(t) = 1 - e^{-\theta\,(I(t) + C(t))}. \tag{1.12}$$

The probability of recovery is a function of the sum of the associative strength to the retrieval cues.

It is to be expected that θ will have a different value in the case of recall as compared to the case of recognition. Both processes occur in the models presented in chapter 2. Therefore, two parameters θ_1 and θ_2 will be introduced: θ_1 will be substituted for θ in equation 1.12 in the case of recognition and θ_2 for recall. As a recognition response is assumed to require a smaller amount of activated information than is needed for the more difficult recall response, it is expected that $\theta_2 < \theta_1$.

If either sampling or recovery fails (i.e. does not lead to a correct response), a new retrieval attempt may be made. The whole search process consists of a number of such retrieval attempts, each consisting of sampling and recovery. In the cued recall tasks that we consider, the search is terminated either when the correct response is recalled or when a fixed criterion number of failures (unsuccessful retrieval attempts) is reached. The stopping criterion is denoted by L_{max}. One restriction that should be mentioned is that successive recovery attempts of the same image are not independent. It is assumed that if the first attempt at recovery has failed, subsequent recovery attempts on the same test trial using the same retrieval cues will also fail.

Retrieval of the correct image is a combination of sampling and recovery. After L_{max} search cycles the probability of retrieval $P_{RET}(t)$ is:

$$P_{RET}(t) = \{1 - (1 - P_{SAM}(t))^{L_{max}}\}\, P_{REC}(t). \tag{1.13}$$

When the correct image is retrieved from long-term store (LTS) through sampling and recovery a correct response will be given. Also a correct response is given in SAM when the item is still present in the STS. It is assumed that after every presentation the elements of the item are held for some time in the STS. An item that is present in the STS at the moment of a following presentation or test is assumed to be always recognized or recalled. We assume that the probability of still being in the STS is given by:

$$P_{STS}(t) = e^{-\lambda t}, \tag{1.14}$$

where λ stands for the rate which with items decay from the STS. The interval t can be replaced by any interval depending on the particular presentation that is being considered.

In the SAM theory for free recall tasks, all items in the STS are assumed to be also part of the rehearsal buffer. All items in the STS are assumed to be actively rehearsed, and all items present in the buffer and in the STS are recalled. However, the STS and the rehearsal buffer do not coincide for the paired-associate paradigm (see also section 1.3.1. above). The associative strengths are formed only during the presentation(s) of a pair, when the pair is actively rehearsed in the rehearsal buffer. This is reasonable, because all presentations within one experiment have the same duration, and the subjects are instructed to attend only the shown pair and not rehearse other pairs at the same time. Associations across pairs are assumed not to be relevant for recall or recognition of paired-associates. Therefore the simultaneous presence in the STS of two different pairs has no consequences for the associative strengths. The STS can be seen as a process that facilitates the recognition or recall of an item. The probability of staying in the STS is assumed to decay rather rapidly.

In the present elaborations of the SAM theory, the inter-item associative strength is a function of the number of presentations, and the context strength is a function of the inter-presentation intervals and the retention interval. These strengths can be directly estimated from the data without using the Monto Carlo simulation technique as in previous tests of the SAM theory. It also enables us to present a number of analytically derived predictions. Further, it enables us to fit the theory quantitatively to experimental data using standard minimization procedures and to analyze potential identifiability problems with respect to the parameters.

In the present paper, the SAM theory will be used to predict spacing and repetition effects as well as related effects (e.g. Ross and Landauer, see section 1.2.2 and chapters 2 and 8) in continuous paired-associate paradigms (see chapter 2 for more details of the model for this paradigm). According to the SAM theory, there are two factors that account for forgetting in such paradigms. First of all, as the retention interval increases, the strength between the retrieval cues and the to-be-retrieved image decreases. In the versions of the model presented here this will be assumed to be due mainly to the context fluctuation process. This process will lead to a decreasing overlap between the context elements stored in the image during presentation of the paired-associate and the context elements active at the time of testing. Secondly, the probability of sampling the image is inversely related to the strengths and number of the other images associated with the retrieval cues. As the retention interval increases, there will be more and more (relatively strong) images that are also activated by the retrieval cues, which also leads to a decrease in probability of recall. The continuous paired-associate experiments, to which the SAM model for multiple presentations is applied, are mentioned in the next section.

1.4. THE CONTINUOUS PAIRED-ASSOCIATE EXPERIMENTS

The version of the SAM model (see chapter 2), elaborated with a model for context fluctuation (Mensink & Raaijmakers, 1989) to account for time-dependent changes, will be used to predict the effects of spacing of repeated presentations. In continuous paired-associate (CPA) experiments the length of both the inter-presentation intervals and the retention intervals can be varied and so totally controlled. The inter-presentation intervals of the same pair and the retention interval (between the last presentation and test) are, in the experiments presented in this paper, filled with presentations and tests of other paired-associates. In figure 1.4 the sequence of events in a typical paired-associate learning task is shown. Two kinds of CPA experiments are common. One consists of pairs which are one-to-one, the other consists of many-to-one pairs, as explained below. The first kind of CPA experiment (the one-to-one type) is composed of trials with presentations of the paired-associate and trials with tests of these paired-associates. The presentations of a specific paired-associate are followed by its test, a paired-associate is tested only once and after the test the paired-associate is not presented and not tested again. Further, no paired-associate was tested without being presented at least once. In the experiments presented in this paper, the stimulus and the

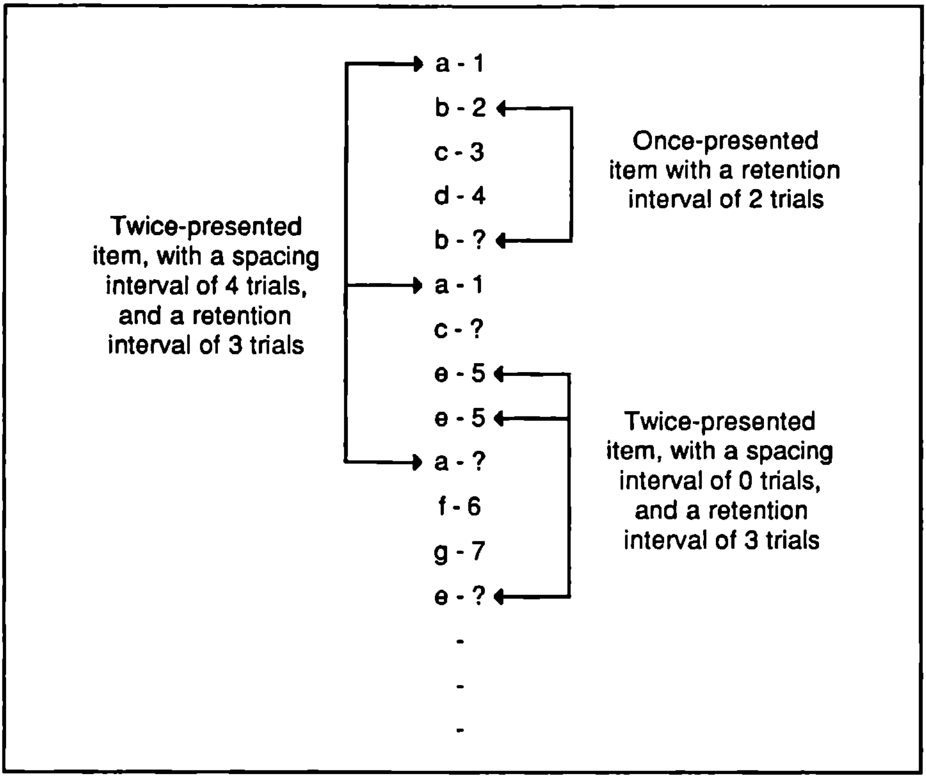

Figure 1.4. Sequence of events in a typical continuous paired-associate task. In the experiments of the one-to-one type used here, to test the model, both the stimulus (indicated by a letter) and the response (indicated by a number) of a pair are words. In the experiment of the many-to-one type every trial in the figure is a combination of an anticipation test and a presentation. The stimuli are letter combinations and the response is one out of three numbers.

response of a pair in the one-to-one type are both words[5] (one stimulus is coupled with only one response). Each word occurred in only one pair and common pre-experimental associations, rhymes, and orthographic similarities were avoided. A stimulus word (in each case the first word of

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[5] To obtain the spacing and repetition effects it is also possible that other stimuli, such as letter combination, nonsense words, number or pictures, are used as stimulus and response.

a pair) presented with a question mark signalled a test. In the second kind of CPA experiment (many-to-one), all trials of the paired-associate are of the anticipation type. An anticipation trial starts with the test of the pair immediately followed by its presentation. In the experiment presented later, the stimulus of the pair is a letter combination and the response is one of three numbers (many stimuli are coupled with one response). A stimulus is, in all presentations, combined with the same response, but the numbers that are used as response can be coupled to more than one stimulus. The subjects were informed which numbers are used as responses. When they did not know the response of a pair they had to guess one of these three numbers.

The SAM model with context fluctuation is elaborated for the following experiments. First, the model will be applied to data where a single presentation is followed by a test after a retention interval filled with presentations and tests of other paired-associates. The general pattern of the experimental results is that an increase in the retention interval

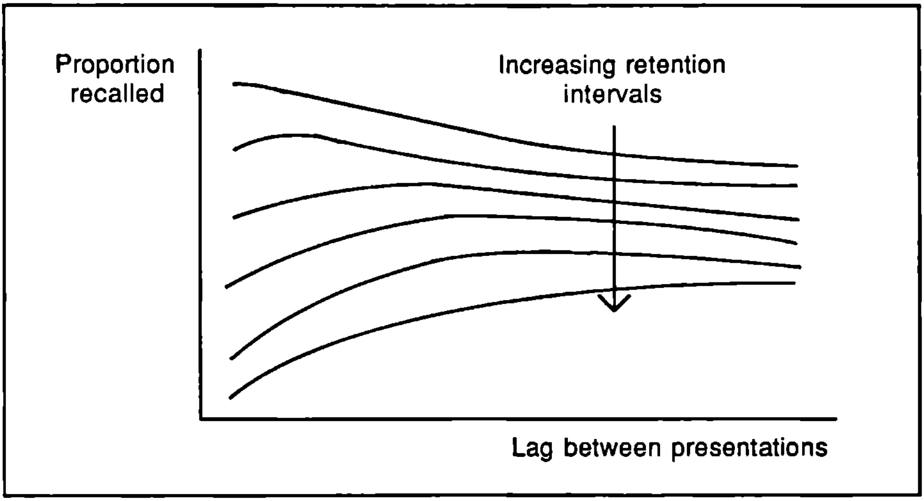

Figure 1.5. The relation between recall probability and lag separating two presentations of an item as a function of the retention interval between the second presentation and test. An idealized family of curves incorporating an absolute superiority of massed practice when testing is almost immediate (Figure 9.11(b) from Crowder, 1976).

leads to a decrease in recall performance (see section 3.1). The most elementary form of the SAM model with context fluctuation as presented in section 2.2 can be used for this kind of experiment.

Secondly, the SAM model with context fluctuation is applied to data where two presentations of the same word pair are followed by a test. Both the spacing interval and the retention interval are filled with trials of presentations or tests of other word pairs. The results of two experiments will be analyzed. One experiment was presented by Glenberg (1976) and the second experiment (experiment I) is designed to replicate the pattern of results of Glenberg's experiment (see sections 3.2 and 3.3). The global pattern of the results of CPA experiments with two presentations followed by a test is summarized by Crowder (1976) in a figure (see figure 1.5). For short retention intervals the curves are non-monotonic functions of the spacing interval: an initial increase in performance is followed by a later decrease. Increasing the retention interval the later decrease changes slowly into an increase. Long retention intervals give a monotonically increasing (negatively accelerated) lag effect with increasing spacing interval. The precise details of the SAM model for two presentations followed by a test are presented in section 2.3.

Thirdly, the SAM model with context fluctuation is applied to the results of an experiment of Rumelhart (1967). In that experiment the presentation of the stimulus-response pair (S-R-pair) is always preceded by its test, and the anticipation method is used. The inter-trial interval (between the trials of the same S-R-pair) is filled with trials of other S-R-pairs. Each S-R-pair is tested and presented six times. The subject can only guess the correct response in the first trial, because the first presentation is after the first test. After the last presentation (the sixth) the S-R-pair is not tested any more. Therefore, only five presentations of each S-R-pair, that are followed by a test, can be distinguished. The inter-trial interval is called lag by Rumelhart (1967) and is given as the number of trials of other S-R-pairs in that interval. Eight different lag combinations were used. One important trend in the learning curves is that the immediately preceding lag strongly determines the probability of a correct answer on any given trial. If the lag is long, the probability of a correct answer will be low, if it is short, the probability of a correct answer will be high (see section 3.4 for more detail). The version of the SAM model for this experimental paradigm is presented in section 2.4.

Finally, the SAM model with context fluctuation is applied to experiment II, which was designed in order to replicate some findings of Ross and Landauer (1978) for a CPA design. Two conditions are combined in one experiment. In the one-stimulus-twice condition a word pair is presented twice followed by a test. In the two-stimuli-once condition two different word pairs are presented with an inter-presentation interval equal to the spacing interval in the one-stimulus-twice condition, and both word pairs are tested after the presentation of the second word pair. The interval between the presentation of the second word pair and the test is equal to the retention interval in case of one-stimulus-twice. For repeated word pairs a spacing effect is observed, and for different stimuli tested with the same spacing and retention intervals no spacing effect is observed (see section 3.5). The model is adjusted to test the conclusion of Ross and Landauer (1978) that a model based on variable encoding cannot correctly predict the probability of a correct answer to at least one of two spaced events (see section 2.5 and chapter 8 for more details).

The fluctuation of context elements affects the storage and so the retrieval of information in a way similar to variable encoding. Therefore, in the SAM models presented in chapter 2 the principles of a rehearsal model and of a model with variable encoding are combined. The SAM model is worked out to account for the results of continuous paired-associate experiments with one and two presentations followed by a test with different spacing and retention intervals. The predictions of the spacing and repetition effects are given in chapter 2. A further elaboration of the SAM model is made for multiple presentations and is worked out to account for the results of a continuous paired-associate experiment with anticipation trials of Rumelhart (1967). In the last section of chapter 2 the model is adjusted to test the conclusion of Ross and Landauer that a model based on variable encoding cannot correctly predict the probability of a correct answer to at least one of two spaced events.

Before we start with the elaborative description of the versions of the SAM model, the methodology of mathematical models will be shortly described in the next section.

1.5. MATHEMATICAL MODELLING

Before we present the SAM models with context fluctuation for multiple presentation in CPA paradigms, we want to discuss some aspects of mathematical modelling, what is involved in constructing a model, and how the model is evaluated[6]. The ultimate goal of most research in experimental psychology is the construction of a general theory about psychological processes. Theories can be expressed as verbal statements. In this case, they are often hard to work with and are not readily subject to exact tests. For the exact representation, necessary for testing, mathematical models are more valuable. Mathematical expressions give a clear and unambiguous formulation of the theory, because the mathematics allows the implications of the theory to be derived in a rigorous manner.

The general SAM theory (Raaijmakers & Shiffrin, 1981a, 1981b) is based on the association theory, and can be seen as an elaboration of the rehearsal buffer theory (Atkinson & Shiffrin, 1968, 1971). The general SAM theory says something about the working of memory in a wide range of situations. But it is nearly impossible for the theory to be both generally applicable, and also specific enough to make unambiguous predictions in specific cases. A completely specified general theory would contain so much detail that it would be hopeless to pin down exactly what the theory does. Too many details founder in a mass of special cases and inconsistencies. Another difficulty concerns making predictions with sufficient precision. If details are only weakly specified, the predictions of the theory are vague and difficult to test exactly. Therefore, the fact that detail is necessary to make exact, testable and useful predictions, is in conflict with the fact that detail is impossible to achieve with high consistency. One solution is to make a general theory that remains broad (as the SAM theory) and to derive more specific models from that general theory for exact predictions in various kind of specific situations[7]. The SAM models for multiple presentations (presented in chapter 2) can be seen as specific cases of the general SAM theory. The SAM models for

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[6] Ideas of Wickens (1982) are used in this section about mathematical modelling.

[7] The term model is used to denote the specific, sometimes limited theories. The term theory denotes the more general theory. Specific SAM models with context fluctuation for multiple presentation are derived from the general SAM theory.

multiple presentations describe the working of the memory in one specific situation (the CPA paradigm), not in others. If the SAM model for multiple presentations proves satisfactory, it provides support for the general SAM theory and its task-related specification.

Because the model makes exact predictions, the rejection of a model must be interpreted with caution. The rejection of the model is the most definite conclusion that can be made. However, a model may easily be wrong in at least some details. It is always necessary to simplify some of the assumptions, in order to derive a tractable model from a general theory. It is always possible to reject a particular model with a sufficiently large group of subjects. A model can fit one set of data nicely, but may fail in slightly different conditions. Hence, the simple statistical testing of a model at a conventional significance level is of little interest in itself. A more useful approach is to look at the way in which a model fits or fails to fit and compare one model to other models.

The logic of the tests of models is formally similar but substantively different from that of conventional statistical testing. Conventional statistical models are models of data, while mathematical models are models representing the psychological processes which generate the data. The statistical models describe what the data look like, while the mathematical models describe the mechanism that underlies the data. The more elaborateness of mathematical models gives them greater power to test psychological theory. The underlying mechanisms described in mathematical models are not directly observable. This can be a problem in the evaluation of the correctness of the model.

The predictions that can be made from these more specific models depend on the numerical values of one or more parameters. Values must be assigned to these parameters in order to tie it to an actual experiment. Things are very simple when the values can be assigned a priori by a logical analysis of the experimental conditions, but, in many cases, the values must be estimated from the data before one can test if the data exhibit the structure predicted by the model.

No set of data will ever be in perfect agreement with a model. The discrepancies of the model and the data are investigated with statistical testing. When the discrepancy is large the model might be rejected. To evaluate how well the model fits two questions can be asked. The first is whether the deviation of the data from the model is greater than that that can be attributed to chance fluctuation. No model is perfect, but given a statistical test of sufficient power this will rarely be the case. The second and often more important question is whether modification of a model leads to improvement.

A model can be set up for any theory and its parameters can be estimated. The fit tells us how well the theory works and the relative impact of sub-processes is indicated by the value of the pertinent parameters. Unfortunately, not every question about a model can be answered by fitting it to the data. It is also, sometimes impossible, to discriminate pairs of models from each other just by fitting. When two different models make precisely identical predictions, there is no way to choose between the models on this basis. These models are *not identifiably different*. Other models that are not confounded are said to be *identiable*.

Problems also arise when parameters whose presence in a model is quite reasonable in terms of psychological assumptions of the model, are *unestimable* or *unidentifiable*. It is then necessary to analyze the mathematical structure of the model in greater depth. Problems with model identification and with the estimation of parameters can sometimes be attributed to the data that are analyzed. In these cases, the problem is that the data are not sufficiently detailed to make necessary tests. The data contain insufficient or no information about the question of interest. In this sense, the problem can only be solved with a qualitatively different type of data.

In chapter 4 of this paper problems with the identification of the parameters of the model are discussed. It is shown that only a limited number of parameters can be estimated from the data. The values of the other parameters must be obtained from other applications of the SAM theory, but that gives a problem (see later). It is also shown that the relative impact of the sub-processes can be influenced by the set of parameter values used, without influencing the goodness of fit. A procedure for further application of the models is described. With simple additional assumptions, specific for this CPA paradigm, the SAM models described in chapter 2 can be further simplified. These assumptions are in terms of the model. In one case, it is assumed that sampling is always successful, while in the other case, recovery is assumed to be always successful. Mensink (1986) has proved that both sampling and recovery must be included in the general SAM theory. Both processes are necessary to explain some aspects of interference phenomena. However, it is possible, that in case of multiple presentations in CPA paradigms, sampling alone or recovery alone is enough to predict the data.

In all applications of the SAM model presented so far the time-dependent changes in sampling and recovery are due to context fluctuation incorporated in the model by means of the context strength. A difficulty with context fluctuation is that it is not possible to measure context changes because there is no empirically identifiable definition of context. The context strength can also therefore be seen as a decay function. In chapter 9 the characteristics of context fluctuation are presented, followed by a critical description of an alternative decay function.

At the end of this introduction we want to make some remarks about the psychological reality and the psychological plausibility in relation to mathematical models. The psychological interpretation of a mathematical model will be in terms of statements about data. Data as implied by the model are compared to observed data. A model is the formal representation of the theoretically assumed processes that lead to the phenomena. These processes are essentially unobservable, and all we can say about them is in terms of the formal representation of the theory, if it fits the data. Psychological plausibility refers to implications (or consequences) of the model about the observed data in terms of predictions and observations. All effects worked out in this paper will be model-effects.

2. THE SAM MODEL ELABORATED FOR MULTIPLE PRESENTATIONS

In this chapter, the SAM theory (Raaijmakers and Shiffrin, 1980, 1981a) is elaborated to explain the effects of spacing of multiple presentations (and related phenomena) in various CPA paradigms. The specific models may be viewed as mathematical formalizations of Glenberg's theory, although they do not incorporate all aspects of that theory. All specific models incorporate a model for context fluctuation developed by Mensink and Raaijmakers (1988, 1989; see also Mensink, 1986) to account for time-dependent changes in context associative strengths. In order to explain repetition effects we will make use of the concept of context fluctuation in modelling the enrichment or strengthening of the memory trace on successive presentations.

In the first section, a brief review of the relevant aspects of the SAM theory (as presented in section 1.3) will be given. The notation will be adjusted to multiple presentations. In the second section, the model is worked out for a single presentation followed by a test. In the third section, the model is elaborated for two presentations followed by a test. The model is worked out to explain the spacing effect (see sections 1.1 and 1.4). In the fourth section, the model is worked out for the data of an experiment designed by Rumelhart (1967). In Rumelhart's experiment five presentations of a particular paired-associate are tested. In the fifth and last section the model is adjusted to test the conclusion of Ross and Landauer (1978) that a model based on variable encoding cannot correctly predict the probability of a correct answer to at least one of two spaced events. A number of details will be discussed in later chapters when we present specific experimental results to test the goodness of fit of the model.

2.1. THE SAM THEORY WITH CONTEXT FLUCTUATION

In section 1.3 of the introduction the SAM theory was presented. In the present section we will shortly review those aspects and formulas of the

SAM theory which are relevant for multiple presentations in the CPA paradigm. The notation is adjusted for multiple presentations. For all formulae there will be a reference to the formula from which it is derived. Further, a review of the inter-presentation and retention intervals (or lags in case of Rumelhart's experiment) is given.

In SAM, the retrieval of information is a two-stage process of sampling and recovery. The first item of a pair and the context at the moment of testing are used as retrieval cues. These retrieval cues are used in the sampling stage to select an image (trace) in memory as a candidate for recall. For recognition the context and both items of the pair are used. The selection of cues is to a large extent a strategy-dependent process. The search process itself is an automatic process. The retrieval cues will activate a number of different images that all have some aspects in common with these cues. The probability of sampling a particular image of a paired-associate ($P_{SAM}(t)$; equation 1.11) t seconds after its presentation is a function of the associative strength between the cues used and that image, relative to other images, and is given by:

$$P_{SAM}(t) = \frac{I(t)\ C(t)}{I(t)\ C(t) + Z},$$

in which $I(t)$ is the inter-item associative strength, $C(t)$ is the context (associative) strength and Z is the residual strength of other images retrieved by the cues.

Sampling of an image is not sufficient for successful reproduction. For example, in recall tasks sufficient information must be activated from the image to enable the reconstruction of the name of the item on the basis of the encoded information. This process is termed *recovery*. The probability of recovery ($P_{REC}(t|\theta)$; equation 1.12) is given by:

$$P_{REC}(t|\theta) = 1 - e^{-\theta\,(I(t) + C(t))}.$$

It is to be expected that θ will have a different value in the case of recall as compared to the case of recognition. Both processes occur in the models. Therefore, two parameters θ_1 and θ_2 will be used. θ_1 will be substituted for θ in equation 1.12 in the case of recognition and θ_2 for recall. As a recognition response is assumed to require a smaller amount of activated information than is needed for the more difficult recall response, it is expected that $\theta_2 < \theta_1$.

If either sampling or recovery fails (i.e. does not lead to a correct response), a new retrieval attempt may be made. The whole search process consists of a number of such retrieval attempts, each consisting of sampling and recovery. In the cued recall tasks that we consider, the search is terminated either when the pair (image) is recognized or recalled or when a fixed criterion number of failures (unsuccessful retrieval attempts) is reached. One restriction that should be mentioned is that successive recovery attempts of the same image are not independent. It is assumed that if the first attempt at recovery has failed, subsequent recovery attempts on the same test trial using the same retrieval cues will also fail.

We assume that the search continues until a criterion number of L_{max} failures is reached, so the probability of retrieval ($P_{RET}(t|\theta)$; equation 1.13) after L_{max} search cycles is:

$$P_{RET}(t|\theta) = \{1 - (1 - P_{SAM}(t))^{L_{max}}\} P_{REC}(t|\theta).$$

In SAM a correct response is given when the pair is retrieved through sampling and recovery from the long-term store, but also when the pair is still in the STS. The probability of still being present in the STS ($P_{STS}(t)$; equation 1.14) t seconds after the last presentation is given by:

$$P_{STS}(t) = e^{-\lambda t},$$

where λ stands for the rate with which pairs decay from the STS.

The procedure which is assumed to occur at a specific presentation or test (e.g. the mth presentation or test) is depicted in figure 2.1. First, it is checked if the pair is still in the STS. In that case the pair is recognized or a correct response is given (recall). Secondly, when the pair is not present in the STS, the retrieval process with sampling and recovery is started. When the pair is retrieved (sampled and recovered) from long-term memory (long-term store or LTS) the pair is also recognized or recalled. When the pair is recognized or the correct response is given after recognition or recall respectively, additional information is added to the

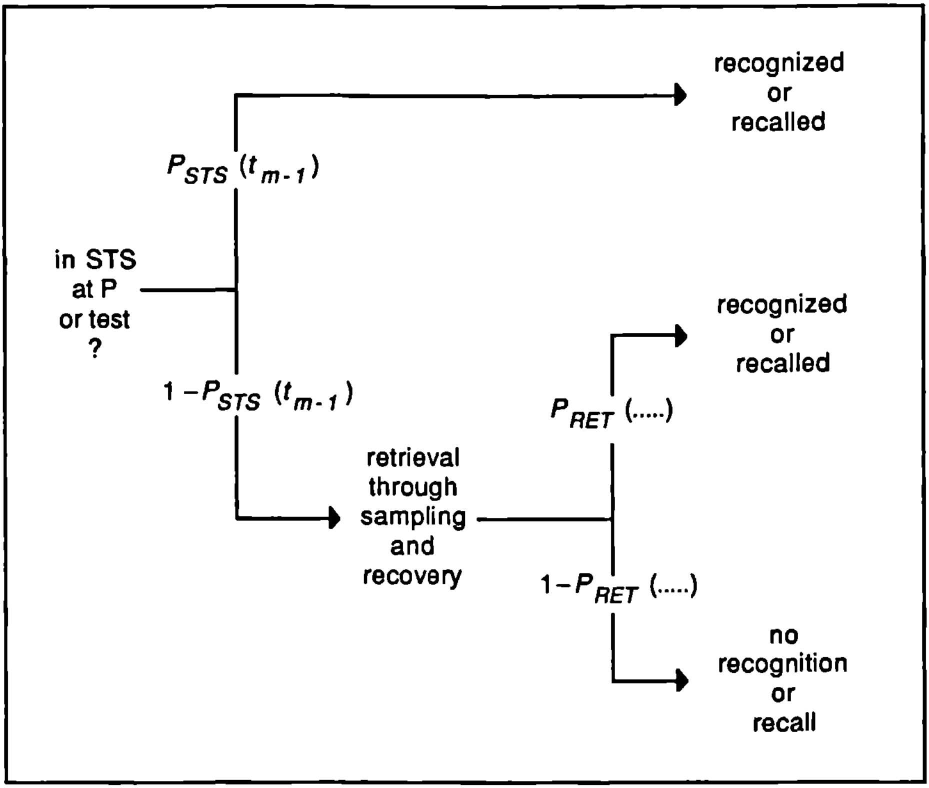

Figure 2.1. Trace depicting the recall or recognition at the mth presentation or test. The pair is recognized or recalled when it is still in STS or when it is retrieved (sampled and recovered) from LTS after leaving STS.

existing trace. The associative strengths are incremented. If the pair is not in the STS and also not retrieved from memory, the pair will not be recognized or no correct response will be given. In that case, we assume that a new trace is formed.

In case of multiple presentations, the probability of retrieval depends on the number of previous presentations and also on the spacings of these presentations. In figure 2.2 an overview is given of the inter-presentation (or spacing) and the retention intervals (or lags in case of Rumelhart's

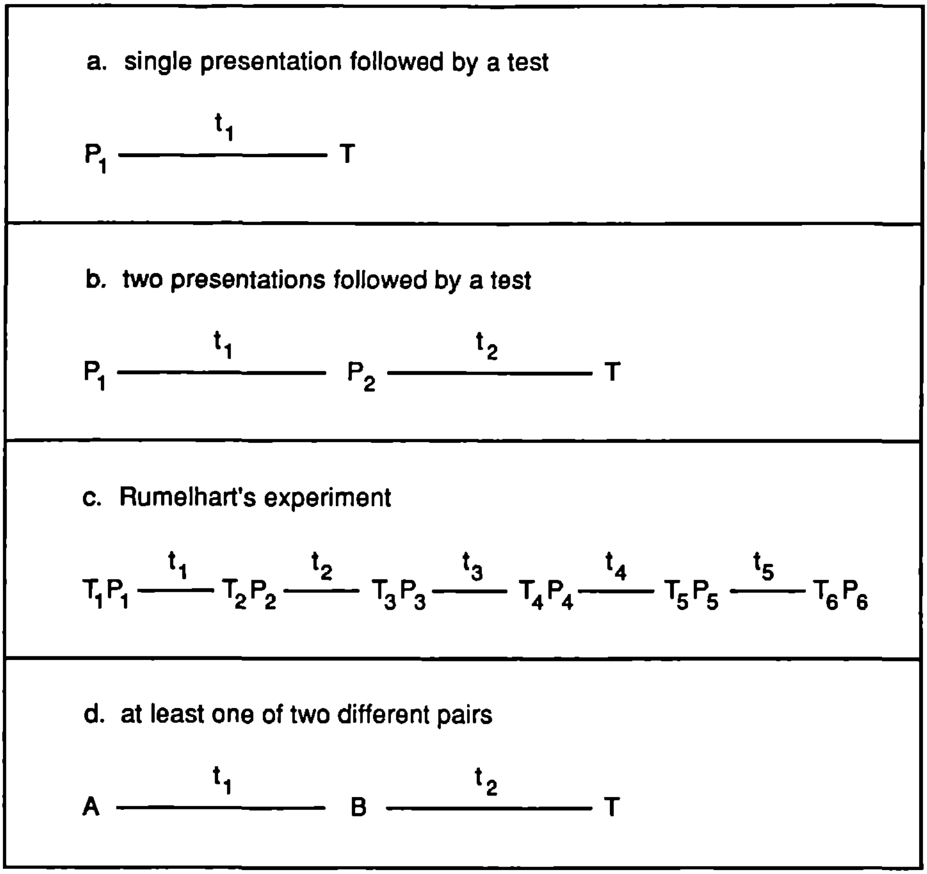

Figure 2.2. An overview of the inter-presentation and retention intervals and the relations between presentations and tests, that are used in the CPA experiment presented in chapter 3.
(a) A single presentation is tested after a retention interval t_1.
(b) Two presentations with a spacing interval t_1 are tested after a retention interval t_2.
(c) Every presentation of the pair is preceded by a test, and the i^{th} trial (i^{th} test and i^{th} presentation) is tested in the $i+1^{th}$ trial after lag (or inter-trial interval) t_i.
(d) Two different paired-associates (A and B) are separated by a spacing interval t_1, and both pairs are tested after the presentation of the second pair. The interval (t_2) between the presentation of the second pair and the test is called the retention interval.

experiment) in the CPA experiments (presented in chapter 3), that are used to test the specific models.

Before we explain the relation of the probability of retrieval with the number of presentations and the spacings between these presentations, we will describe the assumptions that are made for multiple presentations. We assume that at the first presentation a trace or image is stored in LTS. Inter-item associative (information on which the inter-item associative strength is based, see section 1.3.1) and context information is stored. At a second presentation of this pair, the pair is recognized or recalled when the pair is still present in the STS or when the pair is retrieved from long-term memory. After successful recognition or recall the information in the LTS is enriched with additional information, both the inter-item associative and the context strength are incremented (see later). When a pair is not recognized or recalled, we assume that a new image is formed, and further, that it is not possible to retrieve that old image from memory in the future. For subsequent presentations the same procedure as for the second presentation is assumed to take place. That is, the pair is recognized when it is still in the STS or when it is retrieved from LTS. The traces that can be retrieved from LTS, for example at the fourth presentation or test, can be formed in different ways. First, the trace can be formed at the first presentation and incremented with information on the second and the third presentation. Secondly, the trace can be formed at the second presentation (the trace is not recognized or recalled at the second presentation) and at the third presentation additional information is stored. The last possibility is that the trace is just formed at the third presentation (that is not recognized or recalled at the third presentation). We will denote the presentation after which the pair is always recognized or recalled, as the ith presentation (P_i) and the last presentation before the moment of test as the mth presentation (P_m). The probabilities of sampling, recovery and retrieval of a pair (derived from equations 1.11, 1.12 and 1.13 respectively) that is stored at the ith presentation and retrieved after the mth presentation are respectively written as:

$$P_{SAM}(t_i,\ldots,t_m) = \frac{I(t_i,\ldots,t_m)\; C(t_i,\ldots,t_m)}{I(t_i,\ldots,t_m)\; C(t_i,\ldots,t_m) + Z}, \tag{2.1}$$

$$P_{REC}(t_i,\ldots,t_m|\theta) = 1 - e^{-\theta\,(I(t_i,\ldots,t_m) + C(t_i,\ldots,t_m))}, \tag{2.2}$$

and

$$P_{RET}(t_i,\ldots,t_m|\theta) = \{1 - (1 - P_{SAM}(t_i,\ldots,t_m))^{L_{max}}\}\, P_{REC}(t_i,\ldots,t_m|\theta). \tag{2.3}$$

Where $|\theta$ indicates whether the recovery and the retrieval of a pair is in the form of recognition or recall. θ_1 and θ_2, respectively, are to be substituted for recognition and recall. When the ith presentation is the same as the mth presentation ($i = m$), that is, only one presentation is stored and can be retrieved, (t_i,t_m) is written as (t_m). The probability of still being present in the STS depends only on the interval between the last (mth) presentation and the test. We assume that the decay in STS starts again at every presentation of the pair. The probability of still being in the STS (derived from equation 1.14) after the mth presentation is therefore:

$$P_{STS}(t_m) = e^{-\lambda t_m}. \tag{2.4}$$

In figure 2.1 the recall or recognition procedure at the mth presentation was shown. A pair is recognized or recalled when it is still in the STS or when the image is retrieved from LTS. The probability of recognition or recall (of an image from at the ith presentation and enriched until the mth presentation) at the m+1th presentation or test is a conditional probability. That conditional probability (P_R) is given by:

$$P_R(t_i,\ldots,t_m|\theta) = P_{STS}(t_m) + (1 - P_{STS}(t_m))\, P_{RET}(t_i,\ldots,t_m|\theta). \tag{2.5}$$

In case of recognition P_R will be written as P_{RG} and θ as θ_1, and in case of recall P_R will be written as P_{RL} and θ as θ_2.

As mentioned above, both sampling and recovery are functions of the inter-item associative and the context associative strength between the cues and the image. We assume in this paper that the inter-item associative strength is a function of the number of presentations adding information to the retrieved image (see also section 1.3.1). This strength does not depend on the inter-presentation intervals or lags. The inter-item associative strength is given by:

$$I(t_i,\ldots,t_m) = \mathrm{F}(i,m)\, b, \tag{2.6}$$

where b is the inter-item associative strength after a single presentation, and $\mathrm{F}(i,m)$ is a function of the number of presentations that add information to the trace (this number is: $m-i+1$). Although it might be assumed that $\mathrm{F}(i,m)$ is some function of i and m with estimable parameters (e.g. $\mathrm{F}(i,m) = (m-i+1)^{\alpha}$), we will, in most cases, assume that $\mathrm{F}(i,m) = m-i+1$ (the exception is our analysis of Rumelhart's data, see chapter 7).

The context fluctuation model (as presented in section 1.3.1) is used to estimate the context associative strength. A short overview of the most important equations will be presented in this section (see section 1.3.1 for more details). The intervals between the parentheses are specific for multiple presentations. It is assumed, that the context strength $C(t_i,\ldots,t_m)$ is proportional to the overlap $O(t_i,\ldots,t_m)$ at the appropriate event and parameter a is used as a scale parameter. The context strength (derived from equation 1.1) is:

$$C(t_i,\ldots,t_m) = a\, O(t_i,\ldots,t_m). \tag{2.7}$$

The overlap of all stored context elements in a particular image (in this case, the image is formed at the i$^{\text{th}}$ presentation and at every successive presentation additional information is added to the trace until the last (m$^{\text{th}}$) presentation) and the context elements active at the moment of test (derived from equation 1.10) is given by:

$$O(t_i,\ldots,t_m) = A(t_i,\ldots,t_{m-1},0)\, \mathrm{e}^{-\alpha t_m} + K(t_i,\ldots,t_{m-1},0)\, s\, (1 - \mathrm{e}^{-\alpha t_m}) \tag{2.8}$$

where s stands for the equilibrium value of the proportion of elements that is active, and α is the parameter that gives the rate of fluctuation between the active and the non-active states. The proportion of stored elements ($A(t_i,\ldots,t_{m-1},0)$) that are active at the last (m$^{\text{th}}$) presentation (derived from equation 1.8) is given by:

$$A(t_i,\ldots,t_{m-1},0) \;=\; O(t_i,\ldots,t_{m-1}) + w\,(s - O(t_i,\ldots,t_{m-1})), \tag{2.9}$$

and the proportion of all stored elements ($K(t_i,\ldots,t_{m-1})$), both active and non-active, at the last (m^{th}) presentation (derived from equation 1.9) is given by:

$$K(t_i,\ldots,t_{m-1},0) \;=\; K(t_i,\ldots,t_{m-2},0) + w\,(s - O(t_i,\ldots,t_{m-1})). \tag{2.10}$$

The state at time $t_i = 0$ (equation 1.3) is:

$$K(0) \;=\; A(0) \;=\; w\,s, \tag{2.11}$$

where w is the probability of encoding an active element.

All estimations of the associative strengths that are used in the following sections can be derived from the preceding formulae (2.6 to 2.11). All probabilities (of sampling, recovery, retrieval and recall or recognition) can be derived from formulae 2.1 to 2.5. In the next section we will present the model for a single presentation followed by a test in a CPA paradigm.

2.2. THE SAM MODEL FOR STIMULI PRESENTED ONCE

A model, elaborated for multiple presentations in the CPA paradigm, must also be able to explain the result of single presentations in the CPA paradigm (see figure 2.2a). For single presentations a decrease in performance (recognition or recall) to an asymptotic level is found when the retention interval is increased (see section 3.1, and also section 3.2 and 3.3). For once-presented stimuli, the most elementary form of the model can be used. The pair is stored at the presentation and the second word of the pair must be recalled at test. The recall of the second word of the pair is a process with two steps, as depicted in figure 2.1. The second word is recalled when the pair is still in the STS, or when the image is retrieved from LTS if it is not in STS. The probability of recalling the second word from STS or LTS is given in equation 2.5 and is in this case:

$$P_{RL}(t_1|\theta_2) \;=\; P_{STS}(t_1) + (1 - P_{STS}(t_1))\,P_{RET}(t_1|\theta_2). \tag{2.12}$$

All probabilities and strengths that are necessary to estimate the probability in equation 2.12 can easily be derived from equations 2.1 to 2.4 and 2.6 to 2.11. The final probability of a correct response ($P_{CA}(t_I)$) for a single presentation followed by a test is equal to the probability of recall of the second word of the pair given in equation 2.12. The probability of a correct answer for a single presentation followed by a test is:

$$\begin{aligned} P_{CA}(t_I) &= P_{RL}(t_I|\theta_2) \\ &= P_{STS}(t_I) + (1 - P_{STS}(t_I))\, P_{RET}(t_I|\theta_2). \end{aligned} \qquad (2.13)$$

In section 1.3.2 it was mentioned that we assume that the decay from the STS is a very rapid process. The pairs stay only for a short time in the STS. The data (see section 3.1) that are used to test the model, all have relatively long retention intervals. The retention intervals are larger than 25 events (other presentations or tests). We can assume that for these specific data the pair always has left the STS when it is tested, therefore $P_{STS}(t_I) = 0$. The probability of a correct answer for single presentations tested after long retention intervals is then:

$$P_{CA}(t_I) = P_{RET}(t_I|\theta_2). \qquad (2.14)$$

Equation 2.14 will be used in chapter 5 to test the model to the data.

As will be shown in chapter 4 only a limited number of the parameters can be estimated from the data. Further, we will show that the relative importance of the sub-processes, sampling and recovery, can be influenced by the set of parameter values used, without influencing the goodness of fit. Two simplified models will also be tested in chapter 5 and their fit will be compared with the model presented above. These simplified models can be obtained from the model presented in this section by the following assumptions. For the first simplified model, it is assumed that the sampling process is always successful. The assumption for the second model is that the recovery process is always successful. In the next section the specific model for two presentation of a pair followed by a test is presented.

2.3. THE SAM MODEL FOR STIMULI PRESENTED TWICE

The SAM model for two presentations of the same pair followed by a test is presented in this section. Figure 2.2b showed the structure of the CPA experiment for one pair presented twice. We assume that the correct answer for two presentations followed by a test is a two-step process. The first process is the recognition of the trace at P_2, the second process is the recall at time of testing.

At P_1, a proportion of the active context elements is stored in the episodic image (for the context associative strength), together with information concerning the two words of the pair and their mutual association (for the inter-item associative strength). What happens on P_2 depends on whether or not the memory trace stored at the P_1 is recognized on the second presentation. In accordance with conventional terminology, we will use the term *recognition* to denote the (implicit) recognition of the old trace[1]. The pair will be recognized at the second presentation either when the pair is still in the STS or through retrieval from LTS when the pair is not in the STS. The probability of recognition ($P_{RG}(t_l|\theta_1)$; equation 2.5) at the second presentation, either from STS or from LTS is:

$$P_{RG}(t_l|\theta_1) = P_{STS}(t_l) + \{1 - P_{STS}(t_l)\}\, P_{RET}(t_l|\theta_1). \qquad (2.15)$$

All probabilities and strengths that are necessary to estimate the probability of recognition in equation 2.15 can be easily derived from equations 2.1 to 2.4 and 2.6 to 2.11.

We assume that the trace formed at P_1 is incremented at P_2 if the pair is recognized. Further, we assume that when the pair is not recognized, a new trace is formed at P_2. After successful recognition additional information is added to the trace. In section 2.1, it is explained how we assume that the inter-item associative strength is incremented. After recognition the inter-item associative strength is doubled at the second presentation. The context strength is also incremented. The context

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[1] This recognition probability cannot be observed in CPA experiments which always test only recall.

strength after two presentations can be estimated with equations 2.7 to 2.11.

Because the inter-item and the context strengths are incremented after successful recognition, the memory trace of a repeated and recognized item will be stronger than the trace of an item presented once. Always a constant proportion of the context elements is active. After a short interval between two presentations the proportion of elements active at both P_1 and P_2 is greater than after a longer interval, therefore the proportion of elements active at P_2 but not at P_1 will be smaller. The larger the interval between the two presentations, the stronger the memory trace, i.e. the greater the total number of context elements encoded in the trace or the more increment in context strength will follow (provided that the item is recognized at the second presentation). The inter-item associative strength is also greater for repeated and recognized items. The higher the strengths the greater the probability of a correct answer.

The correct response will be given at the test when either the recognized and strengthened trace (formed at P_1) is recalled, or when the new trace (formed at P_2) is recalled. The original and enriched image is recalled when the pair is still in the STS or when the pair is retrieved from LTS. The probability of recall of the original and enriched trace at test ($P_{RL}(t_1,t_2|\theta_2)$; equation 2.5), that is, after retrieving the trace from STS or LTS, will be:

$$P_{RL}(t_1,t_2|\theta_2) = P_{STS}(t_2) + \{1 - P_{STS}(t_2)\}\, P_{RET}(t_1,t_2|\theta_2). \tag{2.16}$$

As described above, a correct response can also be given when the new trace formed at P_2 is recalled. The new trace is recalled when the pair is still in the STS after P_2 or through retrieval from LTS when the pair has left the STS. The probability of recall of the new trace at test ($P_{RL}(t_2|\theta_2)$; equation 2.5), that is, after retrieving the trace from STS or LTS, will be:

$$P_{RL}(t_2|\theta_2) = P_{STS}(t_2) + \{1 - P_{STS}(t_2)\}\, P_{RET}(t_2|\theta_2). \tag{2.17}$$

In the case that recognition is not successful we assume that at the moment of testing only the newly formed trace can be retrieved from memory. Due to the variable context the similarity between the cues at

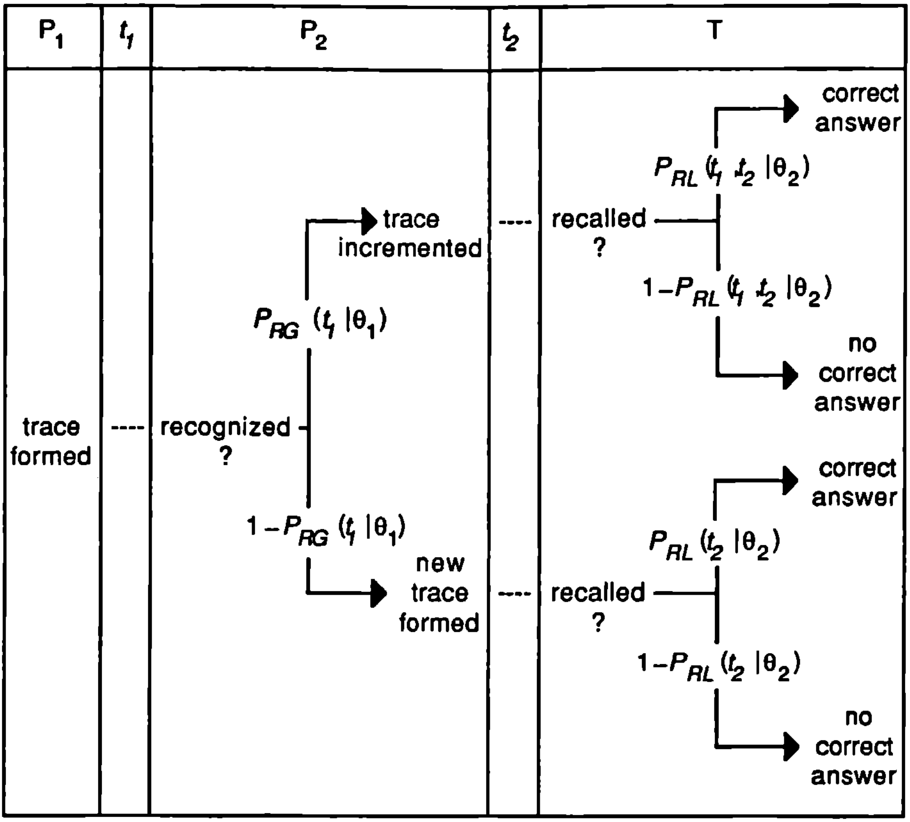

Figure 2.3. The trace depicting the various paths to arrive at the correct answer for an item presented twice before testing. A trace is formed at P_1. When the trace is recognized at P_2 the trace is enriched, but when the trace is not recognized at P_2 a new trace is formed. At test a correct answer is given when either the enriched trace or the new trace is recalled from STS or LTS.

test and the stored image decreases as the interval between storage and test increases. If recognition fails at the second presentation, the similarity between the cues at test and the stored image is small. At the time of testing, the similarity of the cues at test and the stored image of the originally formed trace is still smaller, because the interval is greater[2]. The probability of retrieving the trace of the first presentation at time of testing is smaller than at time of the second presentation. The probability of recall of the originally formed trace at test is smaller than the probability of recognition of the item at the second presentation, because (a) the probability of recall is always smaller than that of recognition, and (b) the similarity of the cues at test and the stored image of the originally formed trace is still smaller. We assume that the trace formed originally can never be retrieved again after a recognition failure.

The model allows us to predict the probability of a correct answer for two presentations followed by a test for every spacing and retention combination. This probability is a combination (weighted sum) of a number of paths to arrive at the correct answer (see figure 2.3). When the pair is recognized at P_2 the enriched trace can be recalled at T, when the pair is not recognized at P_2 the new trace formed at P_2 can be recalled at T. The probability of a correct answer $P_{CA}(t_1,t_2)$ for two presentations followed by a test, is as follows:

$$P_{CA}(t_1,t_2) = P_{RG}(t_1|\theta_1)\, P_{RL}(t_1,t_2|\theta_2) + \{1 - P_{RG}(t_1|\theta_1)\}\, P_{RL}(t_2|\theta_2), \tag{2.18}$$

where P_{RG} and P_{RL} are conditional probabilities that can be estimated from equations 2.15 to 2.17.

The spacing effect found with repetitions (see figure 2.4 and also figure 1.5) shows that the probability of a correct answer decreases with increasing spacing intervals for small retention intervals and increases with increasing spacing intervals for large retention intervals. This interaction is predicted by the presented SAM model elaborated with

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[2] If recognition fails after a spacing interval t_1, there is little similarity between the cues at test and the stored image formed at P_1. The influence of the spacing interval on the probability of retrieval is only through the context strength. The context strength is low when the image is not recognized. When the spacing interval is increased the context strength will be still smaller, and so the probability of recall will also be smaller. The probability of retrieval of the original trace (formed at P_1 but not recognized at P_2) at the moment of testing after a spacing and a retention interval (that is after an interval of $t_1 + t_2$) is still smaller than the probability of retrieval at P_2, because of the elapsed time ($t_1 + t_2 > t_1$). The context strength is smaller after an interval of $t_1 + t_2$ than after an interval of t_1.

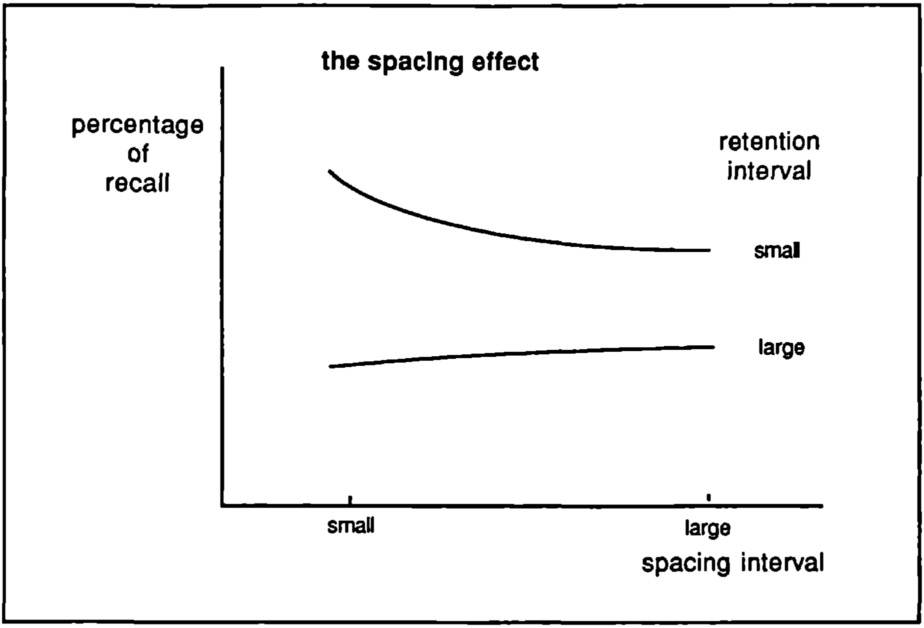

Figure 2.4. The spacing effect, for stimuli presented twice followed by a test. The form of the curves in this figure is obtained from a series of experiments presented by Peterson e.a. (Peterson, e.a., 1962a, 1962b, and 1963).

context fluctuation. In chapter 9 more detailed characteristics of the context fluctuation model are described and shown in figure 9.3. The overlap of active context elements at testing with the stored context elements after two presentations as shown in figure 9.3b has the same pattern as the curves in figure 2.4. In the case of a large retention interval, it is important that many context elements have been stored, in order to recall the item. This can certainly be the case if the trace corresponds to two presentations with a long spacing interval. For small retention intervals the situation is different, because of the high similarity between the contexts at P_2 and T. In that case, a small spacing interval will increase the similarity between storage and test, and hence also the probability of a correct answer.

Equation 2.18 will be used in chapter 6 to test the model to the data. As mentioned before only a limited number of the parameters can be estimated from the data, and the relative importance of sampling and recovery is difficult to determine. Further, it will be shown in chapter 4, that recognition can be eliminated from the model without affecting the goodness of fit. A number of simplified models will therefore be tested in chapter 6 and their fit compared to the model presented above. These simplified models can be obtained from the model presented in this section by one or a combination of the following assumptions:

1 Recognition is always successful,
2. The sampling process is always successful,
3. The recovery process is always successful,
4. The pair has always left the STS at either the second presentation or the moment of test.

2.4. THE SAM MODEL FOR STIMULI PRESENTED FIVE TIMES

In a continuous paired-associative experiment of Rumelhart (1967), the stimulus pair is always tested in a so-called anticipation trial just before the presentation. The design of Rumelhart's experiment (relation between presentations, tests and lags) was shown in figure 2.2c. In this experiment a nonsense trigram is paired with one of three numbers. We assume that when the response of a S-R-pair is correctly recalled at the $i+1^{th}$ test, the trace is enriched at the $i+1^{th}$ presentation. Only traces that are correctly recalled are assumed to be incremented. The response of the S-R-pair is correctly recalled when the S-R-pair is still in the STS or when the image is retrieved (sampled and recovered) from LTS after leaving STS. The probability of recall of a S-R-pair (formed at P_i and enriched up to P_m) after lag m at the $m+1^{th}$ trial is given in equation 2.5, and is, in this case:

$$P_{RL}(t_i,\ldots,t_m|\theta_2) = P_{STS}(t_m) + (1 - P_{STS}(t_m))\, P_{RET}(t_i,\ldots,t_m|\theta_2). \qquad (2.19)$$

As mentioned above, the response to a S-R-pair is one of three numbers (known to the subject), therefore another possibility of arriving at the correct answer is by guessing it. There is always one correct answer in three possible responses. The probability of guessing correctly, when

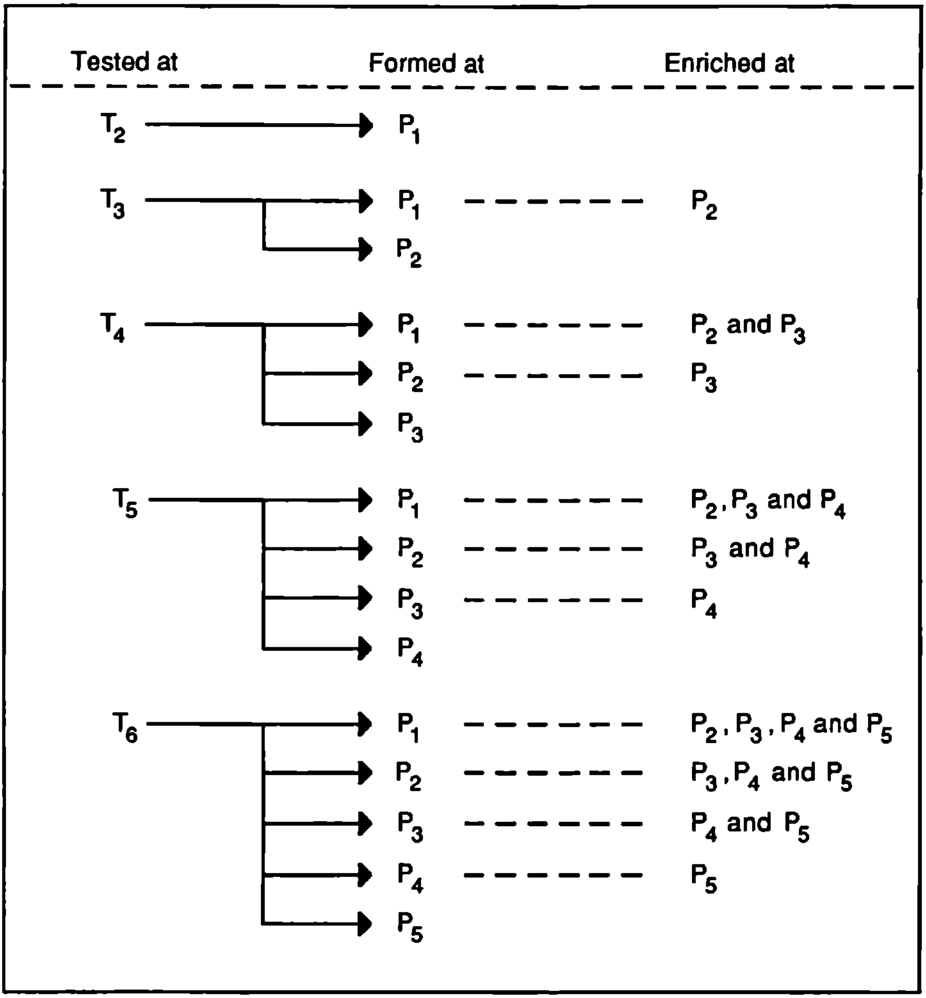

Figure 2.5. For each test the traces are shown that can be retrieved from LTS. These traces may be formed at each presentation, and later presentations before the test add information to the trace.

this is not recalled from STS or LTS, is 1/3. If the correct answer is given through recalling the answer from the memory the strength of the memory trace is incremented. If the answer is incorrect or guessed, a new trace is formed, and we assume that the older trace cannot be retrieved (see also section 2.3).

The probability of a correct recall without guessing at P_n is a sum of all ways to come to a correct recall. A new trace can be formed at every presentation before P_n when the trace is not retrieved, or else the old trace is retrieved and incremented. In figure 2.5, for all relevant tests (tests preceded by a presentation of the tested S-R-pair) all traces that can be retrieved from LTS, are shown. The final probability of recall (P_r) at P_n is dependent upon the recall of the trace at earlier presentations, and is:

$$P_r(t_1,...,t_n)$$
$$= \prod_{i=1}^{n} P_{RL}(t_1,...,t_i|\theta_2) + \sum_{i=1}^{n-1} \{(1-P_r(t_1,..,t_i)) \prod_{m=i+1}^{n} P_{RL}(t_{i+1},..,t_m|\theta_2)\} \tag{2.20}$$

The probability of a correct answer (P_{CA}) at P_n with both recall and guessing, which is used in chapter 7 to fit the data, is:

$$P_{CA}(t_1,...,t_{n-1}) = P_r(t_1,..,t_{n-1}) + \tfrac{1}{3}(1 - P_r(t_1,...,t_{n-1})). \tag{2.21}$$

As previously mentioned, only a limited number of parameters can be estimated from the data, and the relative importance of sampling and recovery can be influenced by the parameter values without affecting the goodness of fit. A number of simplified models will therefore be tested in chapter 7, and their fit compared to the fit of the model presented above. The simplified models can be obtained from the model presented in this section by one or a combination of the following assumptions

1 The pair has always left STS at the next test,
2 Sampling is always successful,
3 Recovery is always successful.

2.5. THE SAM MODEL FOR THE TWO-STIMULI-ONCE CONDITION

The *independence hypothesis*, postulated by Ross and Landauer (1978) explains the spacing effect by a decreasing correlation between the storage of events P_1 and P_2, when the interval between the two presentations increases. Encoding variability and storage locus variability are variants of the independence of presentation theories. Following the *independence theories*, Ross and Landauer argue that the predictions from these theories for two different stimuli presented once (two-stimuli-once condition) must necessarily go in the same direction as the predictions for repeated stimuli (one-stimulus-twice condition). These theories predict that the recall for at least one of two different stimuli, separated by an increasing interval, is better than that for two different stimuli presented close together. In a free recall experiment testing these predictions, Ross and Landauer reported a lag effect[3] for repeated stimuli, but not for the two-stimuli-once condition. They concluded that this fact poses a serious problem for the *independence hypothesis*. However, Ross and Landauer either ignored the possibility of recognition at P_2, or they assumed that a new trace is always formed.

The SAM model elaborated with context fluctuation uses the principles of an encoding variability theory. As an implication of the arguments of Ross and Landauer it would be expected that the SAM model also predicts a spacing or a lag effect for the two-stimuli-once condition just as for the one-stimulus-twice condition. In this section we will briefly show the elaboration of the SAM model to account for the two-stimuli-once condition. We assume data gathered from a continuous paired-associate experiment specially designed to investigate the spacing effects in the two-stimuli-once condition (see section 3.5). The tests of the two stimuli that are coupled in the two-stimuli-once condition, follow each other immediately. At test the second word of a pair must be recalled with the first word and the context as retrieval cues. The recall of each word pair separately is equal to the recall for the stimuli presented once (as presented in section 2.2). The intervals between presentation and test for

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[3] Ross and Landauer (1978) use the term spacing effect instead of lag effect also for free recall experiments.

pair A and pair B were depicted in figure 2.2d. For the first word pair (pair A) that interval is the sum of the spacing and the retention interval ($t_1 + t_2$), and for the second word pair (pair B) that interval is the retention interval (t_2). The probabilities of recalling the second word of pair A or pair B respectively, were given in equation 2.12 and are:

$$\begin{aligned} P_A(t_1+t_2|\theta_2) &= P_{RL}(t_1+t_2|\theta_2) \\ &= P_{STS}(t_1+t_2) + (1 - P_{STS}(t_1+t_2))\, P_{RET}(t_1+t_2|\theta_2), \end{aligned}$$

and

$$\begin{aligned} P_B(t_2|\theta_2) &= P_{RL}(t_2|\theta_2) \\ &= P_{STS}(t_2) + (1 - P_{STS}(t_2))\, P_{RET}(t_2|\theta_2). \end{aligned}$$

We assumed in section 1.3.2 that the decay from STS is a very rapid process. The retention interval, used to test the two-stimuli-once condition, is 25 or 50 events, and therefore relatively long. We assume for the specific data (see section 3.5) to test the model presented in this section (as for the model of once-presented stimuli, presented in section 2.2), that the pair always has left the buffer when it is tested, that is $P_{STS}(t_i) = 0$. The probability of a correct response to the first word pair (P_A) and the probability of a correct response of the second word pair (P_B) can be estimated with equation 2.14 and are respectively:

$$P_A(t_1+t_2|\theta_2) = P_{RET}(t_1+t_2|\theta_2), \tag{2.22}$$

and

$$P_B(t_2|\theta_2) = P_{RET}(t_2|\theta_2). \tag{2.23}$$

A correct answer in the two-stimuli-once condition is given when a correct response is given to both word pairs or to one of the two word pairs. The probability of a correct response to at least one of the two word pairs is given by:

$$P_{CA}(t_1+t_2,t_2|\theta_2) = P_A(t_1+t_2|\theta_2) + P_B(t_2|\theta_2) - P_A(t_1+t_2|\theta_2)\&P_B(t_2|\theta_2). \tag{2.24}$$

Where $P_A(t_1+t_2|\theta_2)\&P_B(t_2|\theta_2)$ is the probability that a correct response is given to both word pairs. When the arguments of Ross and Landauer apply to variable encoding, the probability of a correct response to both word pairs is affected by the similarity of the context, therefore a spacing effect should be predicted. In chapter 8 we will show in detail that in the case of the two-stimuli-once condition no spacing effect is predicted despite the similarity between the contexts of both presentations. Further, we will show that the probability of a correct response to both word pairs given by:

$$P_A(t_1+t_2|\theta_2)\ \&\ P_B(t_2|\theta_2) = P_A(t_1+t_2|\theta_2)\, P_B(t_2|\theta_2) \tag{2.25}$$

gives approximately the same predicted probabilities of a correct answer, as when the context similarity is explicitly taken into account. We will therefore use equations 2.24 and 2.25 to fit the data. In effect we implicitly ignore the influence of the effects of the similarity of the context on the probability of a correct response for both word pairs. We will show in chapter 8, that the SAM theory elaborated with a model for context fluctuation does not predict a spacing effect in case of two-stimuli-once. The arguments of Ross and Landauer, that a variable encoding theory always predicts a spacing effect for two-stimuli-once just as for one-stimulus-twice do not hold for the SAM theory.

Two simplified models will also be tested and their fit will be compared to the model presented above (for the same reasons as mentioned in section 2.2: The limited number of estimable parameters and the instability of the relative importance of sampling and recovery). The simplified models can be obtained from the model presented in this section by the same assumptions as for the model for once-presented stimuli (sampling or recovery is always successful: section 2.2).

3. DESCRIPTION AND RESULTS OF THE EXPERIMENTS

In this chapter we present a description and the results of a number of experiments used to test the different versions of the SAM model introduced in chapter 2. The experiments were briefly described in section 1.4, and now a more detailed description of the design and the experimental results in the form of the percentage correct curves will be given (the analyses of the fit of the models to the data of the experiments are not described in this chapter, but will be presented in chapters 4 to 8).

All experiments are designed as a Continuous Paired-associate (CPA) learning experiment. Two of the presented experiments in this chapter were reported in the literature, and are:

1. A CPA experiment (one-to-one type) of Glenberg (1976). In this experiment two presentations of a word pair were followed by a test. The results of this experiment are used to test the model for two presentations followed by a test, presented in section 2.3.
2. A CPA experiment (many-to-one type) with anticipation trials of Rumelhart (1967). The results of this experiment are used to test the SAM model for stimuli presented five times (presented in section 2.4).

We designed the following three experiments:

1. Experiment I: A CPA experiment (one-to-one type) with two presentations of a word pair followed by a test. This experiment was designed to replicate some findings in the experimental results of Glenberg (1976).
2. Experiment II: A CPA experiment (one-to-one type) to compare the two-stimuli-once to the one-stimulus-twice condition. The two different word pairs (two-stimuli-once) have the same spacing as the repeated word pairs (one-stimulus-twice). Further, the two different word pair are tested after the presentation of the second word pair with the same retention interval as used for the one-stimulus-twice condition. The data to test the SAM model for once-presented stimuli to are extracted from this experiment.
3. Experiment III: A free recall experiment to compare the two-words-once and the one-word-twice conditions.

An overview of the intervals between presentations and/or tests was given in figure 2.2. For the purpose of reporting results, we will use the term "event" to denote presentations and/or tests. The interval between presentation(s) and/or test will likewise be counted by the number of events. Since events have equal duration (except for the experiment of Rumelhart), the time intervals between presentation(s) and/or test are easily derived from the counting of events.

In most of the experiments (reported here) relatively few subjects are used and a great variability in recall performance (percentage correct or recall percentage) of the subjects is found. Consequently, the results show much scatter. An indication of the variability in recall performance of the subjects will be given by reporting the standard deviation of the percentages correct across subjects (only for the experiments I, II and III these are known). As mentioned in section 1.5, when a model is evaluated one of the questions is whether the deviation of the data from the model is greater than can be attributed to chance fluctuation. The discrepancies between the model and the data, when the data show great variability, must be interpreted with great caution. The standard deviation of the mean percentages correct between subjects can give some indications.

In the first section, the data of once-presented word pairs, that are extracted from experiment II (the two-stimuli-once condition), are presented. An experiment of Glenberg (1976) and a replication of the spacing and repetition effects found by Glenberg (experiment I) will also be given. In both experiments two presentations of a word pair are followed by a test. Thirdly, an experiment of Rumelhart is presented for the S-R-pairs with five relevant tests. Next, experiment II, a replication of the Ross and Landauer experiment for paired-associates will be presented. In the last section, the experimental results for the continuous paired-associate experiment will be compared to data of a free recall experiment also designed to observe the effect of the arguments of Ross and Landauer.

3.1. ONCE-PRESENTED WORD PAIRS

From the continuous paired-associate experiment (Experiment II, the two-stimuli-once condition; presented later) some data for once-presented

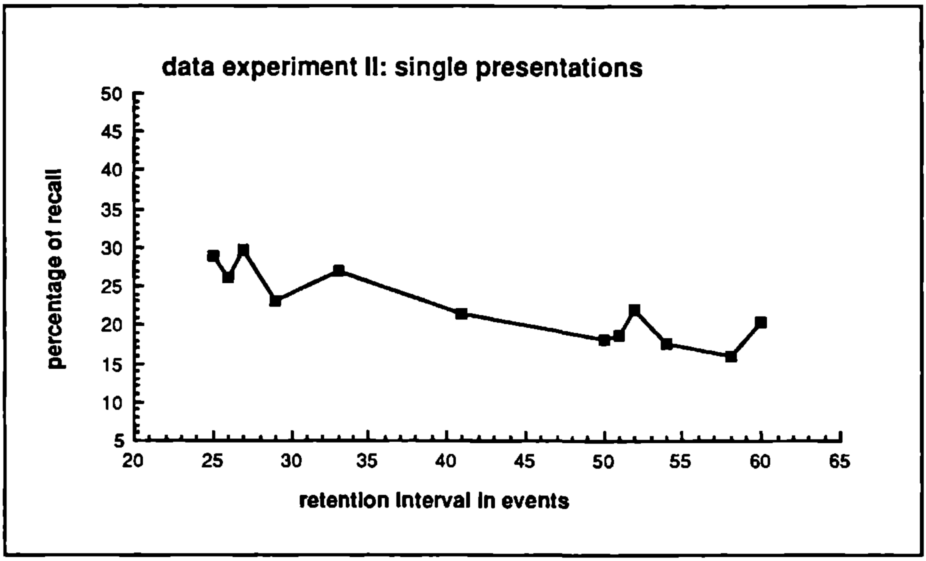

Figure 3.1. Experimental results of experiment II for once-presented word pairs. The recall percentage is given as a function of the retention interval.

word pairs can be extracted. Fifty-seven subjects were presented word pairs (four-, five- and six-letter nouns) that were tested 25, 26, 27, 29, 33, 41, 50, 51, 52, 54, 58 or 66 events after their presentation. Each of these retention interval values occurred five times in the experiment and each event lasted four seconds. The reader is referred to the description of experiment II in section 3.5 for more details about the design.

The results of this part of experiment II are given in Figure 3.1. The results show much scatter due to relatively few subjects and the great variability in recall performance of the subjects. Table 3.1 shows that the standard deviation of the mean percentages correct (across subjects) ranged from 2.5 to 3.5 %. The general pattern of the results is that an increase in retention time leads to an decrease in recall performance toward an asymptotic level of about 17 percent.

Table 3.1. Mean percentage correct and the standard deviation of experiment II for once-presented word pairs.

retention interval (events)	mean percentage correct	standard deviation
25	28.8	3.3
26	26.0	3.5
27	29.8	3.5
29	23.2	3.2
33	27.0	2.5
41	21.4	3.2
50	18.2	2.8
51	18.6	3.0
52	22.1	3.2
54	17.5	2.5
58	16.1	2.4
66	20.4	3.1

3.2. GLENBERG'S EXPERIMENTAL RESULTS (1976)

In the continuous paired-associate experiment of Glenberg (his experiment I, 1976), 108 subjects were presented repeated word pairs (four-letter nouns) with lags of 0, 1, 4, 8, 20 or 40 intervening events and were tested 2, 8, 32 or 64 events after their second presentation. There were five instances of each spacing-retention combination and each event lasted three seconds. The results of this experiment are given in Fig. 3.2. For short retention intervals the curves of the recall percentages are non-monotonic functions of the spacing interval: an initial increase in performance is followed by a later decrease (ignoring the "dip" in the curves for a spacing interval of one event). Longer retention intervals give a monotonically increasing (negatively accelerated) spacing effect with increasing spacing interval.

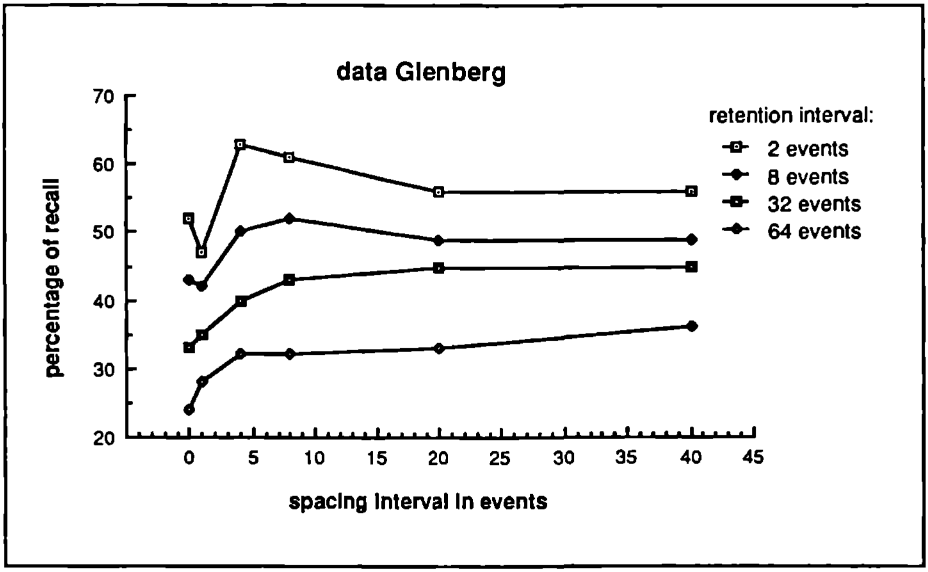

Figure 3.2. Experimental results of experiment I by Glenberg (1976). The relation between the recall percentages and the spacing intervals separating two presentations of a word pair is shown for four retention intervals between the second presentation and the test.

In the data described above a dip is seen in the curves of the recall percentages for short retention intervals and a spacing interval of one event. Glenberg ignored the dip in the discussion of his results, and did not give an explanation for this phenomenon. Since no confidence intervals for the data have been given, no conclusion about the significance of the dip can be made. However, in a theoretical analysis of spacing effects by Reed (1977), the explanation of this dip in the observed data was one of the most crucial aspects. The important question is: How important is the dip? Can it be ignored or is it an essential detail of the spacing effect for small retention times? In order to investigate the importance of the dip and whether it can be replicated, a new experiment was designed.

3.3. CONTINUOUS PAIRED-ASSOCIATE EXPERIMENT I: A "REPLICATION" OF GLENBERG'S EXPERIMENT

In order to investigate whether the dip in the results of the continuous paired-associate experiment of Glenberg (1976) can be replicated, we designed a CPA experiment (Experiment I). Only short retention and spacing intervals were used, because the dip in Glenberg's data was found for short intervals.

3.3.1. Method

3.3.1.1. Subjects

The subjects were 112 students from the University of Nijmegen. Each subject either received Dfl. 8.00 or fulfilled a course requirement for participation in this experiment.

3.3.1.2. Materials and Design

A continuous paired-associate design was used. A scheme with 560 events was designed for the order of the presentations and the tests. The first ten events were warming-up items. Some of the pairs were repeated with 0, 1, 2, 3, 4, or 16 intervening events. They were tested 1, 2, 4, 8 or 16 events after their second presentation. Every spacing-retention interval combination occurred five times. In addition, other pairs were presented only once and also tested after 1, 2, 4, 8 or 16 events (five replications in each condition). Some filler pairs were presented (once or twice) and tested later to make the scheme complete (cf. Appendix A1 for the exact design). These filler pairs will not be used in the presentation of the results. The pairs were composed of common Dutch nouns of four or five letters (cf. Appendix A2 for the word pairs presented). Common pre-experimental associations, rhymes, and orthographic similarities were avoided. For a given subject, each word occurred in only one pair. The order of the presentations and tests was the same for each subject, the assignment of word pairs to the conditions was varied randomly between subjects.

3.3.1.3. Procedure

Four subjects at most were tested at the same time. The subjects were instructed to try to associate the words in a word pair using mental imagery, the construction of a sentence including both words, etc. A practice series of 24 events (18 presentations and six tests) was given, using nouns of four and five letters that were not used in the main series. Next, the main series of 560 events was started. The subjects were informed that the main series lasted about 45 minutes. They were not informed about the warming-up and filler items and about the number of tests used. The subjects tested at the same time were given simultaneously a different random order of the word pairs. The events were presented on a screen controlled by a PDP 11/45 computer. Each event was shown for four seconds. On presentation, the stimulus word and the response word appeared simultaneously on the screen next to each other. A stimulus word (in each case the first word of a pair) presented with a question mark signalled a test. No word pair was tested without being presented at least once. The subjects had to write down the response on an answer sheet during the four seconds that the stimulus word and the question mark were visible. On a single answer sheet 15 responses could be given below each other. A total of 14 sheets was used for the main series.

3.3.2. Results and Discussion

The results of this experiment are shown in fig. 3.3. The percentages of word pairs recalled in each spacing-retention combination is the mean of the scores of all subjects for that combination. The standard deviation of these percentages (across subjects) ranged from 1.7 to 2.9 %. The percentage recalled for the word pairs presented once for retention intervals of 1, 2, 4, 8 and 16 events are respectively 63, 62, 57, 56 and 52 %[1]. It is evident that for spacing intervals smaller than four events the results show much spread and no clear pattern emerges. Figure 3.3 shows that nearly all curves are non-monotonic with the spacing interval and have a peak at about a spacing of three events. The only exception is the bottom curve for the longest retention interval. That curve is negatively

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[1] In considering the data of the once-presented stimuli it strikes that the decrease in performance with an increase in retention time is much smaller than expected from data presented in literature (Crowder, 1976).

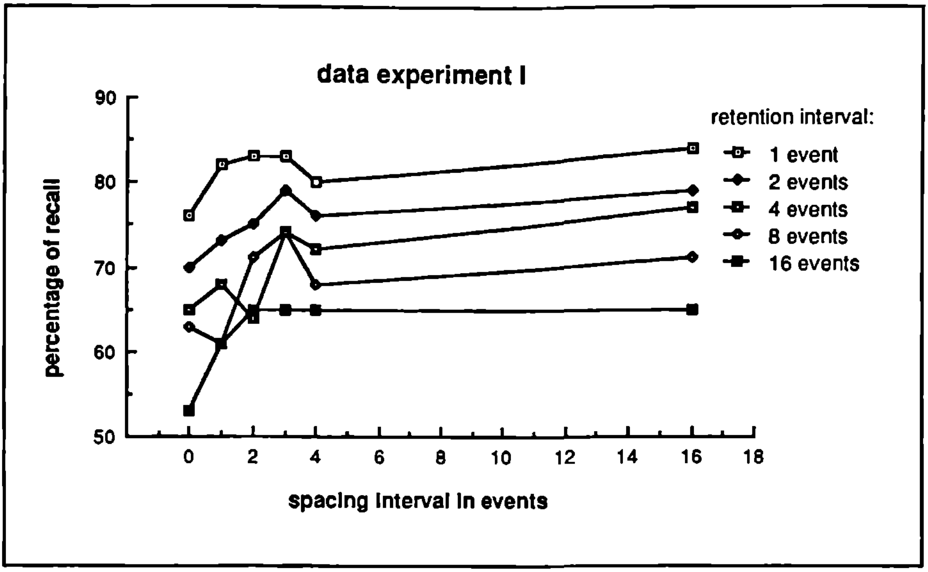

Figure 3.3. Experimental results of experiment I. The relation between the recall percentages and the spacing separating two presentations of a word pair is shown for five retention intervals between the second presentation and the test.

accelerated with increasing spacing. These results show that an increase in spacing leads to a significant increase in recall performance (MANOVA, $p < .01$) and that an increase in retention interval leads to a significant decrease in performance (MANOVA, $p < .01$). Further, there is a significant interaction between the effects of the spacing and retention intervals (cf. Figure 3.3, MANOVA, $p < .01$).

Note that the absolute level of performance of the subjects in this experiment is much higher than that found in the experiment of Glenberg (1976). This might be explained by the longer presentation times used in this experiment (four seconds instead of three seconds). In order to keep the conditions at test trials and at presentations comparable these events have the same duration. These longer presentation times were necessary to give the subject enough time to write down the answer.

No evidence was found for the dip observed in the results of Glenberg. That the pattern is somewhat irregular may be explained by the great number of spacing and retention intervals used in only a small range of intervals. The range of intervals used by Glenberg was much wider, while the number of intervals used was smaller. It is reasonable to expect that the standard deviations of the "percentage correct" in the experiment of Glenberg are about the same as in this experiment (about the same number of subjects and the same number of observations per subject). In that case the differences between a spacing interval of 0 events and of 1 event in Glenberg's data are not statistically significant. Therefore, the dip is not an essential detail of the spacing effect for small retention intervals. It can be concluded that models that predict the spacing effect need not take into account the dip in the data of Glenberg.

3.4. RUMELHART'S EXPERIMENTAL RESULTS

In the continuous paired-associate design of Rumelhart (his experiment I, 1967) 50 subjects were tested. In this learning procedure the first presentation of the stimulus can be on any trial. At each trial the subject was presented with an anticipation trial, i.e. the stimulus member of the S-R-pair was presented and he was asked to give the response member. Immediately following his response the correct S-R-pairing was shown for two seconds. The inter-trial interval lasted three seconds. The S-R-pair was constructed with CVC nonsense syllables as stimuli and the digits 3, 5 or 7 as responses. Each of the responses was paired with 1/3 of the stimuli. Each S-R-pair was presented six times to the subjects, with a variable lag (the number of trials intervening between the i^{th} and the $i+1^{th}$ presentations of a particular item).

Eight different lag combinations were presented to the subjects. For the lag combinations see table 3.2. Some filler items are used to fill the places not necessary for the experimental lag combinations. (For more details see Rumelhart, 1967.) The experimental results are shown in table 3.3 and figure 3.4. The percentages correct of the first trial are deleted for all sequences, because these answers are guessed.

Table 3.2. The eight lag combinations used in experiment I of Rumelhart.

seq. no.	Lag				
	(1)	(2)	(3)	(4)	(5)
1	10	10	10	10	10
2	10	10	1	1	10
3	6	6	6	6	10
4	6	6	1	1	10
5	3	3	3	3	10
6	1	1	10	10	10
7	1	1	6	6	10
8	1	1	1	1	10

The strongest effect evident in these data is the dependence of recall percentage upon the immediately preceding lag. This effect can be readily seen in any of the trial columns 2 through 4, the longer lags being associated with lower percentages correct.

Table 3.3. Percentage correct for each test for each lag-combination. Only tests that were preceded by a presentation of the tested S-R-pair are shown.

seq. no.	Trial				
	(2)	(3)	(4)	(5)	(6)
1	66.0	78.7	84.7	87.3	89.3
2	70.3	79.7	94.3	96.7	88.7
3	73.3	81.0	86.7	92.0	90.7
4	66.0	83.3	91.7	94.3	89.0
5	79.3	86.3	89.3	91.7	87.0
6	85.0	90.7	77.7	85.0	88.0
7	79.3	92.0	84.0	88.3	87.7
8	85.0	91.7	96.7	97.3	89.0

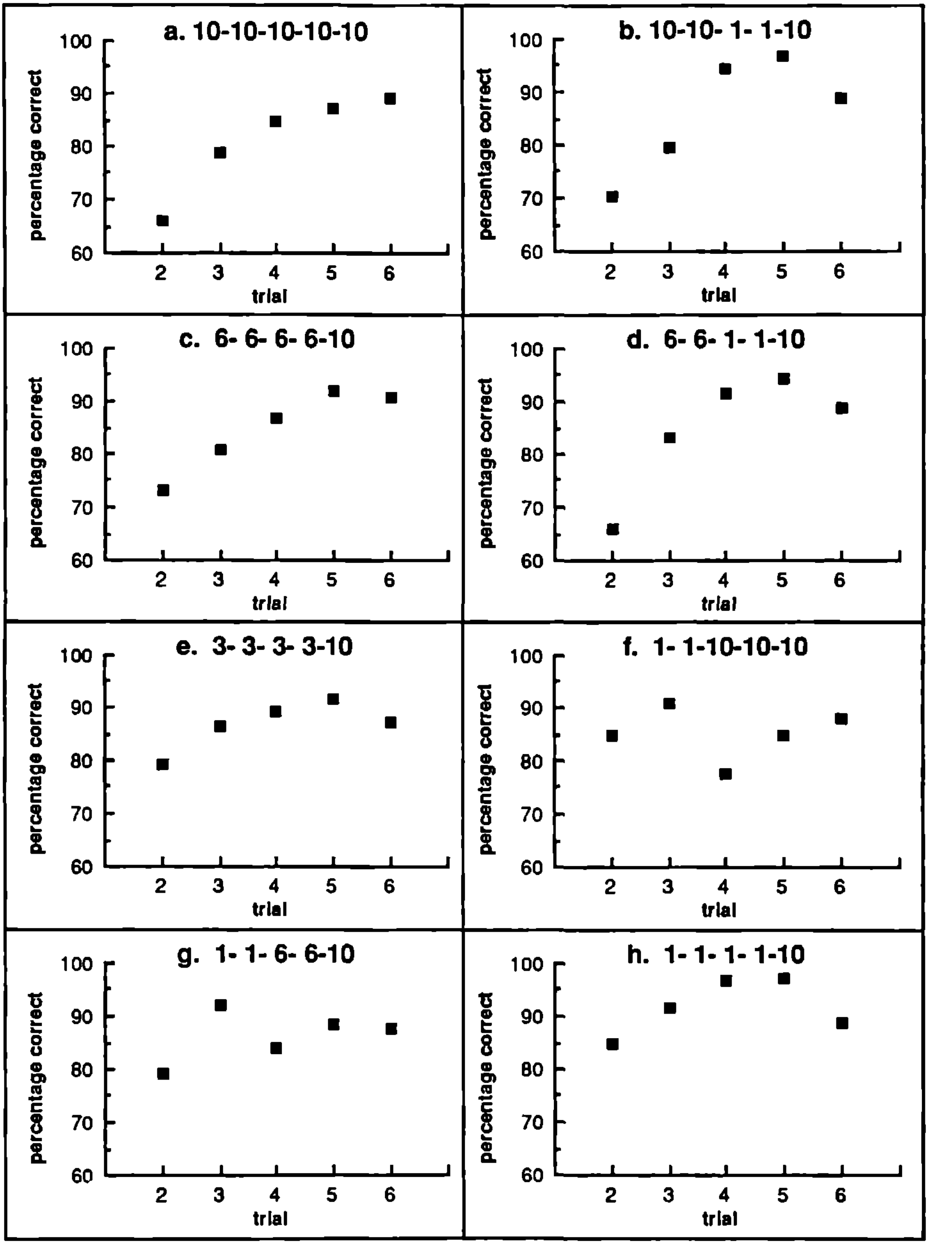

Figure 3.4. Experimental results of Rumelhart (1967). The recall percentages of the tests which were preceded by a presentation of the tested S-R-pair are shown as function of the lag combinations.

A second observation is that in the trial 6 column there is no effect of the preceding sequence of lags on the recall percentages. That is, on trial 6, where the immediately preceding lag is constant and equal to ten for all sequences, the recall percentage is also nearly constant.

A complicating result follows from a comparison of items with different values of the initial two lags but with the same values of lag-3. It is clear that the values of the initial lags affect the recall percentage on trial 4. Generalizing, if lag-3 is long (equal to six or ten), the items with the longer initial lags have more correct answers on trial 4, but if the lag-3 is short (equal to 1) the items with the shorter initial lags have more correct answers on trial 4.

To summarize, three important trends shown by the learning curves have been discussed:

1. The immediately preceding lag strongly determines the recall percentage on any given trial. If the lag is long, the recall percentage will be low, if it is short, the recall percentage will be high.
2. Other than the immediately preceding lag, there appears to be no influence of the preceding sequence of lags on the percentage correct on trial 6.
3. If lag-3 is long, the items with longer initial lags have the most correct answers, but if lag-3 is short the items with the shorter initial lags have more correct answers on trial 4.

3.5. CONTINUOUS PAIRED-ASSOCIATE EXPERIMENT II: ONE-STIMULUS-TWICE AND TWO-STIMULI-ONCE

In order to investigate the effect predicted by Ross and Landauer (1978), we designed a continuous paired-associate experiment (Experiment II) to compare the two-stimuli-once condition to the one-stimulus-twice condition. Ross and Landauer found a lag effect for the repeated stimuli (one-stimulus-twice) and no lag effect for two-stimuli-once in a free recall experiment (Ross and Landauer argue that theories with variable encoding predict a lag or spacing effect for both conditions). We expected to find a spacing effect for the repeated stimuli (one-stimulus-twice) and no spacing effect for two-stimuli-once in a CPA experiment, and this was indeed found. The results of the two-stimuli-once condition will be directly compared with the results of repeated word pairs with the same spacing and retention intervals.

3.5.1. Method

3.5.1.1. Subjects

The subjects were 57 students from the University of Nijmegen. Each subject either received Dfl. 8.00 or fulfilled a course requirement for participation in this experiment.

3.5.1.2. Materials and Design

A continuous paired-associate design was used. A scheme with 580 events was designed for the order of the presentations and the tests. The first ten events were warming-up items. Some of the following pairs were repeated with 0, 1, 2, 4, 8 or 16 intervening events. They were tested 25 or 50 events after their second presentation. Further, two different presentations (two-stimuli-once) spaced with 0, 1, 2, 4, 8 or 16 events and both tested 25 or 50 events after the presentation of the second word pair were presented. Every spacing-retention interval combination occurred five times. Some filler pairs were presented (once or twice) and tested later to make the scheme complete (cf. Appendix B1 for the design). These filler pairs will not be used in the presentation of the results. In the design of the scheme of trials with presentations and tests the order of these trials is alternated. Not more than two trials with tests or eight trials with presentations immediately follow each other. The pairs were composed of common Dutch nouns of four, five or six letters (cf. Appendix B2 for the word pairs presented). Common pre-experimental associations, rhymes, and orthographic similarities were avoided. For a given subject, each word occurred in only one pair. The order of the presentations and tests was the same for each subject, the assignment of word pairs to the conditions was varied randomly between subjects.

3.5.1.3. Procedure

The procedure presented in section 3.3.1.3 for experiment I was also used in this experiment, only deviations from that procedure are

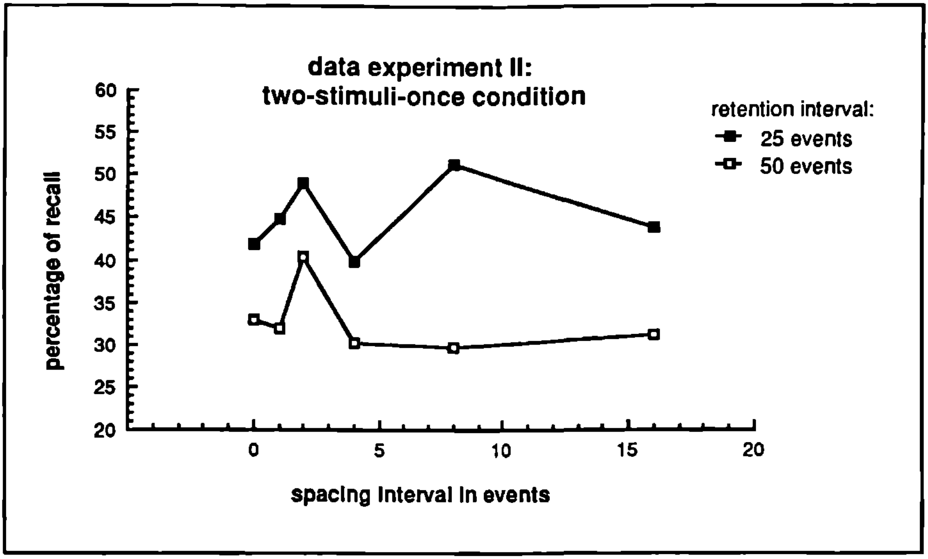

Figure 3.5. Experimental results of the two-stimuli-once condition to replicate the findings of Ross and Landauer. The relation between the recall percentage of at least one of two different word pairs and the spacing separating these presentations is shown for two retention intervals between the presentation of the second word pair and the test.

mentioned here. A practice series of 34 events (28 presentations and 6 tests) was given, using nouns of four, five and six letters that were not used in the main series. Next, the main series of 580 events was started. On a single answer sheet 15 responses could be given below each other. A total of 13 answer sheets was used for the main series.

3.5.2. Results and Discussion

In figures 3.5 and 3.6 the percentage correct (or percentage of recall) for the two-stimuli-once and for the one-stimulus-twice conditions are presented. The levels of the percentage correct of the two-stimuli-once condition and the one-stimulus-twice condition for the same retention interval show only a small difference. The recall percentage for the one-

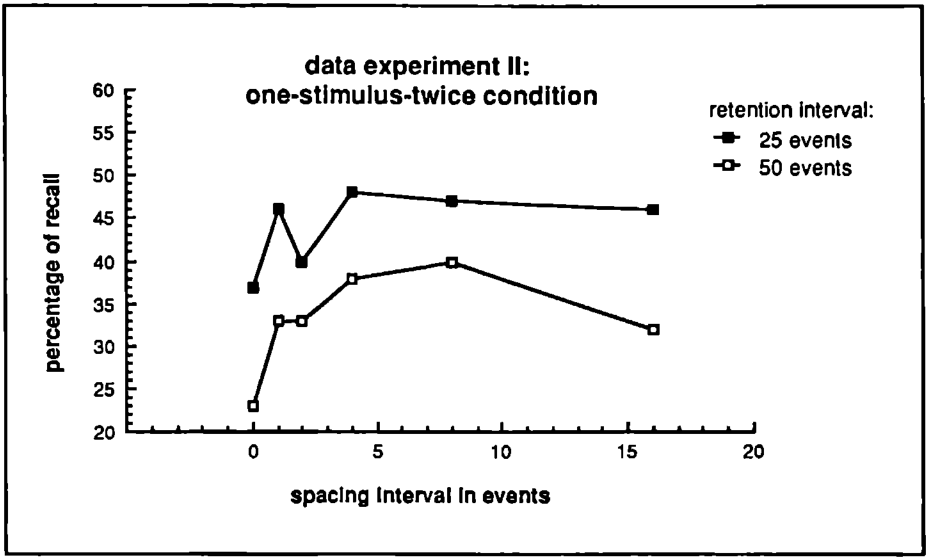

Figure 3.6. Experimental results of the one-stimulus-twice condition, to compare repetition results directly with the results of the two-stimuli-once condition. The relation between the recall percentage and the spacing separating the presentations of two word pairs is shown for two retention intervals between the second presentation and the test.

stimulus-twice condition tends to be somewhat lower for both retention intervals than that for two-stimuli-once condition.

The percentage correct in the case of two-stimuli-once fluctuate around about 45 % and 32 % for retention intervals of 25 and 50 events respectively. For a retention interval of 25 events the recall is significantly (MANOVA, $p < .01$) better than for an interval of 50 events between second presentation and test. An increase in retention interval leads to a decrease in recall performance. No spacing effect is found for the two-stimuli-once condition, the level of recall performance is not significantly increasing with increasing spacing interval. On inspection, the curves in figure 3.5 show an irregular pattern, but in general the curves look like straight horizontal lines. Only the peak at a spacing interval of two events is seen in both curves.

The recall performance for the one-stimulus-twice condition decreases as the retention interval increases: Recall performance is significantly higher (MANOVA, $p < .01$) for a retention interval of 25 events compared to one of 50 events. An increasing spacing interval shows a non-significant increase in recall performance (MANOVA, $p = .058$), that is, a very small spacing effect is found for the one-stimulus-twice condition. The curve of the 25 events retention interval globally presented in figure 3.6 shows an increase in performance to an asymptotic level for increasing spacing, and the curve of the 50 events retention interval shows an increase in recall followed by a decrease between 8 to 16 events of spacing. The spacing effect for the one-stimulus-twice condition is less explicit (not reaching significance) than that found in experiment I.

In summary: In experiment II, a tendency to a spacing effect is found for the one-stimulus-twice condition, but no spacing effect is found for the two-stimuli-once condition. A spacing effect or a lag effect for repeated stimuli is often reported in the literature (see chapter 1). However, only Ross and Landauer (1978) reported experiments with the two-stimuli-once condition, and they found no spacing or lag effect for this condition. Therefore, a theory with variable encoding, such as the SAM theory with context fluctuation, can only be accepted when it predicts both a spacing effect for repeated stimuli and no spacing effect for the two-stimuli-once condition. When the SAM theory with context fluctuation can be accepted, than the argument of Ross and Landauer that a theory with variable encoding predicts a spacing effect for both conditions, is incorrect.

In the free recall experiment reported by Ross and Landauer (Experiment II, 1978) a significant lag effect[2] was observed for repeated items and no lag effect for the two-stimuli-once condition. The lag effect reported by Ross and Landauer is mainly due to the increase in recall for the two smallest spacing intervals. Free recall experiments of Melton (1967) and Madigan (1969) show a more pronounced lag effect for repeated items. In order to compare the effect of an increasing spacing for the one-word-twice (in these free recall tasks a single word is used as stimulus) to that for the two-words-once condition, a free recall

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[2] A lag effect in free recall experiments is comparable to a spacing effect for long retention intervals in CPA experiments.

experiment was designed with the lags or spacing intervals as used by Madigan.

3.6. FREE RECALL EXPERIMENT III: ONE-WORD-TWICE AND TWO-WORDS-ONCE

Our experiment III was designed to replicate Ross and Landauer's experiment II, but with lags or spacing intervals as used by Madigan (1969).

3.6.1. Method

3.6.1.1. Subjects

The subjects were 54 students from the University of Nijmegen. Each subject either received Dfl. 8.00 or fulfilled a course requirement for participation in this experiment.

3.6.1.2. Materials and Design

The design was mainly based on the method employed in Madigan's experiment I (1969) and concerns two different words presented once, as investigated in Ross and Landauer's experiment II (1978). In the experiment two different forms of lists were presented in a random fashion. One form was constructed to replicate the results found by Madigan for the one-word-twice condition and the other form to replicate the results found by Ross and Landauer for the two-words-once condition. All lists in both forms contained six lags: 0, 2, 4, 8, 16 and 32 intervening words.

For the one-word-twice condition two lists were constructed and each of both contained 48 different words and 72 presentations. To prevent that lag effects would mix up with primacy- and recency effects (Crowder, 1976) each list begins with eight "primacy buffer" items taking positions 1 through 8 and ends with eight "recency buffer" words taking positions 65 through 72. Of the other presentations, 48 presentations were repetitions of 24 different words, equally distributed over lags so that each lag was represented in four different words. The remaining eight words were once-presented filler items. The words, excluding the primacy and recency buffer items, were distributed over lists in such a way that the mean serial position of the first and the second presentation of a repeated item for all lags and the mean serial position of the once-presented filler items would roughly by the same. In appendix C1 the scheme for the two list in the one-word-twice condition are given along with the serial positions of the first and second presentations for the repeated items and the serial positions of the eight filler items.

The schemes for the lists used in the two-words-once condition had the same structure as those in the one-word-twice condition, but for every repeated item (P_1 and P_2) one pair of different words (A and B) was substituted and for the eight filler items four items presented twice were substituted. The list transformed in this way now contained 68 different words (64 once-presented and 4 items with repetitions), and 72 presentations (see also appendix C1). For both conditions four, five and six letter nouns were randomly assigned to the schemes of the lists, i.e. nouns were randomly paired with an item number. The presented nouns are given in appendix C2.

3.6.1.3. Procedure

A maximum of 5 subjects was tested at anyone time. All lists were presented in random sequence to every subject. Before the actual experiment started, all subjects were given a practice trial in which a shortened list, consisting of 24 different items and 36 presentations, was shown. For the experimental lists 232 different words were randomly assigned to both list forms (one-word-twice and two-words-once) and intra-list conditions. Words were shown one by one every 2.5 seconds, on a monitor controlled by a PDP-11 computer. Subjects were instructed to recall as many different words as possible, without regard to order of presentation. They were allowed four minutes of written recall after each list presentation. After those four minutes the experimenter would collect the answer sheets, hand out new ones and continue the experiment.

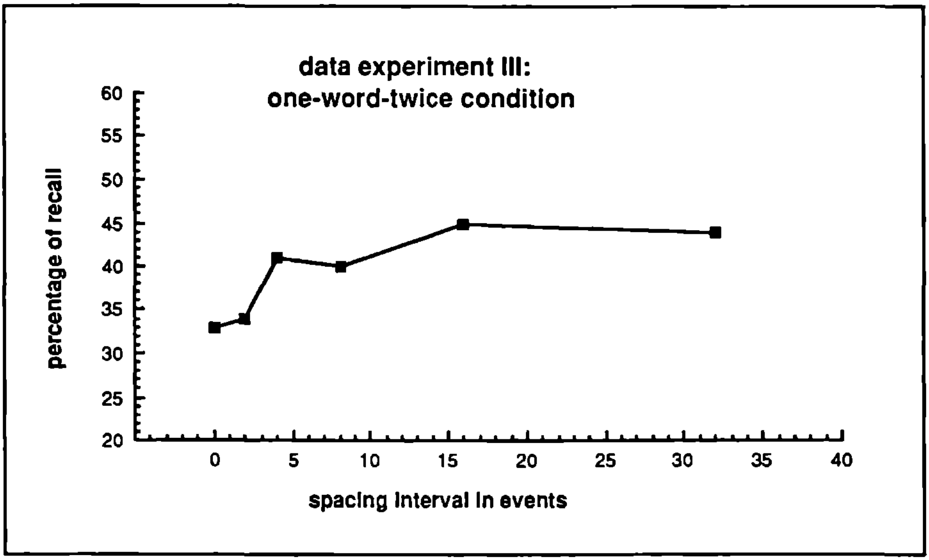

Figure 3.7. Experimental results of the one-word-twice condition. The recall percentages as a function of the spacing interval between the presentations.

3.6.2. Results and Discussion

The results of the repeated words in the one-word-twice condition are presented in figure 3.7. (21 % of the once-presented filler words is recalled, but this is not shown.) The percentage of recall for repeated words is always greater then that of once-presented words. On comparing once-presented words with all lags for repeated words a significant repetition effect is found (ANOVA, $p < .01$). For repeated words the recall increases monotonically with lag. A significant lag effect is found (ANOVA, $p < .01$). Compared to the experiment of Madigan the number of observation per data-point in this experiment differs. In the experiment of Madigan four lists with repeated words were presented instead of two lists in the experiment presented here. The curve of the experiment III suggests an asymptotic value whereas the data of Madigan seem strictly monotonically increasing with lag.

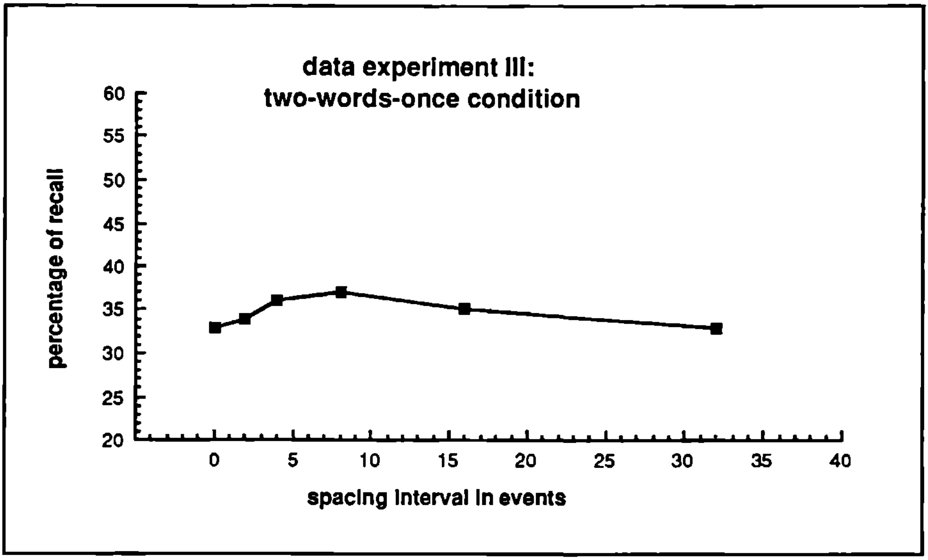

Figure 3.8. Experimental results of the two-words-once condition. The recall percentages as a function of the spacing between the presentations of the two words.

Figure 3.8 gives the results for the two-words-once condition. There was no evidence for a main lag effect (ANOVA, p > .1). The curve in figure 3.8 has a nearly flat form, just as the curves presented by Ross and Landauer (1978).

A significant lag effect is observed for repeated stimuli in the free recall and a tendency to a spacing effect is observed for repeated stimuli in the continuous paired-associate experiment, and no lag or spacing effect is found for the two-stimuli-once condition. The lag or spacing effect is more pronounced for the free recall design than for the continuous paired-associate design. In the free recall experiment an increase in performance to an asymptotic level is shown in the case of repeated stimuli (figure 3.7). The increase to an asymptotic level is less clear for repeated stimuli in the continuous paired-associate experiment (figure 3.6). In the free recall experiment the curve for the two-words-once condition has a nearly flat form (figure 3.8), while the form of the curves for two-stimuli-once (figure 3.5) in the continuous paired-associate experiment is only approximately flat and more irregular. It can be concluded that in both experimental designs (a tendency to) a lag or spacing effect is observed for repeated stimuli and a flat curve is observed for the two-stimuli-once condition.

4. APPLICATION OF THE SAM MODELS TO THE DATA

In section 1.5 we have mentioned that the parameters of the model may not always be identifiable. In the present chapter, we demonstrate these problems by testing the SAM model for two presentations followed by a test (cf. section 2.3) on Glenberg's data (cf. section 3.2). The same kind of problems can be demonstrated to exist for the other SAM models presented in chapter 2. In the first section of this chapter the identification of the parameters will be discussed in general. Next, we will apply the model to Glenberg's data and show that conclusions about the relative importance of the sub-processes can be affected by the set of parameters used, without influencing the goodness of fit. In the last section the procedure for further application of the models to the data, that will be used in the following chapters, will be described.

4.1. GENERAL REMARKS ABOUT THE IDENTIFIABILITY OF PARAMETERS

In chapter 1 the general SAM theory was presented, and in chapter 2 the SAM models for multiple presentations. The identifiability of the parameters of the model mentioned in 1.5 will be discussed in this section. A total of ten parameters, shown in table 4.1, are used in fitting the data. To reproduce the data of the twice-presented stimuli all ten parameters are involved. Except for the recovery parameter, θ_1, used in case of recognition, the same parameters are involved to describe the other data (once-presented stimuli, Rumelhart's data, and two-stimuli-once). Table 4.1 summarizes the parameters.

For the model presented in section 2.3 to reproduce the data of Glenberg and of experiment I – twice-presented stimuli, followed by a test where the final recall probability is based on both recognition and recall – five parameters θ_1, θ_2, Z, I, and a can be mathematically reduced to only four parameters (u, v, w, and y – see later). The probability of a correct answer for two presentations followed by a test, as given in

Table 4.1. The ten parameters involved in the SAM models for multiple presentations and their meaning.

parameter	meaning
C	context associative strength, calculated by means of the following four parameters:
a	scale parameter
s	equilibrium value of the proportion elements that is active
α	rate of fluctuation between the active and non-active states
w	probability of being encoded
I	inter-item associative strength, estimated by means of:
b	inter-item associative strength after a single presentation
Z	residual strength, total strength of all other images activated by the retrieval cues
L_{max}	number of search cycles
θ_1	recovery parameter for recognition
θ_2	recovery parameter for recall
λ	hazard rate of an item leaving the STS

equation 2.18, is a combination of recognition and recall probabilities. The enriched trace can be recalled at T after recognition at P_2, or the new trace formed at P_2 can be recalled when the pair is not recognized at P_2. The probability of a correct answer ($P_{CA}(t_1,t_2)$; equation 2.18) is:

$$P_{CA}(t_1,t_2) = P_{RG}(t_1|\theta_1)\, P_{RL}(t_1,t_2|\theta_2) + \{1 - P_{RG}(t_1|\theta_1)\}\, P_{RL}(t_2|\theta_2),$$

where t_1 and t_2 indicate the spacing and the retention interval, respectively. The probabilities of recognition (P_{RG}) and recall (P_{RL}) are both conditional probabilities (equation 2.5). A pair is recognized or recalled when it is still in STS or when the image is retrieved from LTS. The five parameters θ_1, θ_2, Z, I, and a are all involved in estimating the probability of retrieving the trace from LTS. In equation 2.3 the probability of retrieving a trace from LTS after L_{max} search cycles was given. The probability of retrieving the trace from LTS (in case of recognition) at P_2 is:

$$\begin{aligned} P_{RET}(t_1|\theta_1) &= \{1 - (1 - P_{SAM}(t_1))^{L_{max}}\}\, P_{REC}(t_1|\theta_1) \\ &= \{1 - (1 - \frac{I(t_1)C(t_1)}{I(t_1)C(t_1)+Z})^{L_{max}}\}\, \{1 - e^{-\theta_1(I(t_1)+C(t_1))}\}. \end{aligned} \tag{4.1}$$

Since $I(t_1)$ and $C(t_1)$ are equal to b and $aO(t_1)$ respectively – cf. eqs. 2.6 and 2.7 – and letting $u = \frac{b\,a}{Z}$, $v = \theta_1 b$, and $w = \theta_1 a$, we can rewrite 4.1 as given in 4.1a, below.

The probability of retrieving (in case of recall) the enriched trace at test from LTS is:

$$\begin{aligned} P_{RET}(t_1,t_2|\theta_2) &= \{1 - (1 - P_{SAM}(t_1,t_2))^{L_{max}}\}\, P_{REC}(t_1,t_2|\theta_2) \\ &= \{1 - (1 - \frac{I(t_1,t_2)C(t_1,t_2)}{I(t_1,t_2)C(t_1,t_2)+Z})^{L_{max}}\}\, \{1 - e^{-\theta_2(I(t_1,t_2)+C(t_1,t_2))}\}. \end{aligned} \tag{4.2}$$

$I(t_1,t_2)$ and $C(t_1,t_2)$ in equation 4.2 are equal to $F(1,2)b = 2b$ (cf. equation 2.6) and $aO(t_1,t_2)$ (cf. equation 2.7) respectively. Using again, u, v, and w, as defined above, and furthermore defining $y = \frac{\theta_2}{\theta_1}$, we can rewrite 4.2 as 4.2a below.

Finally, the probability of retrieving of the new trace formed at P_2 from LTS at T is:

$$\begin{aligned} P_{RET}(t_2|\theta_2) &= \{1 - (1 - P_{SAM}(t_2))^{L_{max}}\}\, P_{REC}(t_2|\theta_2) \\ &= \{1 - (1 - \frac{I(t_2)C(t_2)}{I(t_2)C(t_2)+Z})^{L_{max}}\}\, \{1 - e^{-\theta_2(I(t_2)+C(t_2))}\}. \end{aligned} \tag{4.3}$$

Again, using a, b, u, v, w, and y, as before, we can rewrite 4.3 as 4.3a, below.

In summary, the five parameters b, a, Z, θ_1, and θ_2 can be reduced to four parameters:

$$u = \frac{b\,a}{Z}$$

$$v = \theta_1\, b$$

$$w = \theta_1\, a$$

$$y = \frac{\theta_2}{\theta_1}$$

giving the following probabilities of retrieval:

$$P_{RET}(t_1|\theta_1) = \{1 - (1 - \frac{uO(t_1)}{uO(t_1)+1})^{L_{max}}\}\ \{1 - e^{-(v+wO(t_1))}\}, \qquad (4.1a)$$

$$P_{RET}(t_1,t_2|\theta_2) = \{1 - (1 - \frac{uO(t_1,t_2)}{uO(t_1,t_2)+1})^{L_{max}}\}\ \{1 - e^{-y(v+wO(t_1,t_2))}\}, \qquad (4.2a)$$

and

$$P_{RET}(t_2|\theta_2) = \{1 - (1 - \frac{uO(t_2)}{uO(t_2)+1})^{L_{max}}\}\ \{1 - e^{-y(v+wO(t_2))}\}. \qquad (4.3a)$$

One of the five original parameters may be set to an arbitrary value. There are no indications from earlier research what values are reasonable for these parameters, much less which parameter may be set to a fixed value. From the substitutions given in equations 4.1 to 4.3 it can be seen that only the ratio between θ_1 and θ_2 can be determined. Therefore parameter θ_1 is set to the fixed value 1. Theoretically it is expected that the probability of recognition is greater than that of recall, that is, $\theta_2 < 1$.

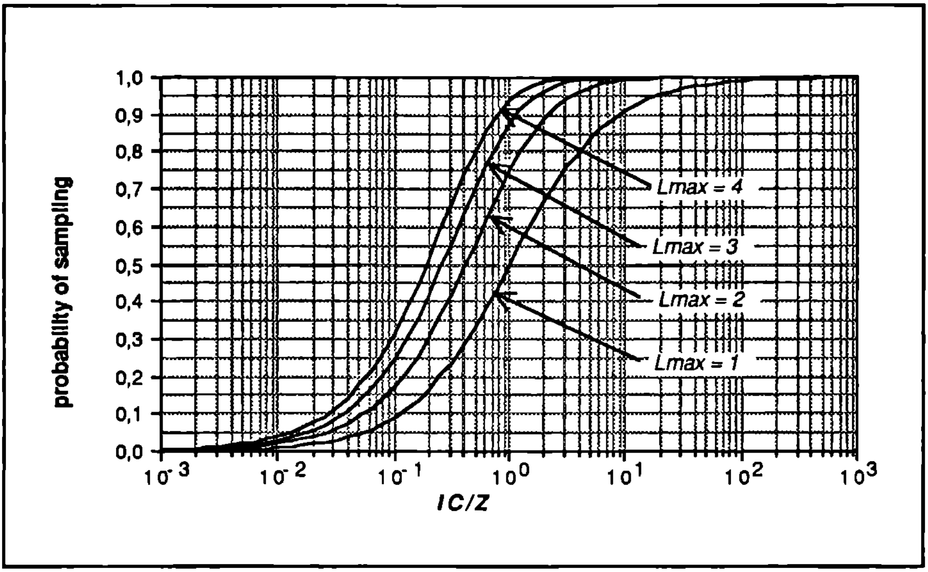

Figure 4.1. The probability of sampling after L_{max} search cycles as function of $\frac{I\,C}{Z}$ for various values of L_{max}.

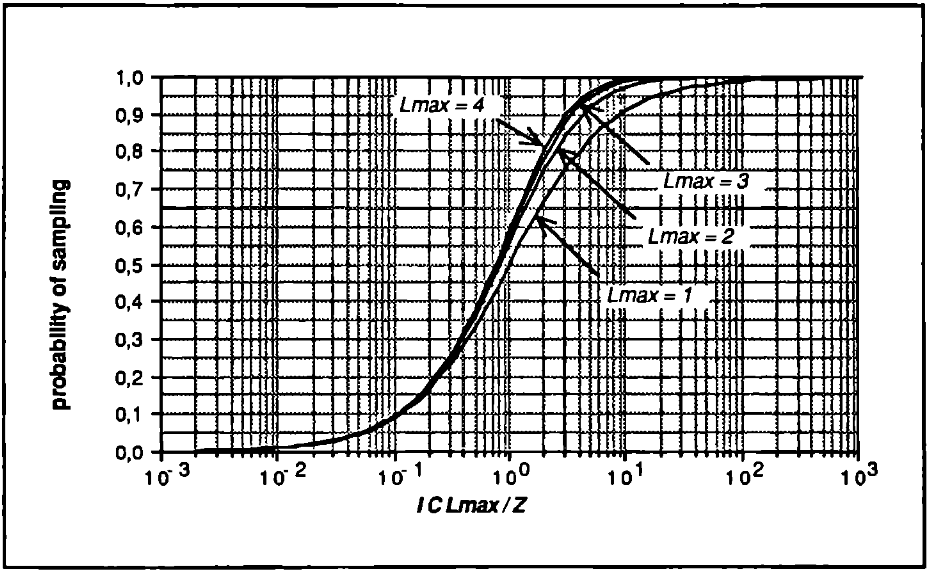

Figure 4.2. The probability of sampling after L_{max} search cycles as function of $\frac{I\,C\,L_{max}}{Z}$ for various values of L_{max}.

Since no *a priori* knowledge is available about the values of most of the parameters, they have to be fitted to the experimental data by an estimation technique such as the least-squares method. Certain random sampling errors are always inherent to observed data. When a parameter can mathematically be shown to have a small influence on the predicted final probabilities of recall, then that influence may not be significant compared to the sampling errors in the recall percentages. Parameters may even seem to be dependent. For instance, the residual sum of squares may be little affected by the particular values of two parameters, if only their ratio is approximately constant.

This effect can readily be shown to exist for L_{max} and Z. The probability of sampling (equations 2.1 and 2.3) after L_{max} search cycles (denoted here as $\overset{*}{P}_{SAM}$) can be shortly written as:

$$\overset{*}{P}_{SAM} = 1 - \left(1 - \frac{I\,C}{I\,C + Z}\right)^{L_{max}}$$

$$= 1 - \left(1 - \frac{\frac{I\,C}{Z}}{\frac{I\,C}{Z} + 1}\right)^{L_{max}} \qquad (4.4)$$

Equation (4.4) shows that $\overset{*}{P}_{SAM}$ is a function of $\frac{I\,C}{Z}$ and L_{max}. It is plotted in figure 4.1 for different values of L_{max}. Both Z and L_{max} occur only in expression 4.4 of the sampling probability, and consequently, L_{max} and Z must be extrapolated from the (estimated) contribution of $\overset{*}{P}_{SAM}$ to the final probability of a correct answer P_{CA}. It turns out that, even in the absence of sampling error, and even if the model is correct, Z and L_{max} are hardly identifiable. To see this, we have plotted $\overset{*}{P}_{SAM}$ as in equation 4.4 against $\frac{I\,C\,L_{max}}{Z}$, for various values of L_{max}. Figure 4.2 shows this plot, and one can observe that different values of L_{max} have hardly any effect if L_{max} is greater then two. In other words: as long as the ratio $\frac{L_{max}}{Z}$ is constant, different values of $L_{max} \geq 2$ have hardly any effect on P^*_{SAM}. Hence, if I and C are known (or estimated), Z and L_{max} are hardly separately identifiable. Only the ratio $\frac{L_{max}}{Z}$ appears identifiable. Therefore, it appears reasonable, for purposes of model testing, to replace $\frac{L_{max}}{Z}$ by a single parameter. This will, of course, have a slight worsening effect on the goodness of fit – assuming the model holds at all – but resolves the algorithmic problem of great instability of the estimates of L_{max} and Z. Alternatively, one of these two parameters might be fixed at some suitably chosen a priori value. We decided to do the latter, and set L_{max} equal to 3 in all analyses. This choice is justified by the fact that in several investigations of the SAM model, $L_{max} = 3$ was used and has turned out to be a reasonable value (Raaijmakers & Shiffrin, 1980, 1981a).

Setting $L_{max} = 3$, and $\theta_1 = 1$ leaves eight parameters to be estimated by means of a least-squares fit to the experimental data.

Similar interdependences can be observed for other parameters. However, due to the complicated nature of the equations, the dependencies are not as easy to show as with L_{max} and Z.

A clear indication of the existence of further dependencies is the fact that widely differing values can be found for each of the eight remaining parameters, with only insignificant differences in the residual sum-of-squares. When the model was used to generate data which were then used as *experimental data* to fit the model to, the fitting procedure yielded the parameters which had been used to generate the data. This shows clearly, (a) that the fitting procedure itself is correct, and (b) that there are no more purely mathematical dependencies between parameters, but that the dependencies are statistical in nature. The least-squares routine also gives information on interdependence of parameters, in the form of covariances between parameter estimators. In this way parameters may be subdivided into groups of interdependent estimates. In the next section the SAM model is fitted to Glenberg's data. The values of the estimates of the parameters will be inspected and the bearing of these parameter values on the relative importance of the sub-processes will be discussed.

4.2. GENERAL PROBLEMS WITH THE FIT PROCEDURE

We started with an application of the model to the twice-presented stimuli, that is to the data of Glenberg's experiment and to those of experiment I. In section 4.1 we showed that the number of search cycles for the sampling phase, L_{max}, can be fixed at 3 and the recovery parameter in case of recognition, θ_1, can be fixed at 1. One further restriction on the estimated values of the parameters is based on theoretical grounds, namely that the recovery parameter for recall, θ_2, is smaller than the recovery parameter for recognition (see section 1.3). With these restrictions we attempted to fit the model to the data and estimate the parameter values.

A number of sets of reasonable parameter values, for which the predictions do not deviate too much from the experimental data, was selected by trial and error. These sets of values were used as starting values in Minuit (James and Roos, 1975), a (least-square) fitting program. Information about the goodness of fit is obtained in terms of a χ^2 criterion and of the covariances between the parameter estimators. The χ^2 criterion is given by:

$$\chi^2 = \sum_{i=1}^{N} [PP_i \frac{(Pr_i - Ob_i)^2}{Pr_i\,(1 - Pr_i)}],$$

with

PP_i number of observations for each spacing - retention combination,
Pr_i predicted recall percentage,
Ob_i observed recall percentage,
N number of spacing - retention combinations,

and the number of degrees of freedom is

$$\mathrm{df} = N - r,$$

where r is the number of estimated parameters.

Table 4.2. Parameter estimates and their standard error for the data of Glenberg.

parameters	estimate	error
b	.00028	.42E-3
s	.387	.40E-2
α**	.0133	.11E-2
w	1.*	–
a	40.09	.55E0
Z	.00073	.11E-2
L_{max}	3.*	–
θ_1	1.*	–
θ_2	.050	.70E-3
λ**	.442	.43E-1
χ^2	81.54	
df	17	

Note: * The value of a fixed parameter.
** The spacing and retention intervals in seconds (number of events times presentation time) are used.

In table 4.2 the parameter estimates for the data of Glenberg are presented and in figure 4.3 the observed and the reproduced recall percentages are shown. For the estimation of parameters from the data the spacing and retention interval in seconds (the interval in events times the duration of a presentation) is used. The reproduced curves have about the same recall level as the observed curves, but are much flatter, especially for small spacing intervals (where the observed curves show a large increase for small spacing intervals). The predicted curves do not reproduce the observed data very well. In terms of χ^2 the fit is not good.

Inspection of the estimated parameter values reveals some striking facts, which appear to indicate that the model might be simplified. These are discussed below.

1. It is unexpected that the estimated inter-item associative and the residual strengths (respectively .00028 and .00073), shown in table 4.2, are very small compared to the estimated context strength (with equations 2.5 to 2.12), that is between 6 and 15.5: The context strength

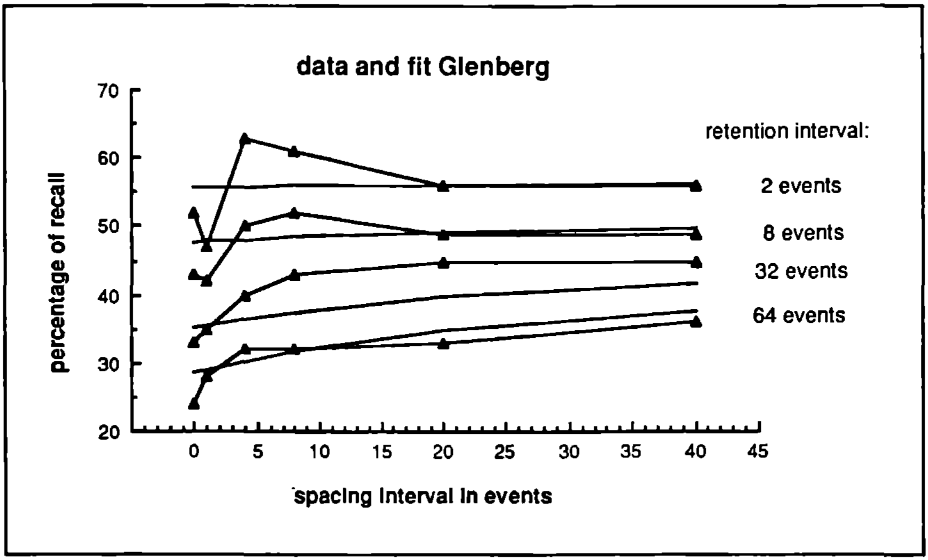

Figure 4.3. Recall percentages for the experiment of Glenberg. The relation between the recall percentage and the spacing interval separating two presentations of a pair is shown for four retention intervals between the second presentation and the test. Filled triangles indicate the observed recall percentage (data) and solid lines indicate the predicted recall percentages (fit).

is more than 800 times larger than the inter-item associative and the residual strengths. Further, the recovery parameter in case of recognition is 20 times as large as that in case of recall. The estimate of parameter *w* is 1, indicating that all active context elements would be encoded in memory.

2. Inspecting the sub-processes which determine the recall percentages, we found that some are not, or only hardly, effective. The probability of recognition turned out to be greater than .98 for all spacing intervals, indicating that recognition is nearly always successful. This implies that both the probabilities of sampling and of recovery are greater than .98. For three sampling cycles the probability of sampling is greater than .96 when the product of the inter-item associative and the context strength ($I\ C$) is twice that of the residual strength (Z). The

product of I and C for the parameters presented in table 4.2 is 2.3 to 60 times greater than Z. The probability of sampling after three search cycles is always greater than .98 for these parameter estimates. The estimated value of the residual strength is small as compared to the product of the inter-item associative and the context strength.

3. The probability of recovery in case of recognition is almost equal to 1. for all spacing intervals. The sum of the inter-item associative and the context strength is so large that the result of the exponential function for all spacing intervals is 1. Even the context strength alone is large enough to give a recovery of 1. The inter-item associative strength is negligible compared to the context strength. As a consequence of the recognition phase always being successful, the STS is not important at the second presentation, and the strength of nearly all items is increased at the second presentation. Rarely is a new trace formed at the second presentation.
4. When an item is present in STS at test a correct answer is given. After the smallest retention interval of 6 seconds only 7 % of the items are still held in STS, after 24 seconds no item is held in STS. The STS has here a small effect in determining the percentages of a correct response. Mostly the incremented trace is retrieved from memory. The probability of sampling an incremented trace is greater than in the case of recognition, because both the context and the inter-item associative strength are greater. Therefore Z is smaller still with respect to the product $I\ C$, and the probability of sampling after three search cycles the increased trace is always almost equal to 1.

From these findings, we conclude the following.

1. As a result of the structure of the model and the apparent extreme probability of the recognition (which implies sampling) the only parameters which can carry differential effects of spacing and repetition are θ_2 and C.
2. The spacing and repetition effects are largely due to the recovery of an incremented trace.
3. Parameter θ_2 determines the level of the recall and the time effect is incorporated through the context strength.
4. The inter-item associative strength is still negligible as compared to the context strength.

In the foregoing the trace is (nearly) always strengthened at the second presentation, that is there is always an effect of repeated presentations. There are two ways that a repetition leads to an increased trace, through presence in STS or through successful retrieval of the trace from LTS. When the incrementing is always through STS (λ is very small), the consequence is that the items will also be in STS at time of testing, and therefore always lead to a correct answer. Since recall is not always successful, the only way to represent incrementing the trace is through an always successful recognition on retrieval the trace at the second presentation, combined with a negligible STS effect.

Using other starting values for the parameters we found other parameter estimates. In some cases these seem to indicate that the STS is only effective at a spacing or retention interval of 0 seconds, as the estimate of λ turned out to be very great. Further we found consistently that the probability of recognition is always almost 1, so that the percentage correct answers is solely determined by the recovery of a strengthened trace.

Using different starting values, the same residual sums of squares were found, but the parameter estimates differ. For some sets of starting values we found that the estimates of θ_2, I, a, and Z are correlated. For other sets s and w are correlated, and still other sets lead to correlations between a, s, and α. Only the estimate of λ is never correlated with one of the other estimated parameters. We also found that when we vary one of the parameters values θ_2, I, s, or λ, and fix the other parameters, these variations resulted in large variations in χ^2. The predicted curves for the different sets of estimates differ slightly, but the general form of these curves is similar to that presented in figure 4.3.

Because of the interdependences of the parameter estimates and the insensitivity of χ^2 for variations of some parameters, it is difficult to obtain a unique set of estimated parameters for the experimental data without imposing restrictions on them. We tried to base these restrictions on theoretical grounds. Besides the restriction that $\theta_1 > \theta_2$, we imposed restrictions on the parameters that determine the inter-item associative and context strengths, in such a way that both strengths are the same order of magnitude. These restrictions did not result in a better reproduction of the data. Further, restricting the residual strength, Z (so that sampling will not always be successful and so that the level of this strength is more comparable to the other strengths) did not result in a acceptable fit. Further, we tried to fit the data with such restrictions that all subprocesses are effective in determining the recall percentages. This also failed.

After these failures in fitting the data with restrictions on the parameters, we tried to fit the model to the data by fixing one or more additional parameters at some arbitrary value. When estimating five, six or seven parameters from the data, variations of the starting values lead to different sets or parameter estimates, estimating only four parameters resulted in a unique set of parameter estimates for variable starting values. We concluded that not all eight parameters can be estimated uniquely for these data. The solution might have been to fix some parameters at values found from other research using the same elaboration of the SAM model, but there are no values of the parameters from earlier research.

An alternative procedure is to reduce the model, not by constraining its parameters, but by constraining certain components (in ways which will become clear in the next sections), and thereby also reducing the number of parameters. Notably, the global form of the curves of the observed data of Glenberg, while taking the sampling error into account, can be reproduced with a model using only three or four parameters[1]. In chapter 9, where more detailed characteristics of the context fluctuation model are given, it will be shown that the overlap of active context elements at testing with the stored context elements after two presentations (cf. figure 9.3b) has the same global pattern as the curves of the observed data of Glenberg. The overlap in context elements is estimated by means of only three parameters. In the next section the procedure, to fit reduced models to the data will be described.

As mentioned in section 1.5, two questions can be asked to evaluate how well the model fits. The first is whether the deviation of the data from the model is greater than can be attributed to chance fluctuation. Given enough power of a statistical test (and enough subjects and stimuli),

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[1] Note, the dip at a spacing interval of one event in the curves with the smallest retention intervals (two and eight events) and the peak in the curve with a retention interval of two events at a spacing interval of four events are not seen as essential details of the spacing effect for small retention intervals and is not replicated in experiment I. For prediction of the dip and the peak one or two additional parameters would be necessary.

this will rarely be the case: no model is perfect. However, the data of the experiments presented in chapters 3 show great variability in recall performance of the subjects, and therefore, most models presented in the next chapters cannot be clearly rejected. Hence, the simple statistical testing of a model at a conventional significance level is of little interest. For the evaluation of the goodness of fit we will use in the later chapters the χ^2 measure and the degrees of freedom mainly as descriptive measure. The second and often more important question concerns whether modification of a model leads to improvement. The χ^2 difference between hierarchically related models has also a χ^2 distribution with the difference of the degrees of freedom of both models as its degrees of freedom. When the models are not hierarchically related (e.g. the model with only sampling compared to the model with only recovery, see later) the differences cannot be interpreted as χ^2, and in that case the χ^2 measure and the number of degrees of freedom can only be used as descriptive measures.

When a modified model is a constrained version of a more general model (the latter having more free parameters), we expect that the modified model will fit somewhat worse; if however the worsening of the fit is not statistically significant, we may conclude that the constrained version is valid if we have accepted the hypothesis that the more general model is valid. An example is the model with only sampling compared to the complete model (see later).

4.3. THE FIT PROCEDURE

The SAM model is a formalized representation of processes which the theory assumes to be involved in storage and retrieval of (episodic) information. Where it fails to fit the data satisfactorily the outcomes of parameter estimation can – in principle – provide indications about which sub-processes might have been inappropriately formalized, at least for specific experimental tasks with which we are concerned. While retaining the theory in its general form, we might assume that a particular component operates differently for specific tasks. For instance, we might assume that recognition is always successful, independent of the associative strengths which determine recall. We will now sketch this procedure with respect to the analysis of Glenberg's data.

In section 4.2, it appeared that some sub-processes which determine the recall percentage for the data of Glenberg are not effective. [Further, it was shown that all eight parameters cannot be estimated uniquely from the data. Because of the problems in fitting the data with the complete model, we decided to fit the data with simplified models derived from the SAM model. Some indications of the simplifications of the model are given in section 4.2.] First, we will assume that the recognition at the second presentation is always successful, and eliminate this phase from the model. Second, we will assume that a word pair is always sampled, thus eliminating the sampling phases from the model. Both retrieval processes - sampling and recovery - have qualitatively the same effect on the probability of retrieval. If the interval between the presentation and the test increases the probabilities of both sampling and of recovery decrease. The rate of decrease is different for each process. In addition but not indicated in section 4.2 is another reduction which assumes that recovery is always successful. In the complete model the recovery of the increased trace is mainly responsible for the recall percentages, because it is the only process that may fail when recognition is always successful.

Another indication of a simplification is to eliminate the STS modelled in chapter 2 from the SAM model. STS is active directly following a presentation of a pair. The probability of being in STS decreases rapidly with time after a presentation. The decrease of the probability of being present in STS is much greater than the decrease of the probability of sampling and recovery for the same interval between presentation and succeeding presentation or test. STS is no longer active three or four events after a presentation, whereas the probabilities of sampling and recovery still can show a decrease after about 50 events. In the STS process all presentations of a stimulus present in STS are seen as an old stimulus and stimuli not present in STS are seen as new. STS is only relevant for experiments that include small intervals between presentation and test.

Another reduction of the SAM model indicated in section 4.2 is the elimination of the inter-item associative strength from the model. The inter-item associative strength is negligible compared to the context strength. In recovery it has no effect at all, and in cases of sampling the effect of the inter-item associative strength can be compensated by parameter Z. Elimination of the inter-item strength from the model means in cases of sampling that it is set to 1 and in cases of recovery it is set to 0.

As it is not possible to estimate all parameters from the data of Glenberg, we attempted to reproduce these data with simplified models. We assumed that recognition was always successful, and checked if that was a correct assumption. We will not discuss models which include a recognition phase, except for those cases where such a model had a better fit than a model which assumes that recognition is always successful. The inter-item associative strength will be eliminated from the model for twice-presented stimuli. However, when re-incorporation of the inter-item associative strength improves the fit, these results will be mentioned. The other data (presented in chapter 3) are fitted with simplified versions of the SAM model. The following processes and combinations thereof will be considered in simplified models:

1. Sampling only,
2. Sampling only and the STS,
3. Recovery only,
4. Recovery only and the STS,
5. Sampling and recovery.

Further, the complete model with sampling, recovery and the STS will be considered. In some applications the STS is deleted from the model because the time lag between the presentations and between presentation and test are too long.

Mathematical reductions of the number of parameters for all simplified models will be presented in the following chapters. If necessary only the estimation of a combination of a set of parameters will be presented. Parameter estimates found in one application are used if possible in the succeeding applications as starting values for the parameters. Firstly these parameters are fixed at those values, after that they are elected to see if the fit has improved. In the next chapter the SAM model will be applied to the data of once-presented stimuli.

5. PREDICTING DATA FROM ONE PRESENTATION

In these applications the data of the once-presented stimuli (data obtained from experiment II described in section 3.1) are predicted with the model as given in section 2.2. The probability of a correct answer ($P_{CA}(t_I)$) for single presentations tested after long retention intervals was given in *equation* 2.14 as:

$$P_{CA}(t_I) \; = \; P_{RET}(t_I|\theta_2).$$

In the present chapter we will test this model and two other simplified models to the data. Initially the prediction from *sampling* only will be presented and following this the prediction for *recovery* only. Finally, the prediction from both sampling and recovery (equation 2.14) will be presented. In these applications of the model the effect of the short-term memory (STS, see also section 2.2) is deleted because the retention intervals are so long that it may be assumed that the STS is not active at time of testing. In the sections below, we show how to calculate 2.14 for various simplifying assumptions.

5.1. DATA FROM ONE PRESENTATION: SAMPLING ONLY

In paragraph 2.2 the model for once-presented data was presented. If only sampling after L_{max} search cycles is considered (assuming that recovery is always successful: $P_{REC}(t_I|\theta_2)$=1) the probability of a correct answer ($P_{CA}(t_I)$) can be derived from 2.14, using equations 2.1 and 2.5, and is simply given by:

$$\begin{aligned} P_{CA}(t_I) \; &= \; 1 - (1 - P_{SAM}(t_I))^{L_{max}} \\ &= \; 1 - (1 - \frac{I(t_I)\, C(t_I)}{I(t_I)\, C(t_I) + Z})^{L_{max}}, \qquad (5.1) \end{aligned}$$

in which $I(t_I)$ is constant in time (equation 2.6) and is given by:

$$I(t_l) = b,$$

and $C(t_l)$ is in equations 2.7 to 2.11 given by:

$$\begin{aligned} C(t_l) &= a\,O(t_l) \\ &= a\,(w\,s\,e^{-\alpha t_l} + w\,s^2\,(1 - e^{-\alpha t_l})) \\ &= a\,w\,(s\,e^{-\alpha t_l} + s^2\,(1 - e^{-\alpha t_l})) \\ &= a\,w\,O'(t_l). \end{aligned} \tag{5.2}$$

The probability of a correct answer can also be rewritten as:

$$P_{CA}(t_l) = 1 - (1 - \frac{O'(t_l)}{O'(t_l) + \frac{Z}{b\,a\,w}})^{L_{max}}. \tag{5.3}$$

Table 5.1. Parameter estimates and values of the fixed parameters for the SAM model using sampling only to predict the data of once-presented stimuli.

parameter	solution
s	.186
α**	.0165
$\frac{Z}{b\,a\,w}$	.540
L_{max}	3.*
χ^2	8.447
df	9
C	.037 - .064

Note: * The value of a fixed parameter.
** The retention interval in seconds (number of events times presentation time) is used.

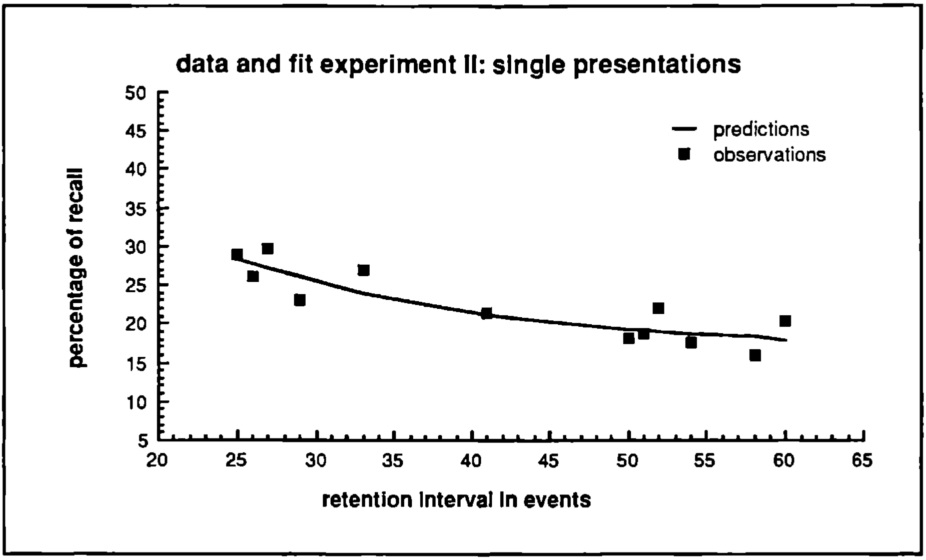

Figure 5.1. Experimental and predicted results of the once-presented stimuli, using only the sampling process to describe the data. The recall percentages as function of the retention interval for the observed (filled squares) and the predicted (solid lines) data.

Thereby mathematically reducing four parameters Z, b, a and w to only one. The value of $\frac{Z}{b\ a\ w}$ is estimated together with s and α. Parameter L_{max} is fixed at 3. In table 5.1 the estimated and fixed parameter values are given and in figure 5.1 the observed and predicted percentage of correct recall are shown. It can be seen that the predictions are good, and that the data can be described by a model with the three free parameters of the sampling process.

5.2. DATA FROM ONE PRESENTATION: RECOVERY ONLY

We now consider the process of recovery only to predict the data (assuming that sampling is always successful: $P_{SAM}(t_l)$=1), so that the probability of a correct answer ($P_{CA}(t_l)$) can be derived from equation 2.14, using equations 2.2 and 2.5, and is given by:

$$P_{CA}(t_l) = 1 - e^{-\theta_2 (I(t_l) + C(t_l))}, \tag{5.4}$$

which can be rewritten, using equations 5.2 and 2.6, as:

$$P_{CA}(t_l) = 1 - e^{-\theta_2 (I(t_l) + awO'(t_l))}$$

$$= 1 - e^{-\theta_2 b - \theta_2 awO'(t_l)}. \tag{5.5}$$

The parameters θ_2, a and w in equation 5.5 can be substituted by one parameter, as can θ_2 and b. The estimates of parameters s and α as found in the previous section using only sampling (table 5.1) are also used in this case. Two parameter combinations $\theta_2 b$ and $\theta_2 aw$ are estimated from the

Table 5.2. Parameter estimates and values of the fixed parameters for the SAM model using recovery only to predict the data of once presented word pairs.

parameter	solution		
	1	2	3
$\theta_2 b$	.011	.0*	.0*
$\theta_2 aw$	5.085	5.320	4.749
s	.186*	.186*	.198
α**	.0165*	.0165*	.0163
χ^2	8.456	8.519	8.455
df[1]	10 (−2)	11 (−2)	9
C	.036 - .063	.036 - .063	.041 - .070

Note: * The value of a fixed parameter.
** The retention interval in seconds (number of events times presentation time) is used.

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[1] Since we did not re-estimate parameters which were estimated in previous analyses, but fixed them at those previous estimates, the table shows the number of degrees of freedom according to the number of parameters which were not fixed. The number of not re-estimated parameters is shown between parentheses behind the number of degrees of freedom.

data and shown in the first solution of table 5.2. The fit is good. The inter-item (associative) strength (.011/5.1=.0022) is less than 10% of that of the context strength. Is the inter-item strength be negligible compared to the context strength? By setting $\theta_2 b$ equal to zero we tried to describe the data without the inter-item strength. The fit shown as solution 2 in table 5.2 is almost as good as solution 1. Taking the degrees of freedom into account, solution 2 is to be preferred.

The parameters s and α have been used above in the recovery process as estimated from the same data assuming only a sampling process. It has been shown above that with these parameters fixed and only $\theta_2 a w$ (solution 2) estimated from the data a good description of the data results. But what is the effect of estimating s and α also from the data but assuming recovery only? The results are given as solution 3 of table 5.2. The estimated value of parameter α is about the same as that in the case of sampling only. The value of parameter s is only 6.5 % greater than in the case of sampling only. The fit is just as good as in the solution were these parameters are fixed at values estimated with the sampling process. The degrees of freedom in solution 3 are less than in solution 2, but in solution 2 the fixed parameters s and α are estimated from the same data set. Both solutions 2 and 3 can be used to predict the data, but solution 2 is preferred, because s and α have the same values as assuming a sampling only process. The recovery process by itself can predict the data very well.

5.3. DATA FROM ONE PRESENTATION: SAMPLING AND RECOVERY

Finally, both sampling and recovery can be used to predict the data. The probability of a correct answer ($P_{CA}(t_l)$; equation 2.14) is in this case the product of equations 5.3 and 5.5, that is:

$$P_{CA}(t_l) = \{1 - (1 - P_{SAM}(t_l))^{L_{max}}\}\, P_{REC}(t_l|\theta_2)$$

$$= \{1 - (1 - \frac{O'(t_l)}{O'(t_l) + \frac{Z}{b\,a\,w}})^{L_{max}}\}\,\{1 - e^{-\theta_2 b - \theta_2 a w O'(t_l)}\}. \quad (5.6)$$

As in the applications given above, only combinations of the parameters b, a, w, θ_2, and Z can be determined from the data, namely $\frac{Z}{b\,a\,w}$, $\theta_2 b$ and $\theta_2 aw$. Parameters s and α are fixed at the values found from the analysis which retained only the sampling process (these parameter values are also acceptable in the case of only the recovery process). The parameter values are shown in table 5.3. The fit is not

Table 5.3. Parameter estimates and values of the fixed parameters for the SAM model using both sampling and recovery to predict the data of once-presented word pairs.

parameter	solution
s	.186*
α**	.0165*
$\theta_2 b$	.402
$\theta_2 aw$	3.774
$\frac{Z}{b\,a\,w}$	.271
L_{max}	3.*
χ^2	8.446
df	9 (–2)
C	.517 - .905
sampling	.428 - .600
recovery	.417 - .474

Note: * The value of a fixed parameter.

** The retention interval in seconds (number of events times presentation time) is used.

better than those for only-sampling or only-recovery. As can be seen in table 5.3, both processes, sampling and recovery, have about an equal contribution to the probability of a correct answer. The value of the inter-item associative strength is in same range as that of the context strength. We checked if the fit became better when parameters s and α are also estimated from the data. It did not.

In the application of the model with sampling the ratio between the inter-item associative strength and the context strength could not be determined. Retaining only recovery the inter-item associative strength could be deleted from the model without making the fit worse. We attempted to fit the data while eliminating the inter-item associative strength completely from the model. (In section 4.3 it was explained that the inter-item associative strength must be set to the following values: $b = 1$ in case of sampling and $b = 0$ in case of recovery.) The probability of a correct answer ($P_{CA}(t_l)$; equation 5.6) is then given by:

$$P_{CA}(t_l) = \left\{1 - \left(1 - \frac{O'(t_l)}{O'(t_l) + \frac{Z}{a\,w}}\right)^{L_{max}}\right\} \left\{1 - e^{-\theta_2 a w O'(t_l)}\right\}. \quad (5.7)$$

Apart from s and α, the parameter combinations $\frac{Z}{a\,w}$ and $\theta_2 aw$ can be estimated from the data. Parameters s and α are fixed at the same values used earlier. The resulting parameter estimates are shown as solution 1 of table 5.4. It turns out that, because the parameter combination $\frac{Z}{a\,w}$ is very small the sampling process has no effect in determining the probability of a correct answer. The item is nearly always sampled. The fit is slightly worse than that given in table 5.2 for only the recovery process. Estimating s and α also from the data results in a slightly better fit. These parameter values are given in the second solution of table 5.4. The probability of sampling is much greater than that of recovery in this solution.

Table 5.4. Parameter estimates and values of the fixed parameters for the SAM model using both sampling and recovery and eliminating the inter-item associative strength to predict the data of once-presented stimuli.

parameters	solution 1	solution 2
s	.186*	.229
α**	.0165*	.0163
$\theta_2 aw$	5.320	4.085
$\frac{Z}{a\ w}$	.000	.205
L_{max}	3.*	3.*
χ^2	8.519	8.452
df	10 (−2)	8
C	1.032 - 1.804	.915 - 1.450
sampling	1. - 1.	.890 - .951
recovery	.177 - .287	.201 - .299

Note: * The value of a fixed parameter.

** The retention interval in seconds (number of events times presentation time) is used.

5.4. DATA FROM ONE PRESENTATION: CONCLUSIONS

The data of the stimuli presented once can be described just as well by a model with only sampling, by a model with only recovery or by a model using both sampling and recovery as presented in section 2.2. Parameter values for s, the proportion of active elements and α, the rate of context fluctuation estimated for one version of the model can be used in the other model versions. The context fluctuation process seems to be a very stable process, because it can be used in both sampling and recovery with the same parameter estimates. In all applications of these versions α is estimated at about .0165, while s is ranged between .186 and .229.

Elimination of the inter-item associative strength from the model worsens the fit slightly in terms of χ^2. In case of only-recovery, χ^2 increases from 8.456 to 8.519, and for the combination of sampling and recovery χ^2 increases from 8.446 to 8.519 (s and α are fixed at the values found from the analysis which retained only the sampling process). The number of degrees of freedom also increases by one when the inter-item associative strength is eliminated, and so we may conclude that the increment in χ^2 after elimination of the inter-item associative strength is not significant. When parameters s and α are also estimated from the data in case of only-recovery and in case of the combination of sampling and recovery the fit is only slightly improved (χ^2 reduces from 8.52 to 8.45), while the number of degrees of freedom is less.

It can be concluded that a model without the inter-item associative strength is preferable. Both simplified versions of the model can describe the data just as well as the complex model with both sampling and recovery. At this point it is not possible to conclude which process, sampling or recovery, must eventually be retained to describe the data best.

6. PREDICTING DATA FROM TWO PRESENTATIONS

In this chapter the data of the twice-presented stimuli (Glenberg's experiment and our replication, which were described in sections 3.2 and 3.3), will be reproduced along with various versions of the model presented in section 2.3. The probability of a correct answer ($P_{CA}(t_1,t_2)$) was given in equation 2.18 by:

$$P_{CA}(t_1,t_2) = P_{RG}(t_1|\theta_1)\,P_{RL}(t_1,t_2|\theta_2) + (1 - P_{RG}(t_1|\theta_1))\,P_{RL}(t_2|\theta_2)$$

First, we try to fit the simplified versions of the model to these data, i.e. with either sampling or recovery only. Secondly, both versions are extended with a short-term store. Thirdly, the predictions of a model with both sampling and recovery are given. Finally, the most complicated version with sampling, recovery and a STS (as in section 2.3, equation 2.18) is illustrated. In the sections below, we show how to calculate 2.18 for various simplifying assumptions.

In chapter 4 we described a number of problems in fitting the SAM model to these data. We showed that the estimated probability of recognition is often very close to 1, and that it is not possible to estimate all parameters uniquely from the data. We have already reported in section 4.2 that the inter-item associative strength is small compared to the context strength, and does hardly contribute to the probability of recovery. It appeared reasonable to assume that the word pair is always recognized at the second presentation, and that we might eliminate the inter-item associative strength from the model. For every version of the model we checked whether the assumptions of successful recognition and the elimination of the inter-item associative strength were sustained.

6.1. DATA FROM TWO PRESENTATIONS: SAMPLING ONLY

In paragraph 2.3 the complete model for twice-presented data was given. The simplified model with only sampling as effective retrieval process will be given in the present section. This reduction of the model is equivalent to the following four assumptions:

1. The word pair is always recognized at the second presentation: $P_{RG}(t_1|\theta_1) = 1$;
2. The short-term store is not active at a subsequent presentation or test: $P_{STS}(t_2) = 0$;
3. The image is always recovered from memory after a successful sampling phase: $P_{REC}(t_1,t_2|\theta_2) = 1$; and
4. The inter-item associative strength is eliminated: $I(t_1,t_2) = 1$.

From these four simplifying assumptions, it follows that the probability of a correct response ($P_{CA}(t_1,t_2)$; using equation 2.16) is:

$$P_{CA}(t_1,t_2) = 1 - (1 - P_{SAM}(t_1,t_2))^{L_{max}},$$

which can be rewritten, using equations 2.1 and 2.7, as:

$$\begin{aligned} P_{CA}(t_1,t_2) &= 1 - \left(1 - \frac{C(t_1,t_2)}{C(t_1,t_2) + Z}\right)^{L_{max}} \\ &= 1 - \left(1 - \frac{O(t_1,t_2)}{O(t_1,t_2) + \frac{Z}{a}}\right)^{L_{max}}. \qquad (6.1) \end{aligned}$$

The parameters for the overlap of stored context elements with the context elements active at the moment of the test can be estimated from the data. Besides these context fluctuation parameters (s, α and w), the value of the parameter combination $\frac{Z}{a}$ can be estimated from the data. As argued in chapter 4, parameter L_{max} is set to 3. The estimated value of w turned out to be always equal to the limit value of 1, implying that all active context elements are stored. Parameter w is therefore set at the fixed value of 1 in the present analyses. Table 6.1 presents the estimated and fixed parameter values for the data of Glenberg and for those of experiment I.

Figures 6.1a and 6.1b show the observed and the predicted percentages (probability times 100) of a correct answer for the data of Glenberg (estimated with the parameter values shown in table 6.1). The observed and predicted percentages for experiment I (estimated with the parameter

Table 6.1. Parameter estimates and values of fixed parameters for the SAM model with only sampling as retrieval process to predict the data of twice-presented stimuli. The second presentation is always recognized implying that the context strength is incremented. Further, the inter-item associative strength is eliminated from the model.

parameter	Glenberg	experiment I
s	.333	.336
α**	.0169	.108
w	1.*	1.*
$\frac{Z}{a}$	1.036	.374
L_{max}	3.*	3.*
χ^2	87.03	72.77
df	21	27

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

values shown in table 6.1) are shown in figures 6.2a and 6.2b, respectively. It appears that the predicted percentages in both figures 6.1b and figure 6.2b approach an asymptotic value for each retention interval. The predicted curves for retention intervals of 8 and 16 events in experiment I are nearly the same, while in the observed data this tendency is not observed. Another aspect is that the peaks and the dips in the observed curves are not reproduced. In the presentation of the experiments and their results in sections 3.2 and 3.3 we argued that the dips and the peaks are likely due to sampling error. When we make allowance for the dips and the peaks not being reproduced, the fit is reasonably good.

In this version of the model, the inter-item associative strength is eliminated from the model. When equation 6.1 is elaborated with the inter-item associative strength, that is with $I(t_1,t_2) = \mathrm{F}(1,2)b$ (equation 2.6), only the parameter combination $\frac{Z}{\mathrm{F}(1,2)\, b\, a}$ can be estimated from the

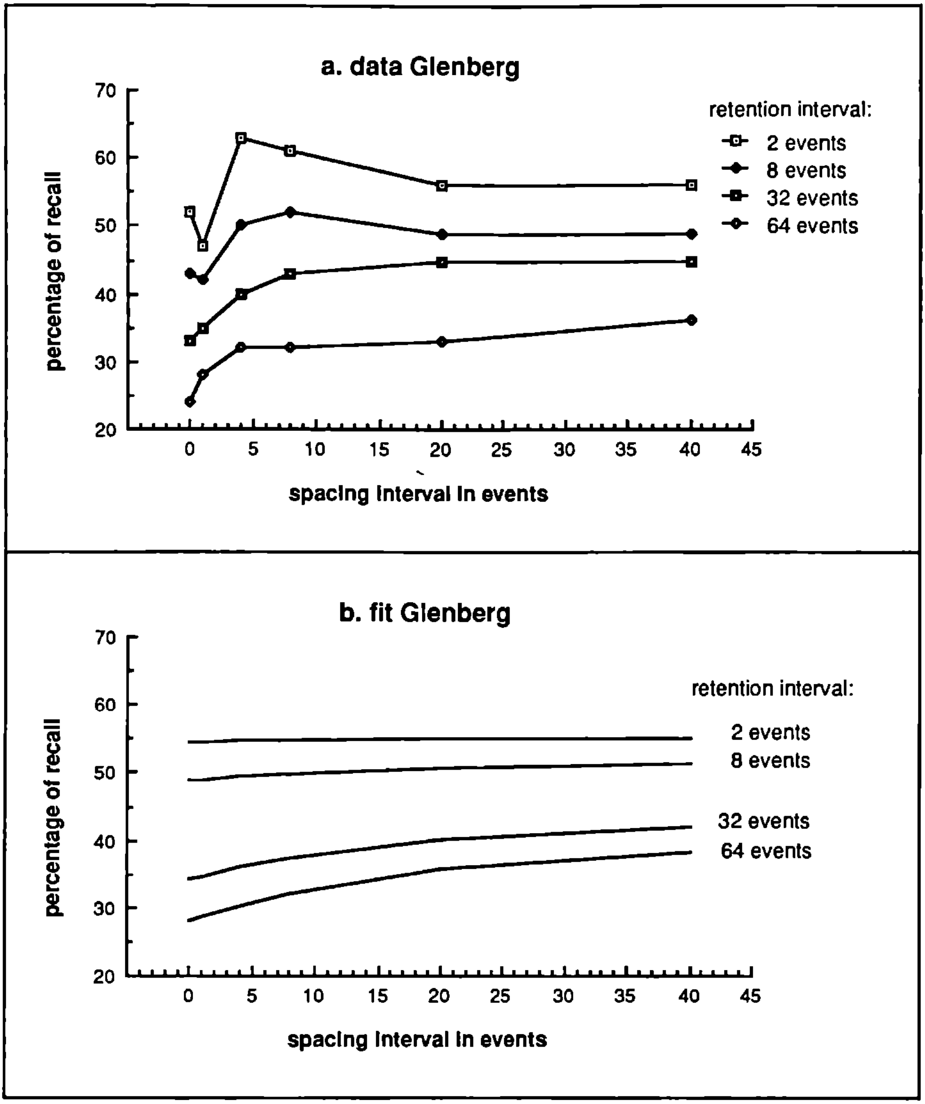

Figure 6.1. The observed data of the experiment of Glenberg are shown in panel a, and the predicted percentage of a correct response, using only the sampling process, are shown in panel b. The recall percentages as function of the spacing interval are shown for various retention intervals. The parameters values of table 6.1 are used to reproduce the data.

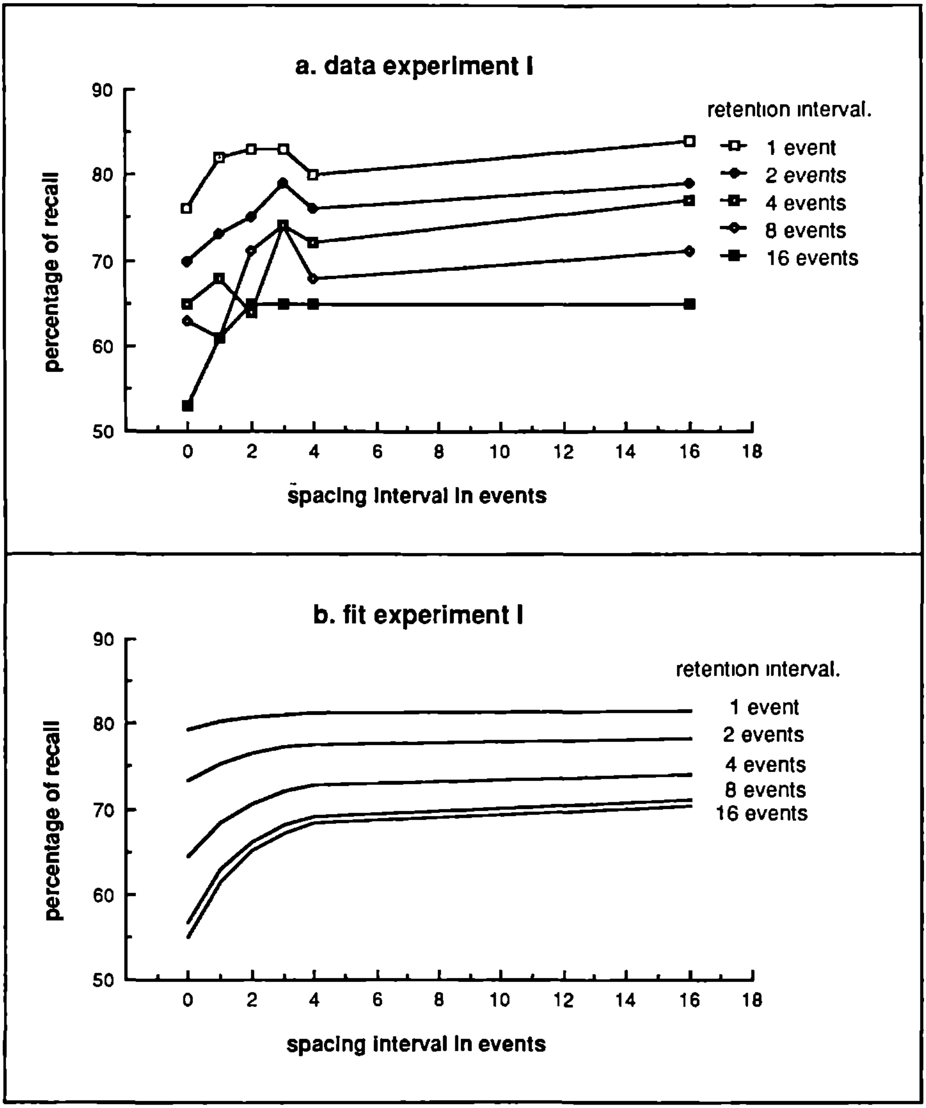

Figure 6.2. The observed percentage of a correct response for experiment I are shown in panel a, the predicted, using only the sampling process, are shown in panel b. The recall percentages as function of the spacing interval are shown for various retention intervals. The parameters values of table 6.1 are used to reproduce the data.

data after rewriting the equation. The parameter b cannot be estimated uniquely from the data, but only in combination with Z and a. Furthermore, the value of the function F(1,2) can only be determined relative to the parameters b, Z, and a.

The data cannot be reproduced when we assume that recognition is not always successful. We attempted to fit the data with the following elaborations of the model where recognition is not always successful.

1. The inter-item associative strength is incorporated. In this case parameter b cannot be uniquely estimated from the data, but only in combination with Z and a. The value for the function to increment the inter-item associative strength cannot be determined. The fit is worse than that presented in table 6.1.
2. When the model is elaborated by a recognition phase and the inter-item associative strength, the probability of recognition is equal to the probability of recall (of a trace formed on a single presentation) for the same interval between presentations or between presentation and test. The inter-item associative strength is used in the same way in recall and recognition. In the literature it is mostly found that the probability of recognition is greater than that of recall (see e.g. Crowder, 1976). On considering the results of experiments with paired-associates it seems reasonable to assume that there are more retrieval cues in the case of recognition than for recall. When a pair must be recognized, both words of a pair are presented, while for recall the first word is presented together with a question mark. It is possible that this aspect of the test is responsible for the failure of the model to describe the data adequately. However, even if we change the model, with a recognition phase and the inter-item associative strength, in such a way that both words are used as cues for recognition, the data are not better reproduced.

It can be concluded that when both data sets have to be described with a model that only incorporates the sampling process it is best to assume that recognition is always successful. This implies that the context strength is always incremented at the second presentation. The fit is not excellent, but it is the optimal fit for a model containing only the sampling process. The inter-item associative strength can be eliminated from the model: this strength cannot be estimated independently from the data.

In the model, using only the sampling process, presented in equation 6.1, the value of the parameter combination $\frac{Z}{a}$ only can be estimated from the data, apart from the context fluctuation parameters s and α. It is not possible to include an additional storage parameter. This storage parameter w is as before fixed at a value equal to 1, implying that all active context elements are stored. Parameter s, the proportion of active elements, is estimated for Glenberg's data to be .333 and for the data of experiment I to be .336. This parameter is estimated consistently at about .33 for both data sets. Parameter α is .0169 for the data of Glenberg and .108 for the data of experiment I, that is the rate of context fluctuation is more rapid for experiment I. The parameter combination $\frac{Z}{a}$ is about three times larger in case of Glenberg's data. The word pairs and the durations of the presentations differ in both experiments as does the level of performance, so that we expect some differences in parameter estimates.

6.2. DATA FROM TWO PRESENTATIONS: RECOVERY ONLY

In section 2.3, the complete model for the twice-presented data was given. We will now assume that only recovery is effective as retrieval process. Compared to the complete model, this implies:

1. The word pair is always recognized at the second presentation: $P_{RG}(t_1|\theta_1) = 1$;
2. The sampling process is always successful: $P_{SAM}(t_1,t_2) = 1$;
3. The short-term store is not effective at a subsequent presentation: $P_{STS}(t_2) = 0$;
4. The inter-item associative strength is eliminated from the model: $I(t_1,t_2) = 0$.

From these four simplifying assumptions, it follows that the probability of a correct answer ($P_{CA}(t_1,t_2)$; using equation 2.16, and rewritten with equations 2.2 and 2.7) is:

$$
\begin{aligned}
P_{CA}(t_1,t_2) &= P_{REC}(t_1,t_2|\theta_2) \\
&= 1 - e^{-\theta_2 C(t_1,t_2)} \\
&= 1 - e^{-\theta_2 a O(t_1,t_2)} .
\end{aligned}
\tag{6.2}
$$

From equation 6.2, it follows that besides the context fluctuation parameters (s, α and w), only $\theta_2 a$ can be estimated from the data. In the previous section (with only sampling as effective retrieval process), two overlap parameters (s and α) have been estimated, and the third overlap parameter (w) fixed at 1. These values can now be used as fixed values in the present application. We also checked the effect of allowing more free parameters. The results are shown in table 6.2. We fixed α at the value

Table 6.2. Parameter estimates and values of fixed parameters for the SAM model with recovery as only retrieval process to predict the data of twice-presented stimuli. Recognition is assumed to be always successful implying that the context strength is always incremented. The inter-item associative strength is eliminated.

parameter	Glenberg	experiment I
$\theta_2 a$	2.318	4.750
s	.362	.406
α**	.0169*	.098
w	1.*	1.*
χ^2	86.5	72.9
df[1]	22 (−1)	27
C	.14 - .36	.16 - .41

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

---

[1] Since we did not re-estimate parameters which were estimated in previous analysis, but fixed them at those previous estimates, the table shows the number of degrees of freedom according to the number of parameters which were not fixed. Between parentheses the number of not re-estimated parameters is shown.

obtained in the previous section. For the data from Experiment I, fixing α at the same value resulted in a very poor fit. So we estimated α anew for Experiment I. This leads to a fit for both data sets which is about equal as shown in section 6.1 (sampling only).

We also attempted to reproduce the data when the word pair is not always recognized at the second presentation. We assume for the present analysis also that (1) the sampling process is always successful, (2) the STS is not effective, and (3) the inter-item associative strength is eliminated. In that case the probability of a correct answer is given by equation 2.18. The probabilities of recognition and recall were given in equations 2.15, 2.16 and 2.17, and can be rewritten, using equations 2.2 and 2.7, as:

$$\begin{aligned} P_{RG}(t_1|\theta_1) &= P_{REC}(t_1|\theta_1) \\ &= 1 - e^{-\theta_1 aO(t_1)}, \end{aligned} \tag{6.3}$$

$$\begin{aligned} P_{RL}(t_2|\theta_2) &= P_{REC}(t_2|\theta_2) \\ &= 1 - e^{-\theta_2 aO(t_2)}) \\ &= 1 - e^{-\frac{\theta_2}{\theta_1}\theta_1 aO(t_1)}, \end{aligned} \tag{6.4}$$

and

$$\begin{aligned} P_{RL}(t_1,t_2|\theta_2) &= P_{REC}(t_1,t_2|\theta_2) \\ &= 1 - e^{-\theta_2 aO(t_1,t_2)} \\ &= 1 - e^{-\frac{\theta_2}{\theta_1}\theta_1 aO(t_1,t_2)}. \end{aligned} \tag{6.5}$$

It is possible to reduce the three parameters θ_1, θ_2 and a mathematically to two parameters with the following substitutions (see also section 4.1):

$$u = \theta_1 a,$$

$$y = \frac{\theta_2}{\theta_1},$$

giving the following probabilities of recognition and recall:

$$P_{RG}(t_1|\theta_1) = 1 - e^{-uO(t_1)}, \tag{6.3a}$$

$$P_{RL}(t_2|\theta_2) = 1 - e^{-yuO(t_2)}, \tag{6.4a}$$

$$P_{RL}(t_1,t_2|\theta_2) = 1 - e^{-yuO(t_1,t_2)}. \tag{6.5a}$$

Therefore, one out of the three parameters θ_1, θ_2 and a cannot be estimated independently. Mathematically it is possible to estimate five parameters from this model, that is the context fluctuation parameters s, α, and w, for the overlap of active elements, and the two parameter combinations $\theta_1 a$ and $\frac{\theta_2}{\theta_1}$. $\theta_2 < \theta_1$ follows from the fact that the probability of recognition is greater than that of recall, and therefore that $\frac{\theta_2}{\theta_1} < 1$. In the application of the model with only sampling as effective retrieval process (see section 6.1.), two of the three overlap parameters (s and α) have been estimated and are used as starting values, the third overlap parameter, w, is as before, set to 1.

The results for this section are shown in table 6.3. The fit for the data of Glenberg in terms of χ^2 is similar to that found in table 6.2 (recovery only and recognition always successful), but the number of degrees of freedom is smaller. The fit for the data of experiment I in terms of χ^2 is better than that presented in table 6.2, while the number of degrees of freedom is 26 in stead of 27. Inspecting the predictions for the probabilities of recognition, we see that this probability is greater than .99 and .82 for the data of Glenberg and experiment I, respectively.

Furthermore, we attempted to fit the data after re-incorporation of the inter-item associative strength in the model, but the estimated value of the

Table 6.3. Parameter estimates and values of fixed parameters as found from the SAM model with recovery as effective retrieval process to predict the data of twice-presented stimuli. Recognition is assumed to be not always successful implying that the recognition process is an effective retrieval process. The inter-item associative strength is eliminated from the model.

parameter	Glenberg	experiment I
$\theta_1 a$	17.48	10.03
s	.366	.412
α**	.0169*	.102
w	1.*	1.*
$\frac{\theta_2}{\theta_1}$	.132	.475
χ^2	86.4	68.3
df	21 (–1)	26
recognition	.994 - .998	.818 - .984

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

inter-item associative strength turned out to be approximately zero. Therefore the inter-item associative strength can indeed be eliminated.

We conclude that the data of Glenberg can be described by the model presented in equation 6.2, that is assuming that recognition is always successful. Incorporating a recognition phase in the model does not improve the fit, and the estimated recognition probability is nearly 1. For the data of experiment I the model assuming that recognition is not always successful, is somewhat better than the model for which recognition is assumed to be always successful, but the benefit in terms of χ^2 is small, and there is a small loss in terms of the number of degrees of freedom. We conclude that both data can be described using a model where recognition is always successful, when assuming only recovery as effective retrieval process. The assumption that recognition is always successful, implies that the context strength is always incremented at the second presentation. The fit is not excellent, but is the optimal fit for a model containing only the recovery process.

In this model only s, α, w and $\theta_2 a$ could be estimated from the data. The storage parameter w was always equal to 1, implying that all active elements are stored. Parameter s, the proportion of active elements, and α, the rate of context fluctuation, were estimated for Glenberg's data at about .36 and .0169 respectively, and for the data of experiment I at .41 and .10. These values are essentially the same as reported in section 6.1, and the comments given there also apply here.

6.3. DATA FROM TWO PRESENTATIONS: SAMPLING AND STS

In this section the version of the model with only sampling is elaborated with a short-term store. In section 6.1 the model using only sampling and assuming that recognition is always successful at a second presentation ($P_{RG}(t_1|\theta_1) = 1$) gave a good description of the data, and therefore the STS is not effective at P_2. The strength of the trace is always increased at P_2. We now re-incorporate a short-term store in this model. At the moment of testing, the strengthened trace can be retrieved from long-term memory or the correct answer given when the item is still in the STS. The recovery process is still eliminated, or equivalently, is assumed to be always successful, that is: $P_{REC}(t_1,t_2|\theta_2) = 1$. The inter-item associative strength is eliminated ($I(t_1,t_2) = 1$), as before. The probability of a correct answer, $P_{CA}(t_1,t_2)$, can be derived from equation 2.16, which can be rewritten (using equations 2.1, 2.4, and 2.7) as:

$$\begin{aligned} P_{CA}(t_1,t_2) &= P_{STS}(t_2) + \{1 - P_{STS}(t_2)\}\ \{1 - (1 - P_{SAM}(t_1,t_2))^{L_{max}}\} \\ &= e^{-\lambda t_2} + \{1 - e^{-\lambda t_2}\}\ \{1 - (1 - \frac{O(t_1,t_2)}{O(t_1,t_2) + \frac{Z}{a}})^{L_{max}}\}. \end{aligned} \tag{6.6}$$

The three context fluctuation parameters s, α and w, the combination of parameters $\frac{Z}{a}$ and the STS parameter λ can be estimated from the data. We fixed parameter L_{max} at 3, and parameter w at 1, because in the applications to both data sets the estimated value of the latter parameter turned out to be always equal to 1. In table 6.4 the estimated and fixed parameter values are shown. In the first and third solutions the results are shown when parameters s, and α are fixed at values found in the application with only sampling as retrieval process (presented in table 6.1). Only two parameters (or parameter combinations) λ and $\frac{Z}{a}$ are estimated from the data. In solutions 2 and 4, the results are shown when parameter s and α are also estimated from the data. The probability of being in the STS is small: With a retention interval of 1 or 2 events there is a between 2 and 13 % chance that the item is still in STS. As can be seen by comparing the results in table 6.4 with those in table 6.1, the model elaborated with a short-term store can describe the data slightly better than a model without a STS. For Glenberg's data the χ^2 value is reduced from 87.0 to 81.7 with one degree of freedom less when the

Table 6.4. Parameter estimates and values of fixed parameters for the SAM model using sampling and a STS to describe the data of Glenberg and experiment I. We assume here that recognition is always successful, and eliminate the inter-item associative strength from the model.

parameters	Glenberg		experiment I	
	1	2	3	4
s	.333*	.357	.336*	.396
α**	.0169*	.0137	.108*	.094
w	1.*	1.*	1.*	1.*
$\frac{Z}{a}$	1.055	1.212	.376	.499
L_{max}	3.*	3.*	3.*	3.*
λ**	.561	.436	.778	.514
χ^2	84.70	81.68	71.29	68.48
df	22 (−2)	20	28 (−2)	26

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

model with sampling is extended with a short-term store. There is also a significant improvement of the fit for the data of experiment I. χ^2 reduces from 72.8 without STS to 68.5 with STS. Even when the context fluctuation parameters are fixed at values estimated for the model without STS, the fit for the model with STS is appreciably better.

We also checked the assumption that recognition may not always be successful at the second presentation. No acceptable fit could be obtained, when the recognition is not always successful. We formulated the probability of recognition in different ways (for example using both words as separate cues in case of recognition), and tried to reproduce the data with an effective recognition phase (not always successful), but failed. It should be noted that taking the inter-item associative strength into account cannot improve the fit when recognition is always successful, because the inter-item associative strength can only be estimated in combination with parameters Z and a, as the parameter combination $\frac{Z}{F(1,2)b\,a}$ (cf. section 6.1).

It can be concluded that a model using both the sampling process and a short-term store and assuming that the word pairs are always recognized at a second presentation can describe the data better than a model using only the sampling process. A model with 4 parameters can describe the data slightly better than a model with 3 parameters.

6.4. DATA FROM TWO PRESENTATIONS: RECOVERY AND STS

In the previous section, we elaborated the model in section 6.1 (sampling only) with a STS. We will now elaborate the model of section 6.2 (recovery only) with a STS. As in section 6.2, we assume:

1. The item pair is always recognized at the second presentation: $P_{RG}(t_1|\theta_1) = 1$. Therefore the strength of the trace is always increased at P_2;
2. The inter-item associative strength is eliminated, as before: $(I(t_1,t_2) = 0)$;
3. The sampling phase is eliminated, or equivalently, is assumed to be always successful, that is: $P_{SAM}(t_1,t_2) = 1$.

At testing a correct answer is given when the item is still present in the STS or when the item is recovered from long-term memory. The probability of a correct answer $P_{CA}(t_1,t_2)$ can be derived from equation 2.16, which may be rewritten (using equations 2.2, 2.4, and 2.7) as:

$$\begin{aligned} P_{CA}(t_1,t_2) &= P_{STS}(t_2) + \{1 - P_{STS}(t_2)\}\, P_{REC}(t_1,t_2|\theta_2) \\ &= e^{-\lambda t_2} + \{1 - e^{-\lambda t_2}\}\,\{1 - e^{-\theta_2 a O(t_1,t_2)}\}. \end{aligned} \tag{6.7}$$

Apart from the three context fluctuation parameters s, α and w, the parameter combination $\theta_2 a$, and the STS parameter λ can be estimated from the data. In table 6.5 the fixed and estimated parameter values of these parameters are shown. In solutions 1 and 3, the results are given when parameters s and α are fixed at the values found earlier for recovery only (table 6.2). The fits improve slightly compared to those shown in table 6.2, which was based on only recovery as retrieval

Table 6.5. Parameter estimates and values of fixed parameters using recovery and a STS to describe the data of both Glenberg and experiment I. We assume here that recognition is always successful, and eliminate the inter-item associative strength from the model.

parameters	Glenberg		experiment I	
	1	2	3	4
$\theta_2 a$	2.287	2.023	4.722	3.742
s	.364*	.385	.406*	.466
α**	.0169*	.0133	.098*	.0867
w	1.*	1.*	1.*	1.*
λ**	.577	.441	.749	.498
χ^2	84.68	81.56	71.07	67.99
df	22 (−2)	20	28 (−2)	26

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

process. In solutions 2 and 4, the results are shown when s and α are also estimated from the data. For the data of Glenberg the χ^2 reduces from 86.5 to 81.6 and for the data of experiment I from 72.9 to 68.0 when the model using the recovery process is extended with a short-term store, but with actually one degree of freedom less. The probability of being in the STS is small after 1 or 2 events for all four solutions. The fits of the model using both recovery and a STS are significantly better than those of the model using only recovery.

We also attempted to fit the data using a model for which recognition is not always successful at the second presentation, and found that this can reproduce the data of experiment I slightly better than the model presented just above (equation 6.7). We also assume here that the sampling process is always successful and we eliminate the inter-item associative strength from the model. In this case the probability of a correct answer, $P_{CA}(t_1,t_2)$, is given by equation 2.18, and can be rewritten, using equations 2.2, 2.4, 2.5, and 2.7, as:

$$\begin{aligned} P_{CA}(t_1,t_2) = {} & \{e^{-\lambda t_1} + (1-e^{-\lambda t_1})(1-e^{-\theta_1 aO(t_1)})\} \times \\ & \{e^{-\lambda t_2} + (1-e^{-\lambda t_2})(1-e^{-\theta_2 aO(t_1,t_2)})\} \\ & + [1-\{e^{-\lambda t_1} + (1-e^{-\lambda t_1})(1-e^{-\theta_1 aO(t_1)})\}] \times \\ & \{e^{-\lambda t_2} + (1-e^{-\lambda t_2})(1-e^{-\theta_2 aO(t_2)})\}. \qquad (6.8) \end{aligned}$$

The context fluctuation parameters s, α and w, the STS parameter λ, and the two parameter combinations $\theta_1 a$ and $\frac{\theta_2}{\theta_1}$, can be estimated from the data. Parameters L_{max} and w are fixed at 3 and 1 respectively. In table 6.6 the starting values were the parameter values found for the case of only recovery (table 6.2). In solutions 1 and 3, the results are shown for which parameters s and α are fixed. In solutions 2 and 4, the results are shown when s and α are also estimated from the data, resulting in a slightly better fit. For solutions 1, 2 and 4, the probability of being in the STS is small for spacing or retention intervals that are greater than 0 events. For solution 3, the pair is in the STS only after a spacing or retention interval of 0 events. The results presented in table 6.6 using the data of Glenberg

Table 6.6. Parameter estimates and values of fixed parameters using recovery and a STS to describe the data of both Glenberg and experiment I. We assume here that recognition is not always successful, and eliminate the inter-item associative strength.

parameters	Glenberg		experiment I	
	1	2	3	4
$\theta_1 a$	25.658	36.211	11 072	9.678
s	.364*	.385	.406*	.453
α**	.0169*	.0133	.098*	.0916
w	1.*	1.*	1.*	1.*
$\frac{\theta_2}{\theta_1}$	.0892	.0559	.437	.413
λ**	.580	.441	532.187***	.570
χ^2	84.66	81.57	68.69	65.66
df	21 (−2)	19	27 (−2)	25
recognition	.98–1.00	1.00–1.00	.84–.99	.86–.99

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

*** For all values of $\lambda \geq 1.5$ the effect of the buffer is negligible for retention intervals of 4 seconds and greater.

(solutions 1 and 2) are just as good as those in table 6.5, but with one fewer degree of freedom. Because the estimates of the parameters are such that the estimated probability of recognition turned out to be greater than .98, that is recognition has nearly always success, adding a recognition phase does not improve the results. For the data of experiment I, the results presented in table 6.6 (solutions 3 and 4) are slightly better than those in table 6.5 (a χ^2 of 68.7 instead of 71.1, and a χ^2 of 65.7 instead of 68.0 with one degree of freedom less), and show a high probability of recognition.

We also attempted to fit the data with the inter-item associative strength added to the model, but a zero inter-item associative strength gives the better prediction. For other values of the inter-item associative strength the fit is worse.

In summary: Elaboration of the model using the recovery process with a short-term store improves the fit slightly (For Glenberg's data χ^2 is 81.6 instead of 86.5, and for experiment I, χ^2 is 68.0 instead of 73.0). For experiment I, incorporating a recognition phase in the model leads to a slightly better fit but this has no effect at all for the data of Glenberg.

6.5. DATA FROM TWO PRESENTATIONS: SAMPLING AND RECOVERY

Next, we attempt to fit the model with both sampling and recovery as retrieval processes. As before, we assume:

1. Recognition is always successful: $P_{RG}(t_1|\theta_1) = 1$;
2. The STS is not active at the second presentation and at testing: $P_{STS}(t_2) = 0$;
3. The inter-item associative strength is eliminated.

From these simplifying assumptions, it follows that the probability of a correct response (derived from equation 2.16, and rewritten, using equations 2.1, 2.2, 2.3, and 2.7) is:

$$\begin{aligned} P_{CA}(t_1,t_2) &= \{1 - (1 - P_{SAM}(t_1,t_2))^{L_{max}}\}\, P_{REC}(t_1,t_2|\theta_2) \\ &= \{1 - (1 - \frac{O(t_1,t_2)}{O(t_1,t_2) + \frac{Z}{a}})^{L_{max}}\}\, \{1 - e^{-\theta_2 a O(t_1,t_2)}\}. \qquad (6.9) \end{aligned}$$

The context fluctuation parameters s and α, and the combinations $\frac{Z}{a}$ and $\theta_2 a$ can be estimated from the data. As before, parameter L_{max} is fixed at 3. and w at 1. Fixing s and α at values obtained for sampling only (table 6.1) gives slightly better results than those found when using only recovery (table 6.2) to predict the data. These results are shown as solutions 1 and 3 of table 6.7. Solutions 2 and 4, both include parameters s and α estimated from the data. Estimates using both s and α do not improve the fit.

Table 6.7. Parameter estimates and values of fixed parameters for the SAM model using sampling and recovery to describe the data of both Glenberg and experiment I. We assume here that recognition is always successful, and we eliminate the inter-item associative strength.

parameters	Glenberg		experiment 1	
	1	2	3	4
$\theta_2 a$	30.21	2.426	506.47	235.35
s	.333*	.452	.336*	.337
α**	.0169*	.0138	.108*	.108
w	1.*	1.*	1.*	1.*
$\frac{Z}{a}$	1.029	.522	.373	.374
L_{max}	3.*	3.*	3.*	3.*
χ^2	86.34	85.23	72.78	72.77
df	22 (–2)	20	28 (–2)	26
sampling	.27 - .71	.66 - .84		
recovery	.97 - 1.00	.42 - .66	1.00	1.00

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

For the data of Glenberg the estimated value of the parameter combination $\theta_2 a$ in solution 1 is much larger than that in solution 2, also the estimated probability of recovery is close to 1 implying that the influence of a recovery process on the probability of a correct answer is very small. For solution 2, both sampling and recovery have a substantial contribution to the probability of a correct answer. The other estimated parameters in solution 2 are different from those in solution 1 because they are adjusted to the level of the value of $\theta_2 a$.

For experiment I (solutions 3 and 4), the estimated value of the parameter combination $\theta_2 a$ is very large, which implies that the estimated probability of recovery is almost 1. If the value of the parameter combination $\theta_2 a$ is ≥ 50, the probability of recovery is close to 1 for the parameter s and α values presented in solutions 3 and 4. The exact value of the parameter combination does not matter.

The fits for both data sets are just as good as those for only sampling (cf. section 6.1) or only recovery (cf. section 6.2; table 6.2), assuming that recognition is always successful. The fit is somewhat worse for the data of experiment I compared to that of the model with only recovery assuming that recognition is not always successful (cf. section 6.2; table 6.3).

We also checked the effect of the assumption that recognition is not always successful. We found that the reproduction of the data was just as good in terms of χ^2 as that for the model with only recovery and a sometimes successful recognition phase, but there were fewer degrees of freedom.

The sampling probability is a multiplicative function of inter-item associative and context strengths, and the recovery probability is an additive function of these. If either sampling or recovery, but not both, is assumed the two strengths cannot be estimated independently, but when both sampling and recovery are assumed, the ratio between these strengths can be estimated. We checked the effect of re-incorporation of the inter-item associative strength in the model, presented in equation 6.9. We found no fit improvement in terms of χ^2 and the number of degrees of freedom was smaller. We found that the estimated probability of recovery turned out to be nearly 1, so that the probability of a correct answer was largely determined by the sampling process.

We conclude that a model with both sampling and recovery as retrieval processes can reproduce the data no better than a model with sampling only or a model with recovery only.

6.6. DATA FROM TWO PRESENTATIONS: SAMPLING, RECOVERY AND STS

Finally, in this section we will use a model with sampling, recovery and a STS to reproduce the data. We assume that recognition is always successful ($P_{RG}(t_I|\theta_1) = 1$) and that the inter-item associative strength is eliminated from the model. The probability of a correct answer,

$P_{CA}(t_1,t_2)$, can be derived from equation 2.16, which can be rewritten (using equations 2.1 to 2.5, and 2.7) as:

$$
\begin{aligned}
&P_{CA}(t_1,t_2)\\
&\quad = P_{STS}(t_2) + \{1-P_{STS}(t_2)\}\{1-(1-P_{SAM}(t_1,t_2))^{L_{max}}\}\, P_{REC}(t_1,t_2|\theta_2)\\
&\quad = e^{-\lambda t_2} + \{1-e^{-\lambda t_2}\}\{1-(1-\frac{O(t_1,t_2)}{O(t_1,t_2)+\frac{Z}{a}})^{L_{max}}\}\{1-e^{-\theta_2 a O(t_1,t_2)}\}.
\end{aligned}
\tag{6.10}
$$

Parameters s, α, and λ, and the combinations $\frac{Z}{a}$ and $\theta_2 a$ can be estimated from the data. Parameters L_{max} and w are fixed at respectively 3 and 1. In solutions 1 and 3 in table 6.8 the results are shown when s and α are fixed at the values found earlier (using only sampling; table 6.1), and in solutions 2 and 4, the results are shown when these are also estimated from the data.

Estimation of s and α from the data results in a slightly better fit than fixing these parameters. The estimated parameter combination $\theta_2 a$ for Glenberg's data in solution 1 is greater than in solution 2. In solution 1 the probability of recovery is very large, showing that sampling is largely the effective retrieval process, this is because there are no word pairs in the STS after retention intervals greater than zero. Solution 2 shows all three processes are effective in determining the probability of a correct answer. The word pairs are no longer in the STS after a retention interval greater than zero for solution 1, because λ is so large. For all values of $\lambda \geq 1$, the STS is no longer active at a retention interval of two events (or six seconds in case of Glenberg's data). For solution 2 the effect of the STS is very small.

The parameter combination $\theta_2 a$ for experiment I in solutions 3 and 4 is so large that the recovery turned out to be always successful in both solutions. That is, recovery is not effective here as retrieval process; sampling and the STS determine the probability of a correct answer. The effect of the STS is very small: Only for the two smallest retention intervals of one and two events (or four and eight seconds) is there a small probability that the word pair is still present in the STS.

Table 6.8. Parameter estimates and values of fixed parameters for the SAM model using sampling, recovery and a STS to describe the data of both Glenberg and experiment I. We assume here that recognition is always successful, and eliminate the inter-item associative strength.

parameters	Glenberg		experiment 1	
	1	2	3	4
$\theta_2 a$	30.205	6.869	168.76	52.659
s	.333*	.447	.336*	.396
α**	.0169*	.0121	.108*	.0939
w	1.*	1.*	1.*	1.*
$\frac{Z}{a}$	1.029	1.422	.376	.500
L_{max}	-3.*	3.*	3.*	3.*
λ**	457.77***	.420	.778	.513
χ^2	86.34	78.20	71.29	68.48
df	21 (−2)	19	27 (−2)	25
sampling	.27 - .56	.54 - .74	.54 - .81	.56 - .79
recovery	.97 - 1.	.79 - .95	1.	1.

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

*** For all values of $\lambda \geq 1.5$ the effect of the buffer is negligible for retention intervals of 4 seconds and greater.

The fit to the data of Glenberg (solution 2) is better than the fits of the models presented before. For experiment I the fit seems to be just as good as for models with sampling or recovery both elaborated with a STS.

We tried to fit the data using the assumption that the word pair is not always recognized at the second presentation, but the fit did not improve. Neither did elaboration of the model of equation 6.10 with an additional parameter for the inter-item associative strength improve the reproduction of the data.

6.7. DATA FROM TWO PRESENTATIONS: CONCLUSIONS

A model with sampling only (section 6.1) can reproduce the data just as well as a model with recovery only (section 6.2). Both can describe the data to an acceptable level, in terms of χ^2, but both models elaborated with a short-term store (sections 6.3 and 6.4) can describe the data somewhat better. The model with both sampling and recovery (section 6.5) as retrieval processes does not improve the fit compared to the two models with either only sampling or only recovery.

A model with all three processes, sampling, recovery and a short-term store (cf. section 6.6) can describe Glenberg's data slightly better than the more simple models in terms of χ^2. However, when the number of degrees of freedom are taken into account we prefer the more simple models of sampling with a STS or recovery with a STS. For the reproduction of the data of experiment I, the χ^2 for the model with sampling, recovery and a STS is equal to that for the models with sampling and a STS, or with recovery and a STS, but the number of degrees of freedom is smaller.

The only model that can describe the data better, in terms of χ^2, than the two models of sampling and recovery, both being elaborated with a STS, is the model with recovery and a STS in which the word pairs are not always recognized at the second presentation.

For both the data of Glenberg and those of experiment I, parameter s, the proportion of active context elements, is estimated at a value of about .40. The rate of fluctuation of context elements (α) between active and non-active states is for the data of Glenberg about .015 and for that of experiment I about .100. The differences in this rate of context fluctuation can be due to differences in the experimental design and conditions of both experiments. The inter-item associative strength can be eliminated from the model without making the fit worse. The inter-item associative strength was, therefore, not estimated from the data. A model without the inter-item associative strength, using only the context strength, can be used to describe both the data of Glenberg and those of experiment I.

We conclude that the two SAM models, sampling elaborated with a short-term store and recovery with a STS, can be used to describe the data.

7. PREDICTING RUMELHART'S DATA

Nonsense words coupled with one out of three numbers (3, 5 or 7) were presented in the continuous paired-associate experiment of Rumelhart described in section 3.5. Each presentation was preceded by an anticipation trial of the pair, where the nonsense word was presented and the number has to be recalled. In this section the data of Rumelhart will be described by various versions of a model based on the general model presented in section 2.4, where the final probability of retrieval ($P_F(t_1, \ldots, t_n)$) without guessing at the nth presentation, P_n, is given in equation 2.20 by:

$$P_F(t_1,..,t_n)$$
$$= \prod_{i=1}^{n} P_{RL}(t_1,..,t_i|\theta_2) + \sum_{i=1}^{n-1} \left[\{1 - P_F(t_1,..,t_i)\} \prod_{m=i+1}^{n} P_{RL}(t_{i+1},..,t_m|\theta_2) \right],$$

which can be rewritten, using equation 2.19, as:

$$P_F(t_1,..,t_n) = \prod_{i=1}^{n} \left[P_{STS}(t_i) + (1 - P_{STS}(t_i))\, P_{RET}(t_1,..,t_i) \right]$$
$$+ \sum_{i=1}^{n-1} \left[\{1 - P_F(t_1,..,t_i)\} \prod_{m=i+1}^{n} \{ P_{STS}(t_m) + (1 - P_{STS}(t_m)) P_{RET}(t_{i+1},..,t_m) \} \right], \tag{7.1}$$

and the probability of a correct answer ($P_{CA}(t_1,\ldots,t_{n-1})$) at P_n with both retrieval and guessing is given by equation 2.21 as:

$$P_{CA}(t_1,\ldots,t_{n-1}) = P_F(t_1,\ldots,t_{n-1}) + \tfrac{1}{3}\,(1 - P_F(t_1,\ldots,t_{n-1})) \tag{7.2}$$

First, we tried to predict the data with the most simplified versions of the model, i.e. with either sampling or recovery only. Second, both versions are extended with a short-term store. Third, the predictions of a model with both sampling and recovery are given. Finally, the most complicated version is illustrated. In the sections below, we show how to apply equation 7.1 to a variety of simplifying assumptions.

7.1. DATA FROM RUMELHART: SAMPLING ONLY

The model with only sampling as the effective retrieval process is effectively making the following assumptions:

1. The short-term store is not active at a subsequent presentation or test, that is: $P_{STS}(t_i) = 0$ for all i;
2. The image is always recovered from long-term memory after a successful sampling phase, i.e.: $P_{REC}(t_i,\ldots,t_m|\theta_2) = 1$ for all i and m.

Therefore, the probability of retrieval from LTS (equation 2.19 and 2.3) depends only on the sampling process and is given by:

$$P_{RET}(t_i,\ldots,t_m) = 1 - \{1 - P_{SAM}(t_i,\ldots,t_m)\}^{L_{max}} \qquad \text{for all } i \text{ and } m.$$

This can be rewritten, using equations 2.1, 2.6 and 2.7, as:

$$P_{RET}(t_i,\ldots,t_m) = 1 - \{1 - \frac{\mathrm{F}(i,m)\, O(t_i,\ldots,t_m)}{\mathrm{F}(i,m)\, O(t_i,\ldots,t_m) + \frac{Z}{b\,a}}\}^{L_{max}} \qquad (7.3)$$

for all i and m.

Equation 7.3 shows that the parameter combination $\frac{Z}{b\,a}$ together with the context fluctuation parameters s, α and w can be estimated from the data. As in the applications of the model to other kinds of data L_{max} is fixed at 3.

We will compare the effect of not incrementing the inter-item associative strength to that of incrementing it.

1. When the inter-item associative strength is not incremented after successful recall the value of the function F(i,m) (equation 2.6) is constant, and is equal to 1 for all i and m. In the first solution of table 7.1 the parameter estimates and the values of the fixed parameters are shown for this analysis. The parameter values for s and α found using only sampling to predict the data of experiment I are used as starting values. Only about 20 % of the active context elements are estimated to

Table 7.1. Parameter estimates and values of fixed parameters for the SAM model using sampling only to describe the data of the experiment of Rumelhart.

Parameters	Increment of inter-item strength	
	no	yes
s	.369	.217
α	.366	.147
w	.196	1.00
$\frac{Z}{b\,a}$	.087	.351
L_{max}	3.*	3.*
F(i,m)	1.	$m-i+1$
χ^2	82.52	79.25
df	36	36

Note: * The value of a fixed parameter.

be stored in memory and the fit is reasonable. Note that parameter b (the inter-item associative strength after a single presentation) cannot be estimated uniquely from the data, but only in combination with parameters Z and a. When the inter-item associative strength is not incremented after successful recall (F(i,m) = 1), the inter-item associative strength is a constant ($I(t_i,\ldots,t_m)$=F$(i,m)b=b$) and can, therefore, be eliminated from the model without making the fit worse.

2 When the inter-item associative strength is incremented after a successful recall the function F(i,m) is equal to $m-i+1$ (equation 2.6). This implies that after every successful recall the inter-item associative strength is increased by the basic value for a single presentation. The second solution shown in table 7.1 shows the estimates if both the inter-item associative strength and the context strength are incremented after every successful recall. This leads to a slightly better fit. When the inter-item associative strength is incremented after successful recall the estimated value of parameter w turned out to be equal to 1, implying that all active context elements are stored in memory.

Note that the estimates of parameters s and α shown in solution 1 of table 7.1 are both about twice those in solution 2, whereas the estimates of the parameter combination $\frac{Z}{b\ a}$ and of parameter w are about four and five times smaller, respectively. The ratio of the context overlap and the parameter combination $\frac{Z}{b\ a}$ is about the same for both solutions, and therefore so is the probability of sampling. When the inter-item associative strength is incremented after successful recall, the parameter b (the inter-item associative strength after a single presentation) can only be estimated in combination with the parameters Z and a. Only the function to increment the inter-item associative strength is independent of the estimable parameters. The exact values of the inter-item associative strength cannot be estimated, and parameter b can be eliminated from the model without making the fit worse.

It can be concluded that the model incrementing both the inter-item associative strength and the context strength fits the data somewhat better than if only the context strength is incremented. The parameter b (the inter-item associative strength after a single presentation) can be eliminated from the model without worsening the fit. However, inclusion of the function used to increase the inter-item associative strength, in the model gives rise to a somewhat better fit than if the model is used without this function. Using only the sampling process as retrieval process can describe the data to an acceptable level.

7.2. DATA FROM RUMELHART: RECOVERY ONLY

Next, we assume that only recovery is used as effective retrieval process. That is equivalent to making the following assumptions:

1. The STS is not effective at time of testing: $P_{STS}(t_i) = 0$ for all i;
2. The image is always sampled from memory, that is: $P_{SAM}(t_i,\ldots,t_m) = 1$ for all i and m.

The probability of retrieval from LTS (equations 2.3 and 2.19) depends only on the recovery process and is given by:

$$P_{RET}(t_i,\ldots,t_m|\theta_2) = P_{REC}(t_i,\ldots,t_m|\theta_2) \quad \text{for all } i \text{ and } m,$$

which can be rewritten, using equations 2.2, 2.6 and 2.7, as:

$$P_{RET}(t_1,\ldots,t_m|\theta_2) = 1 - e^{-\theta_2 b\ \mathrm{F}(i,m) + \theta_2 a O(t_1,\ldots,t_m)} \qquad (7.4)$$

for all i and m.

In addition to the context fluctuation parameters s, α and w, only $\theta_2 b$ and $\theta_2 a$ can be estimated. As in the previous section (only sampling), we will compare here the effect of incrementing and not incrementing the inter-item associative strength. The parameter estimates and the values of the fixed parameters are given in table 7.1. For the values shown in solution 1 and 2, we assume that there is no increment of the inter-item associative strength ($\mathrm{F}(i,m)=1$ for all values of i and m). The parameter values for s, α and w found in table 7.1 with only sampling as retrieval process, are used as starting values. In the first solution in table 7.2, the parameters s, α and w are fixed at these starting values. The fit is somewhat better than that presented in table 7.1. Next, the effect of estimating some or all of the parameters s, α and w from the data is

Table 7.2. Parameter estimates and values of fixed parameters for the SAM model with recovery only to describe the data of the experiment presented by Rumelhart.

Parameters	Increment of inter-item strength			
	no	no	yes	yes
$\theta_2 b$	.219	.000	.109	.000
$\theta_2 a$	21.794	10.648	9.736	10.648
s	.369*	.424	.369*	.424
α	.366*	.330	.366	.330
w	.196*	.404	.500	.404
F(i,m)	1.	1.	$m-i+1$	$m-i+1$
χ^2	76.88	67.12	68.42	67.12
df	38 (−3)	35	36 (−1)	35

Note: * The value of a fixed parameter.

checked. Estimating all three parameters from the data results in the best fit. The second solution shows these parameter estimates. The fit is better than that presented in table 7.1 and an improvement on solution 1. The inter-item associative strength (b) can only be estimated in combination with parameter θ_2. The estimated value of this parameter combination is zero (see solution 2). This implies that the inter-item associative strength can be eliminated from the model without worsening the fit (note that the degrees of freedom become larger after the elimination). Therefore, the function $F(i,m)$, which is multiplied with the parameter combination $\theta_2 b$, has no effect either. About 40 % of the active context elements are estimated to be stored in memory.

Next, we assume that the inter-item associative strength is incremented after every successful recall, that is $F(i,m)=m-i+1$ for all i and m as described in section 2.1. The parameter values found in solution 2 of table 7.1 while using only sampling are used as starting values. Fixing parameters s, α and w at these values results in a poor fit. Estimating all 5 parameters from the data with these values as starting values turned out to be impossible. Some of the parameters, a and w, attained extreme high or low values, respectively, and no minimum χ^2 was found. A reasonable solution was reached when we used the values of solution 1 of table 7.2 as starting values for s, α and w, and fixed only s. The results of this analysis are shown as solution 3. The fit is about as good as that of solution 2. There is some effect of the inter-item associative strength, but this effect is small compared to the context strength (1 : 7). The best solution was reached by estimating all parameters from the data with the values of solution 1 as starting values. The parameter values presented in solution 4 are the same as those of solution 2, despite the different function used to increment the inter-item associative strength. This function turns out not to be effective because $\theta_2 b$ is estimated at zero, and hence $F(i,m)$ has no effect (cf. equation 2.6). Obviously, the inter-item associative strength can be eliminated from the model without worsening the fit. After eliminating the inter-item associative strength from the model the same parameter estimates are found as those presented as the second solution in table 7.2, but the degrees of freedom are 36 instead of 35 (because parameter combination $\theta_2 b$ is not estimated). The predictions

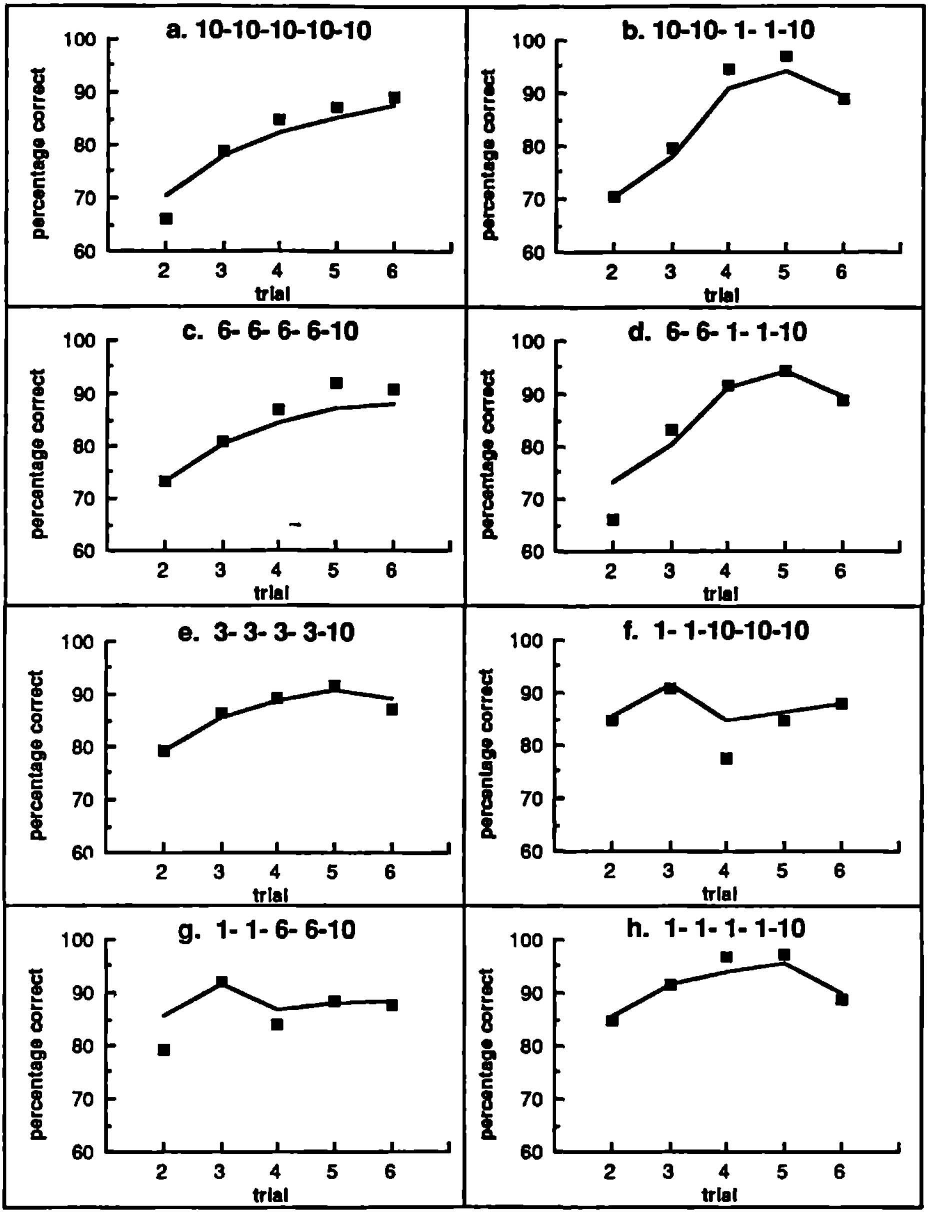

Figure 7.1. Experimental (filled squares) and predicted percentage (probability times 100) correct (solid lines) of the experiment of Rumelhart. The recall percentages of the tests which were preceded by a presentation of the tested S-R-pair are shown as function of the lag combination. The SAM model using only the recovery process is used to reproduce the data.

of the probabilities of a correct answer for this solution (table 7.2; solutions 2 or 4) are shown in figure 7.1.

It can be concluded that a model only incorporating the recovery process (this section) can predict these data better than a model utilizing only the sampling process (section 7.1). It is not necessary to use the inter-item associative strength to reproduce the data.

7.3. DATA FROM RUMELHART: SAMPLING AND STS

Let us now assume that both the sampling process and the short-term store are effective in recalling the correct answer, therefore:

1. The probability of being still in the STS (equation 2.4) is:

$$P_{STS}(t_i) = e^{-\lambda t_i} \quad \text{for all } i;$$

2. The recovery phase will be always successful, that is:
   $P_{REC}(t_i,\ldots,t_m|\theta_2) = 1$ for all i and m.

Accordingly, the probability of retrieval from LTS is only dependent on the sampling process, and is given, using equations 2.19 and 2.3, by:

$$P_{RET}(t_i,\ldots,t_m|\theta_2) = 1 - \{1 - P_{SAM}(t_i,\ldots,t_m)\}^{L_{max}} \quad \text{for all } i \text{ and } m,$$

which can be rewritten, using equations 2.1, 2.6 and 2.7, as:

$$P_{RET}(t_i,..,t_m|\theta_2) = 1 - \{1 - \frac{\mathrm{F}(i,m)\, O(t_i,..,t_m)}{\mathrm{F}(i,m)\, O(t_i,..,t_m) + \frac{Z}{b\, a}}\}^{L_{max}} \qquad (7.5)$$

for all i and m.

The context fluctuation parameters s, α and w, the parameter combination $\frac{Z}{b\, a}$, together with parameter λ, the rate of leaving the STS, can be estimated from the data. L_{max} is here also fixed at 3.

Table 7.3. Parameter estimates and values of fixed parameters for the model using sampling and STS to reproduce the data of the experiment presented by Rumelhart.

parameters	increment of item strength		
	no	yes	yes
s	.369*	.217*	.258
α	.366*	.147*	.119
w	.196*	1.*	1.*
$\frac{Z}{b\,a}$	.087	.357	.485
L_{max}	3.*	3.*	3.*
λ	53.40	2.437	1.635
$F(i,m)$	1.	$m-i+1$	$m-i+1$
χ^2	82.52	76.41	72.69
df	38 (−3)	38 (−3)	36 (−1)

Note: * The value of a fixed parameter.

As before, we compare the effect of not incrementing and incrementing the inter-item associative strength. In the first analysis presented in solution 1 of table 7.3 the inter-item strength is not incremented after successful retrieval, that is $F(i,m)=1$ for all i and m. The parameter values found using only the sampling process (section 7.1; table 7.1; solution 1) were taken as starting values. Parameters s, α and w were fixed at their starting values. The estimate of parameter λ is very high, so that the STS is no longer effective at time of testing. Only sampling turns out to be effective in this analysis. The effect of also estimating some or all of the other parameters s, α and w from the data was checked. This does not result in a better description of the data and the effect of the STS is always minimal (λ is always estimated to be so large, that the S-R-pair has always left STS at the successive test, even with the smallest lag). The parameter b (the inter-item associative strength after a single presentation) can only be estimated in combination with the parameters Z and a, and the values of the function to increment to inter-item associative strength is a constant. Therefore, the inter-item associative strength can be eliminated from the model without worsening the fit.

We attempted to fix parameter λ at values that led to STS being effective, while estimating some or all other parameters from the data. This did not lead to a good fit. In general, increasing the values of λ gives a better fit until the STS has no effect at all. Note that the STS is no longer active if $\lambda > 4$.

Next, we assume that the inter-item associative strength is also incremented after successful recall, with $F(i,m)=m-i+1$ for all i and m. The parameter values used as starting values were taken from the analysis which used sampling as retrieval process (see table 7.1; solution 2). In solution 2 of table 7.3 the results while fixing the three parameters s, α and w are shown. The fit is slightly better than that using only the sampling process (section 7.1). The effect of the STS is small. The effect of estimating some or all context fluctuation parameters from the data was checked. Estimating s and α also from the data gives the best results and is presented in solution 3 of table 7.3 (note that estimating parameter w from the data also results in exactly the parameter values as those presented here). This fit is better than the other two fits (table 7.3; solutions 1 and 2) and the effect of the STS is somewhat greater than in the second solution. The inter-item associative strength for a single presentation (b) can be eliminated from the model. Its value can only be estimated in combination with the parameters Z and a. However, the function to increase the inter-item associative strength after correct recall cannot be deleted as it has a beneficial effect on the fit (compare solution 2 with solution 1).

It can be concluded that a model using both sampling and a STS can describe the data to an acceptable level, but the fit is worse than that of a model using only recovery (section 7.2) to reproduce the data. Only in situations where the inter-item strength is incremented, has the STS some effect. Whether the fit of a model using sampling with a short-term store is better than that of a model using sampling without a STS is not clear.

7.4. DATA FROM RUMELHART: RECOVERY AND STS

We will now assume that both recovery and short-term store are effective in recalling the correct answer, therefore:

1. The probability of being in the STS is given in equation 2.4 by:

$$P_{STS}(t_i) = e^{-\lambda t_i} \quad \text{for all } i.$$

2. The sampling phase is always successful, therefore the probability of sampling is: $P_{SAM}(t_i,...,t_m) = 1$ for all i and m.

Therefore, the probability of retrieval from LTS only depends on the recovery process and is given, using equations 2.19 and 2.3, by:

$$P_{RET}(t_i,...,t_m|\theta_2) = P_{REC}(t_i,...,t_m|\theta_2) \quad \text{for all } i \text{ and } m,$$

which can be rewritten, using equations 2.2, 2.6 and 2.7, as:

$$P_{RET}(t_i,...,t_m|\theta_2) = 1 - e^{-\theta_2 b\, F(i,m) + \theta_2 a O(t_i,...,t_m)} \qquad (7.6)$$
$$\text{for all } i \text{ and } m.$$

The context fluctuation parameters s, α, w, the combinations $\theta_2 b$ and $\theta_2 a$ and the STS parameter λ can be estimated from the data.

As before, we compare the effect of incrementing and not incrementing the inter-item associative strength. First, we assume that the inter-item associative strength is not incremented after successful recall ($F(i,m)=1$ for all i and m). The starting values of the parameters are the same as that found for only the recovery process (table 7.2; solution 2), except for $\theta_2 b$. The starting value of $\theta_2 b$ is set to 1.00 instead of 0.00. Parameters s, α and w are fixed, the other parameters or combinations are estimated from the data. The estimated and fixed parameter values are given in table 7.4 in solution 1. Both $\theta_2 b$, and $\theta_2 a$, are estimated at the same value as in the earlier analysis using only recovery (table 7.2). The estimated value of parameter λ is very large implying that there is no effect of the STS (fixing λ at such values that the STS is active at a successive test did not improve the fit). To check the fit, the other

Table 7.4. Parameter estimates and values of fixed parameters for the SAM model using a model with recovery and STS to describe the data of the experiment presented by Rumelhart.

parameters	increment of item strength		
	no	yes	yes
$\theta_2 b$	.000	.000	.000
$\theta_2 a$	10.62	10.62	10.65
s	.424*	.424*	.424
α	.330*	.330*	.330
w	.404*	.404*	.404
λ	20.03	781.08	981.68
$F(i,m)$	1.	$m-i+1$	$m-i+1$
χ^2	67.12	67.12	67.12
df	37 (−3)	37 (−3)	34

Note: * The value of a fixed parameter.

parameters were also estimated from the data but no better solution was reached. The inter-item associative strength can be deleted from the model; it has no effect at all because the estimated value of b in combination with θ_2 is always zero.

Secondly, the data were fitted with a model version which assumes that the inter-item associative strength is incremented after successful recall, $F(i,m)=m-i+1$ (section 2.1). The estimated parameter values shown in solution 2 in table 7.4 are about the same for all parameters, except λ, as in the other analysis presented in solution 1 of table 7.4. Parameter λ is even larger, but in both cases the effect of the STS is minimal (The effect of the STS is always minimal as $\lambda \geq 5$ in case of the Rumelhart experiment). Fixing parameters s, α, and w, at values found earlier or estimating these 3 parameters from the data results in the same values in all cases. When the inter-item associative strength is completely eliminated from the model (this has an equivalent effect as: $\theta_2 b=0$) the same values for the parameters are estimated as those given in table 7.4, but with one degree more freedom.

It can be concluded that recovery alone (section 7.2) can describe the data just as well as the combination of the recovery process and a STS (this section). In these cases the effect of the STS appears negligible, as expressed in a estimated larger value of λ. Retrieval of an item turned out to depend on the process of context fluctuation. The effect of the inter-item strength cannot be determined from these data.

7.5. DATA FROM RUMELHART: SAMPLING AND RECOVERY

In this section both sampling and recovery as retrieval processes will be assumed to reproduce the data. The short-term store is assumed not to be effective, that is: $P_{STS}(t_i) = 0$ for all i. The probability of retrieval from LTS is given in equation 2.3 by:

$$P_{RET}(t_i,\ldots,t_m|\theta_2) = \{1 - (1 - P_{SAM}(t_i,\ldots,t_m))^{L_{max}}\}\, P_{REC}(t_i,\ldots,t_m|\theta_2)$$
$$\text{for all } i \text{ and } m,$$

which can be rewritten, using equations 2.1, 2.2, 2.6 and 2.7, as:

$$P_{RET}(t_i,\ldots,t_m|\theta_2) = \left[1 - \left\{1 - \frac{\mathrm{F}(i,m)\,O(t_i,\ldots,t_m)}{\mathrm{F}(i,m)\,O(t_i,\ldots,t_m) + \frac{Z}{b\,a}}\right\}^{L_{max}}\right] \times$$
$$\left[1 - e^{-\theta_2 b\,\mathrm{F}(i,m) + \theta_2 a O(t_i,\ldots,t_m)}\right] \qquad (7.7)$$
$$\text{for all } i \text{ and } m.$$

Apart from the context fluctuation parameters s, α and w, the parameter combinations $\frac{Z}{b\,a}$, $\theta_2 b$ and $\theta_2 a$ can be estimated from the data. Parameter L_{max} is fixed at 3. In table 7.5 the parameter estimates are shown. In the first solution the results are shown when the inter-item associative strength is not incremented (that is $\mathrm{F}(i,m)=1$) and when the overlap parameters s, α and w are fixed at the values found for sampling only (table 7.1; solution 1). In solution 2, the results are shown when the inter-item associative strength is incremented (that is $\mathrm{F}(i,m)=m-i+1$) and when parameters s, α and w are fixed at the values found for sampling

Table 7.5. Parameter estimates and values of fixed parameters for the SAM model with sampling and recovery the describe the data of Rumelhart. The inter-item associative strength is not eliminated from the model.

Parameters	Increment of inter-item associative strength	
	no	yes
$\theta_2 b$	12.183	11.127
$\theta_2 a$	1.058	2.318
s	.369*	.217*
α	.366*	.147*
w	.196*	1.*
$\frac{Z}{b\,a}$	.087	.350
L_{max}	3.*	3.*
F(i,m)	1.	m-i+1
χ^2	82.52	79.25
df	37 (–3)	37 (–3)

Note: * The value of a fixed parameter.

only in solution 2 of table 7.1. The reproduction of the data is better using the parameter estimates of solution 2 than if those of solution 1 are used. Results of table 7.5 are compared with corresponding previous analyses (tables 7.1 to 7.4) incrementing or not incrementing inter-item associative strength. Both fits are in terms of χ^2 just as good as those for models using only sampling or for models using sampling with a STS, but with less degrees of freedom actually. Both fits are worse than those for models using only recovery or using recovery with a STS. Neither fits improved when some or all of the parameters s, α and w were also estimated from the data or when other starting values for the parameters were used.

In sections 7.1 to 7.4 the inter-item associative strength could not be estimated from the data. In cases that assume the sampling process, this strength is estimated only in combination with Z and a, and in cases assuming recovery it is estimated such that it takes (in the parameter combination $\theta_2 b$) the value 0. Now, we tried to fit the data while eliminating the inter-item associative strength from the model. The probability of retrieval (equation 7.7 after elimination of $I(t_i,...,t_m)$) will be:

$$P_{RET}(t_i,..,t_m|\theta_2) = \left[1 - \left\{1 - \frac{O(t_i,..,t_m)}{O(t_i,..,t_m) + \frac{Z}{a}}\right\}^{L_{max}}\right] \left[1 - e^{-\theta_2 a O(t_i,...,t_m)}\right]$$

$$\text{for all } i \text{ and } m. \qquad (7.8)$$

As well as the context fluctuation parameters s, α and w, the parameter combinations $\frac{Z}{a}$ and $\theta_2 a$ can be estimated from the data. The number of sample cycles L_{max} is set at 3. The values for parameters s, α and w as found in sections 7.2 (table 7.2; solution 2) using only recovery are used here as starting values. In solution 1 of table 7.6 the results are shown when parameters s, α and w are fixed at those values. In the second solution of table 7.6 the results are shown when these three parameters are also estimated from the data. The fit shown in solution 2 is significantly better that that shown in solution 1. χ^2 reduces from 74.01 to 64.51, with actually the same number of degrees of freedom. The estimate of the parameter combination $\theta_2 a$ is in solution 2 half the value of that in solution 1, implying that the probability of recovery is also smaller. However, the estimates for s and w are somewhat greater in solution 2 than in solution 1, implying that the probability of recovery is higher. That is, the effect of recovery on the total probability of recall is greater in the solution presented in solution 2 than it is in the first solution. In solution 1 the probability of recovery is close to 1, which implies that the sampling process is more important in determining the probability of retrieval than the recovery process. In solution 2 the probability of recovery is smaller than 1, implying that both sampling and recovery are effective processes in retrieval from LTS. In the previous sections, it was shown that recovery could reproduce the data better than sampling, therefore it can be expected that the parameter estimates in solution 2 lead to a better reproduction of the data.

Table 7.6. Parameter estimates and values of fixed parameters for the SAM model using sampling and recovery to predict Rumelhart's data. The inter-item associative strength is eliminated.

Parameters	solution 1	solution 2
$\theta_2 a$	19.293	9.512
s	.424*	.463
α	.330*	.314
w	.404*	.480
$\frac{Z}{a}$	.166	.127
L_{max}	3.*	3.*
χ^2	74.01	64.51
df	38 (−3)	35

Note: * The value of a fixed parameter.

For a model with sampling (without recovery), fixing the inter-item associative strength at a value of 1 has the same effect as eliminating this strength, while for a model with recovery (without sampling) the value of the inter-item associative strength must be set to 0 to effectively eliminate this strength. In cases where the sampling is used without recovery, we have seen that the inter-item associative strength can only be estimated in combination with parameters Z and a. For models using just the recovery process, it turns out that the reproduction of the data is better or just as good when the inter-item associative strength is eliminated. After combination of both processes to reproduce the data, the inter-item associative strength cannot take a value such that it is completely ineffective in determining both the sampling and the recovery. The conflicting effect of the inter-item associative strength in sampling compared to recovery leads to a poorer fit (table 7.5) than when the inter-item associative strength is eliminated (table 7.6). A model using sampling and recovery as retrieval processes can reproduce the data better when the inter-item associative strength is eliminated from the model.

The model using both sampling and recovery, and assuming that the inter-item associative strength is eliminated, can reproduce the data better (table 7.6) than a model using only sampling (table 7.1), and better than a model using only recovery (table 7.2). Extending the model using only recovery (table 7.2) with a sampling process (table 7.6) reduces χ^2 from 67.12 to 64.51, while the number of degrees of freedom decreases from 36 to 35. The model using sampling and recovery is more complex than a model using only recovery. Despite the significantly worse fit, the model using only recovery can be sometimes preferred in reproducing the data, because this model is a more simple model and the cost is only small.

7.6. DATA FROM RUMELHART: SAMPLING, RECOVERY AND STS

Finally, we tried to-reproduce the data of Rumelhart by the complete model. The probability of being still in the STS (equation 2.4) is:

$$P_{STS}(t_i) = e^{-\lambda t_i} \quad \text{for all } i,$$

and the probability of retrieval from LTS through sampling and recovery is given (according to equation 7.7) by:

$$P_{RET}(t_i,\ldots,t_m|\theta_2) = \left[1 - \left\{1 - \frac{F(i,m)\ O(t_i,\ldots,t_m)}{F(i,m)\ O(t_i,\ldots,t_m) + \frac{Z}{b\ a}}\right\}^{L_{max}}\right] \times$$

$$\left[1 - e^{-\theta_2 b\ F(i,m) + \theta_2 a O(t_i,\ldots,t_m)}\right] \quad \text{for all } i \text{ and } m.$$

As well as the context fluctuation parameters s, α and w, the parameter combinations $\frac{Z}{b\ a}$, $\theta_2 b$, $\theta_2 a$, and the STS parameter λ can be estimated from the data. Parameter L_{max} is fixed at 3. In solution 1 of table 7.7 the results are shown when the inter-item associative strength is not incremented (that is $F(i,m)=1$) and when the parameters s, α and w, as found for sampling only (table 7.1; solution 1), are fixed at those values. The estimated value of the STS parameter λ is very high, implying that the effect of the STS is minimal. The other estimated parameters are about the same as those found for a model using sampling and recovery

Table 7.7. Parameter estimates and values of fixed parameters for the SAM model with sampling, recovery and STS to describe the experimental data presented by Rumelhart. The inter-item associative strength is not eliminated.

Parameters	Increment of inter-item associative strength		
	no	yes	yes
$\theta_2 b$	10.465	11.238	11.555
$\theta_2 a$	4.359	.410	3.881
s	.369*	.217*	.258
α	.366*	.147*	.119
w	.196*	1.*	1.*
$\frac{Z}{b\ a}$	.087	.357	.485
L_{max}	3.*	3.*	3.*
λ	337.84	2.437	1.635
F(i,m)	1.	m-i+1	m-i+1
χ^2	82.52	76.42	72.69
df	36 (−3)	36 (−3)	34 (−1)

Note: * The value of a fixed parameter.

without a STS, assuming no increment of the associative strength (table 7.5; solution 1). In the second and third solution of table 7.7 the results are shown when it is assumed that the inter-item associative strength is incremented after correct recall (that is F(i,m)=m-i+1). In the second solution parameters s, α and w are fixed at the same values as those found for sampling only (table 7.1; solution 2). The fit is better than that for a model using sampling and recovery (table 7.5; solution 2) without a STS: χ^2 reduces from 79.3 to 76.4 with one degree of freedom less. Estimating s and α also from the data does improve the fit further: χ^2 reduces from 76.4 to 72.7 (table 7.7; solution 3). The fit of a model with sampling, recovery and a STS, assuming that the inter-item associative strength is incremented, is just about as good as that of a model using sampling and a STS (table 7.3), but it is worse than the fit of a model with only recovery (table 7.2).

In sections 7.1 to 7.4 the inter-item associative strength could not be estimated from the data using the sampling process, and could be eliminated using the recovery process. In case of the sampling process it was estimated only in combination with Z and a, and in case of recovery the estimated value was zero.

Now, we tried to fit the data while eliminating the inter-item associative strength from the model. The probability of retrieval will be equal to that given in equation 7.8 and is:

$$P_{RET}(t_i,..,t_m|\theta_2) = \left[1 - \left\{1 - \frac{O(t_i,..,t_m)}{O(t_i,..,t_m) + \frac{Z}{a}}\right\}^{L_{max}}\right]\left[1 - e^{-\theta_2 a O(t_i,..,t_m)}\right]$$

for all i and m.

Apart from the context fluctuation parameters s, α and w, the parameter combinations $\frac{Z}{a}$ and $\theta_2 a$, and the STS parameter λ can be estimated from the data. The number of sample cycles L_{max} is set at 3. The results are shown in table 7.8. In the first solution the overlap parameters are fixed at values found for recovery only (table 7.2; solution

Table 7.8. Parameter estimates and values of fixed parameters for the SAM model with sampling, recovery and STS to describe the data presented by Rumelhart. The inter-item associative strength is eliminated.

Parameters	solution 1	solution 2
$\theta_2 a$	19.295	9.591
s	.424*	.278
α	.330*	.314
w	.404*	.464
$\frac{Z}{a}$	.166	.131
L_{max}	3.*	3.*
λ	528.217	9.969
χ^2	74.01	64.95
df	37 (−3)	34

Note: * The value of a fixed parameter.

2), and in solution 2 these are estimated. In both solutions of table 7.8, it is shown that the STS parameter λ is very large, implying that the STS has no effect at all. In all other respects, the results are comparable to those presented in section 7.5, table 7.6. When the model with both sampling and recovery after elimination of the inter-item associative strength, is extended with a short-term store, the effect of the STS turns out to be negligible.

7.7. DATA FROM RUMELHART: CONCLUSIONS

A model with sampling and recovery, and elimination of the inter-item associative strength (section 7.5; table 7.6) can reproduce the data best. The predictions of a model using only recovery (section 7.2; table 7.2) are somewhat worse (χ^2 = 67.12 instead of 64.51 with only one extra degree of freedom), but this model may be preferred in some situations where a simple model is essential. A model using only sampling (section 7.1; table 7.1) is often much poorer at reproducing the data than other models and therefore should not be chosen.

Elaboration of the model with a short-term store did not improve the predictions. In many analyses the estimates of the STS parameter λ are so large ($\lambda > 4$) that the effect of the STS is negligible. Restriction of the STS parameter, so that the effect of the STS is not negligible, leads to poorer predictions. Rumelhart's experiment always includes one presentation of another pair preceded by an anticipation trial between the repetition of a S-R-pair. We found it reasonable to conclude that the STS is no longer active at the moment of the repetition, because the total time of anticipation trial and presentation is relatively long. It is also possible to assume that because the intervening trial has taken so much attention from the subject, the STS is no longer active and the preceding stimuli are neglected.

The benefit of elimination of the inter-item associative strength from the model is extensively described in section 7.5

8. PREDICTING DATA FROM TWO-STIMULI-ONCE

We will now investigate if the SAM model predicts a spacing effect for two different stimuli tested at the same time, as Ross and Landauer (1978) argued. In section 2.5, the probability of recalling at least one correct answer for at least one of two different word pairs was given (equation 2.24) by:

$$P_{CA}(t_1+t_2) = P_A(t_1+t_2) + P_B(t_2) - P_A(t_1+t_2) \,\&\, P_B(t_2).$$

In the first part of this chapter, we will prove that the spacing effect is not predicted for the case of the two-stimuli-once condition. Further, it is demonstrated that for the prediction of at least one correct answer in the two-stimuli-once condition, the similarity between the contexts of both presentations can be ignored. Sampling only, recovery only and their combination will be considered as retrieval processes. As discussed in section 2.5, we assume that, because of the relative long interval between presentation and testing, the short-term store is not effective in recalling the correct answer.

8.1. SPACING EFFECT FOR TWO-STIMULI-ONCE ?

As mentioned previously (paragraph 1.2.2, sections 1.4, 2.5 and 3.5), the crucial aspect in Ross and Landauer (1978) is that they argue that variable encoding theory predicts a dependence of the images of two different pairs of words, so that the recall of one word pair depends on the recall of the other word pair. They postulate the so-called *independence hypothesis* for theories with a variable encoding. This attributes spacing effects to increasing independence (decreasing correlation) between some variable attribute of storage events, as the events are more widely separated. Ross and Landauer argue that a spacing effect is predicted by a variable encoding theory for the recall in case of the two-stimuli-once condition just as in the one-stimulus-twice condition, and predict that the correct retrieval of at least one of two different presentations is given by:

$$P(R_A \text{ or } R_B) = P(R_A) + P(R_B) - P(R_A \text{ and } R_B), \tag{8.1}$$

where $P(R_A)$ and $P(R_B)$ are the probabilities of retrieving presentation A and presentation B respectively, and $P(R_A \text{ and } R_B)$ is the probability of success on both retrievals. If the context is sufficiently similar on the two learning trials, then only one context at time of retrieval will serve to release information stored at either learning trial. The variable encoding theory implies that the same predictions of a spacing effect must be made for the probability correct both in the case of one stimulus repeated and in the case of at least one of two different stimuli. Therefore an increasing separation between two different items will produce a decreasing correlation between memory in both cases, and this decrease in correlation will lead to a higher probability that one only will be remembered. The idea seems to be that when "traces" are spread over a large area a random search is likely to find one, whereas, when "traces" are clustered, a random search may find none, or, if one is found, the others are also found.

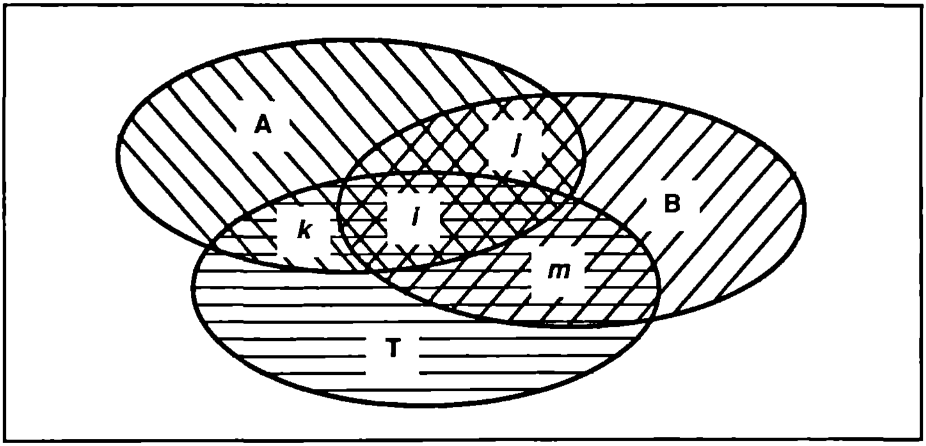

Figure 8.1. Partition of active (and encoded) context elements at the presentations of word pair A and word pair B, and active context elements at testing.

The SAM model as presented in chapter 2 is based on variable encoding of the context, and when the arguments of Ross and Landauer apply to variable encoding, the SAM model should predict a spacing effect in both the one-stimulus-twice and the two-stimuli-once conditions.

The predictions of the SAM model for two-stimuli-once will be demonstrated with only a limited set of active (n) and non-active (N) context elements ($N + n = 50$ is usually used) instead of a proportion of active context elements, such as that used in the presentation of the model in chapter 2 (except in this case $s = \frac{n}{N+n}$). At every moment n context elements are active and encoded at a presentation, or active and used for retrieval at testing. Of the n context elements active at testing, k were also active at the presentation of word pair A (the word pair presented first), m elements were also active at presentation of pair B (second presentation), and i were also active at both presentations (see figure 8.1). Inactive at time of testing but active at both presentations are j context elements. In table 8.1 a summary of the symbols used in the present section is presented.

Table 8.1. Symbols used in section 8.1 to compare the predictions of the SAM model assuming independence or dependence between the images.

symbol	context active at	number of active context elements
A	presentation word pair A	n
B	presentation word pair B	n
T	testing	n
AB	presentations word pair A and B	$i+j$
AT	presentation word pair A and testing	$i+k$
BT	presentation word pair B and testing	$i+m$
ABT	presentations word pair A and B, and testing	i
$A\bar{B}T$	presentation word pair A and its testing, but not at presentation word pair B	k

The probability of a correct response for at least one of the word pairs (equation 8.1) is given by Ross & Landauer (1978) as:

$$P(R_A \text{ or } R_B) \;=\; P(R_A) + P(R_B) - P(R_A \text{ and } R_B).$$

The probabilities of a correct response for word pair A, word pair B, or both, are further calculated with the SAM model. The probabilities of a correct response for word pair A ($P(R_A)$) and for word pair B ($P(R_B)$) are calculated in the same way. First, we will give the equations used to calculate the probability of a correct response for word pair A, followed by the equations for the probability of a correct response for word pair B.

The probability $P(R_A)$ of a correct response for word pair A as a function of the number of active context elements is, by elementary probability theory:

$$P(R_A) \;=\; \sum_{i+k=0}^{n} \{P(R_A|AT{=}i{+}k)\, P(AT{=}i{+}k)\}. \tag{8.2}$$

The probability of correctly recalling word pair A, depends on the number of context elements active at both the presentation and the test, that is $i{+}k$. The probability of correctly recalling word pair A given that $i{+}k$ context elements are active ($P(R_A|AT{=}i{+}k)$) can be calculated with the formulae for sampling (after L_{max} search cycles) and recovery presented in chapter 2 (equations 2.1, 2.2 and 2.3), and is given by:

$$P(R_A|AT{=}i{+}k) \;=\; \{1 - (1 - \frac{ba\,\frac{i+k}{N+n}}{ba\,\frac{i+k}{N+n} + Z})^{L_{max}}\}\;\{1 - e^{-\theta_2(b + a\,\frac{i+k}{N+n})}\}. \tag{8.3}$$

The word pair A is presented only once: Therefore the inter-item associative strength will be equal to b. The probability that $i{+}k$ elements are active at both the presentation of word pair A and at the moment of testing ($P(AT{=}i{+}k)$) is given by the binomial expression:

$$P(AT=i+k) \;=\; \binom{n}{i+k} P_3^{\,i+k} \,(1 - P_3^{\,n-i-k}), \tag{8.4}$$

where P_3 is the probability that anyone element is active on both occasions. P_3 can be determined with formulae for the overlap of a context element, as presented in chapter 2, and is given by:

$$P_3 \;=\; e^{-\alpha(t_1+t_2)} \;+\; s\,(1 - e^{-\alpha(t_1+t_2)}). \tag{8.5}$$

The probability of a correct response for word pair B can likewise be calculated with formulae 8.2 through 8.5. Therefore, substitution of B for A, $i+m$ for $i+k$, P_2 for P_3, and t_2 for t_1+t_2 in equations 8.2 through 8.5 gives the probability of correctly recalling word pair B by:

$$P(R_B) \;=\; \sum_{i+m=0}^{n} \{P(R_B|BT=i+m)\,P(BT=i+m)\}, \tag{8.6}$$

where the probability of a correct response to word pair B given that $i+m$ elements are active at both the presentation of word pair B and at its testing (cf. equation 8.3) is:

$$P(R_B|BT=i+m) = \{1 - (1 - \frac{ba\,\frac{i+m}{N+n}}{ba\,\frac{i+m}{N+n} + Z})^{L_{max}}\}\;\{1 - e^{-\theta_2(b\,+\,a\,\frac{i+m}{N+n})}\}. \tag{8.7}$$

The probability that $i+m$ context elements are active at both the presentation of word pair B and its testing (cf. equations 8.4 and 8.5) is:

$$P(BT=i+m) \;=\; \binom{n}{i+m} P_2^{\,i+m} \;(1 - P_2^{\,n-i-m}) \tag{8.8}$$

with

$$P_2 \;=\; e^{-\alpha t_2} \;+\; s\,(1 -\; e^{-\alpha t_2}). \tag{8.9}$$

The probability of a correct response to both word pair A and word pair B, is determined by the following factors. The probabilities of correct responses for word pair A and word pair B. It also depends on the exact size of the overlap of context elements of A, B and T. The probability of a correct response to both word pair A and word pair B, is given by:

$$P(R_A \text{ and } R_B)$$
$$= \sum_{i=0}^{n} \sum_{j=0}^{n-i} \sum_{k=0}^{n-i-j} \sum_{m=0}^{M} P(R_A, R_B, AT=i+k, BT=i+m)$$
$$= \sum_{i=0}^{n} \sum_{j=0}^{n-i} \sum_{k=0}^{n-i-j} \sum_{m=0}^{M} \{P(R_A|R_B, AT=i+k, BT=i+m) \times$$
$$P(R_B|AT=i+k, BT=i+m)\, P(AT=i+k|BT=i+m)\, P(BT=i+m)\},\qquad (8.10)$$

with M = Min $(n-i-j, n-i-k)$ [1], and the summations are over all possible values of i, j, k, and m, keeping in mind that the total number of active context elements may not exceed n.

Details of these probabilities can be further calculated from:

1. The probability of a correct response to word pair A given that (a) the response to word pair B was correct, (b) the number of active context elements at both the presentation of word pair A and its testing is $i+k$, and (c) $i+m$ is the number of context elements active at both the presentation B and at the moment of its testing, is:

   $$P(R_A|R_B, AT=i+k, BT=i+m) = P(R_A|AT=i+k). \qquad (8.11)$$

   The probability $P(R_A|AT=i+k)$ is given in equation 8.2 above.
2. The probability of a correct answer to word pair B given conditions (b) and (c) above is:

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[1] It is necessary to restrict the value of M, because the sum of i, j, and k must be equal to or smaller than n (see figure 8.1). If the restriction of M is not given the sum $i+j+k$ can take a value greater than n.

$$P(R_B|AT=i+k,BT=i+m) = P(R_B|BT=i+m). \tag{8.12}$$

The probability $P(R_B|BT=i+m)$ is given in equation 8.6 above.

3. The probability that there are exactly $i+k$ context elements active at the presentation of word pair A and at its testing, when it is given condition (c) only, is:

$$P(AT=i+k|BT=i+m) = \sum_{j=0}^{n-i-k-m} P(AT=i+k \;\&\; AB=i+j|BT=i+m)$$

$$= \sum_{j=0}^{n-i-k-m} \left\{ P(AT=i+k|AB=i+j,BT=i+m)\, P(AB=i+j|BT=i+m) \right\}$$

$$= \sum_{j=0}^{n-i-k-m} \left\{ P(ABT=i \;\&\; A\bar{B}T=k|BT=i+m,AB=i+j)\, P(AB=i+j) \right\}$$

$$= \sum_{j=0}^{n-i-k-m} \frac{\binom{i+j}{i}\binom{n-i-j}{m}}{\binom{n}{i+m}} \; \frac{\binom{n-i-j}{k}\binom{N-n+i+j}{n-m-i-k}}{\binom{N}{n-i-m}} \; P(AB=i+j). \tag{8.13}$$

The probability $P(AB=i+j)$ that $i+j$ context elements are active at both presentations is similar to the probability that $i+k$ context elements are active at both presentation of word pair A and the moment of testing. This is given in equations 8.3 and 8.4 (substitute $i+j$ for $i+k$, P_1 for P_3, AB for AT, and t_1 for t_1+t_2). The probability that $i+j$ context elements are active at both presentations is therefore:

$$P(AB=i+j) = \binom{n}{i+j} P_1^{\,i+j} \; (1 - P_1^{\,n-i-j}) \tag{8.14}$$

with

$$P_1 = e^{-\alpha t_1} + s\,(1 - e^{-\alpha t_1}). \tag{8.15}$$

4. The probability $(P(BT=i+m))$ that $i+m$ context elements are active at the presentation of word pair B and at the moment of testing was given in equations 8.8 and 8.9.

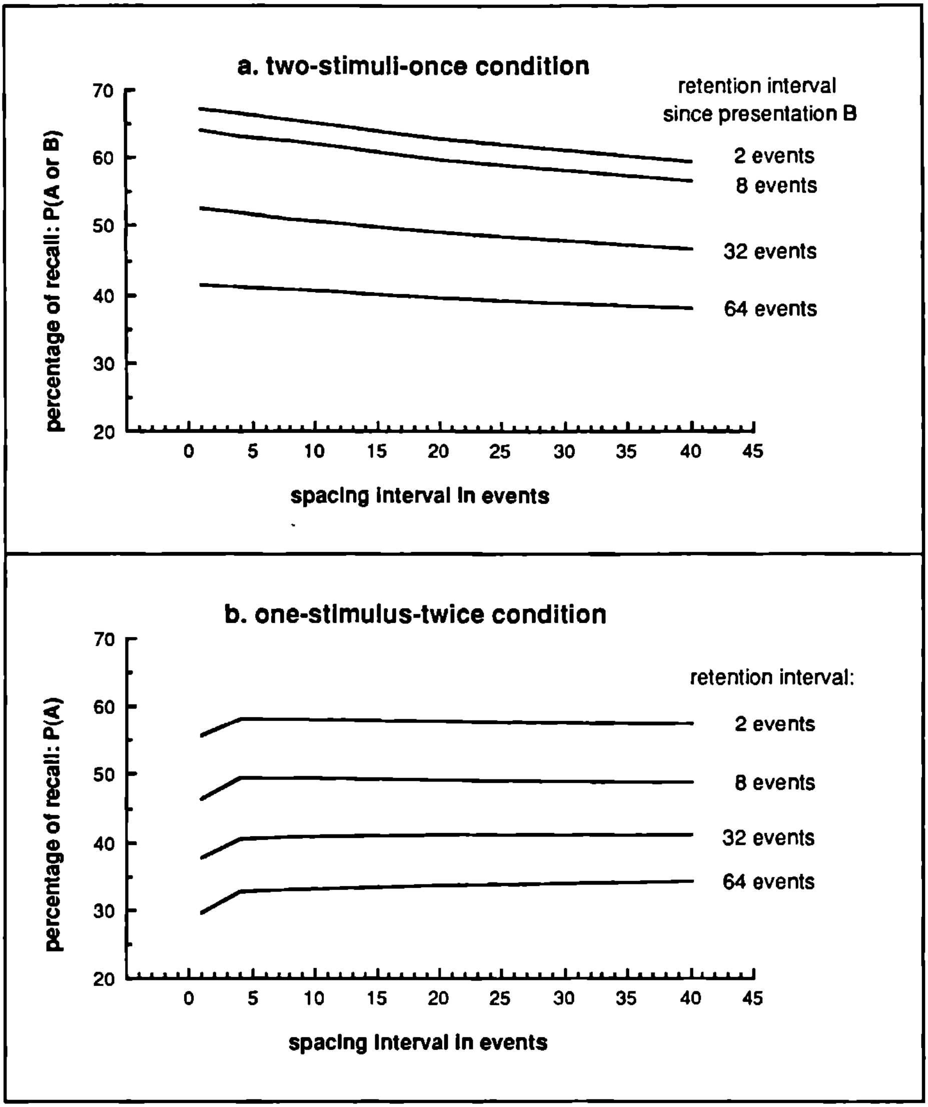

Figure 8.2. Predictions of the percentage (= probability × 100) of (a) at least one correct answer for the two-stimuli-once and (b) a correct answer for the one-stimulus-twice condition for spacing and retention intervals as used in Glenberg's experiment. The percentage correct as function of the spacing interval for four different retention intervals.
The parameter values used, are α=.006, s=.40, b=.075, a=16.4, Z=1., L_{max}=3., θ_1=1., θ_2=.15, λ=.341, n=20 and N=30.

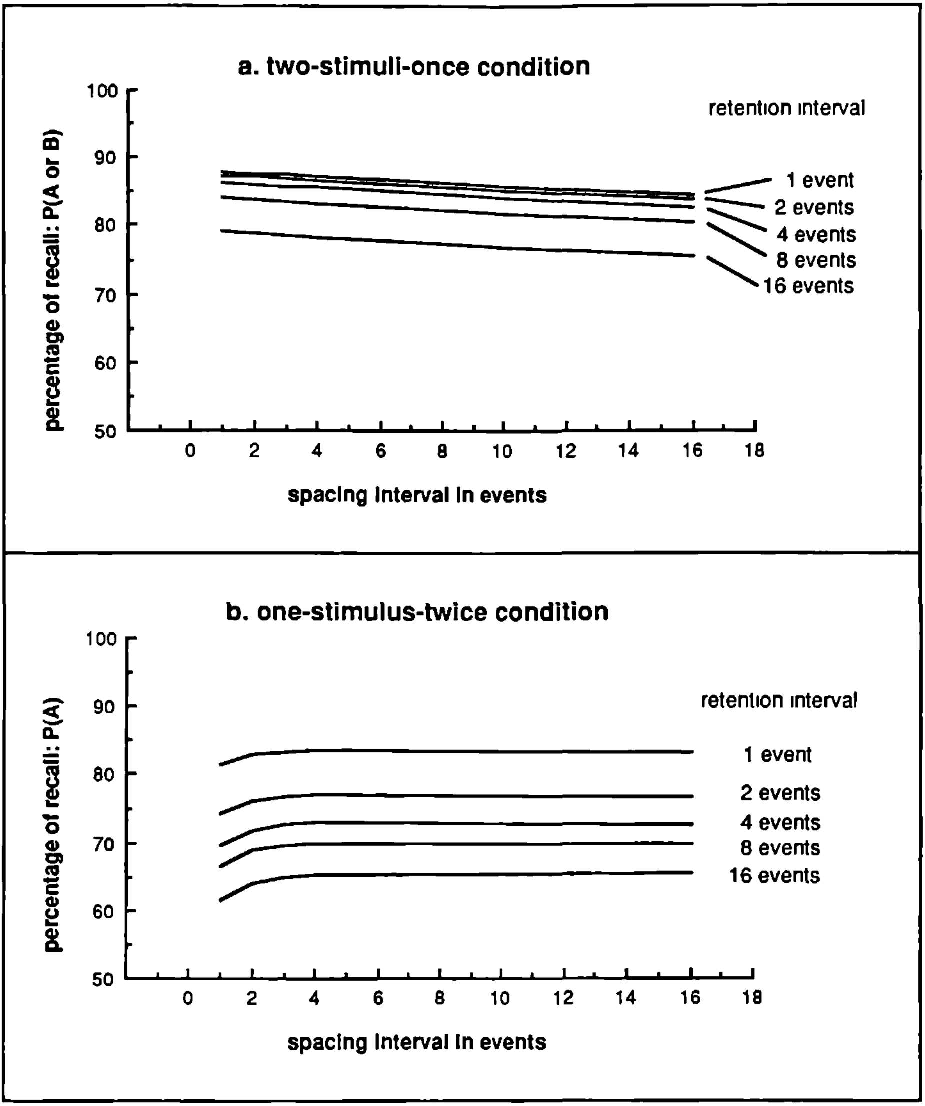

Figure 8.3. Predictions of the percentage (= probability × 100) of (a) at least one correct answer for the two-stimuli-once and (b) a correct answer for the one-stimulus-twice condition for spacing and retention intervals as used in experiment I. The percentage correct as function of the spacing interval for five different retention intervals.

The parameter values used, are $\alpha=.006$, $s=.34$, $b=.075$, $a=28.08$, $Z=1.$, $L_{max}=3.$, $\theta_1=1.$, $\theta_2=.183$, $\lambda=.255$, $n=17$ and $N=33$.

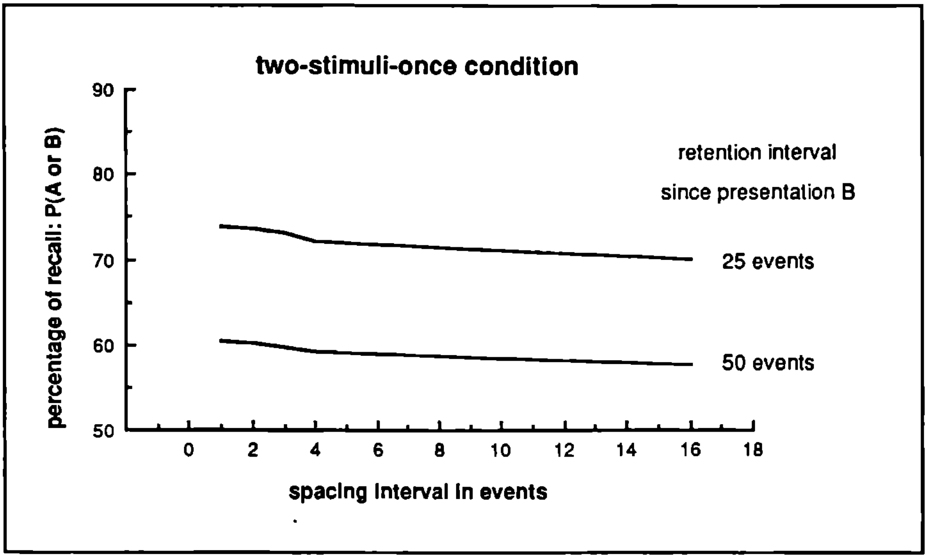

Figure 8.4. Predictions of the percentage (= probability × 100) of a correct answer for the two-stimuli-once condition for spacing and retention intervals as used in experiment II. The percentage correct as function of the spacing interval for two different retention intervals.
The parameter values used, are α=.006, s=.34, b=.075, a=28.08, Z=1., L_{max}=3., θ_2=.183, n=17 and N=33.

The predictions of the SAM model for two-stimuli-once are presented in figure 8.2 and 8.3 for two sets of parameters [2], where the spacing effect is clearly present for repeated stimuli. In figures 8.2 and 8.3 the predictions for the probability of a correct answer of two-stimuli-once together with the predictions for the one-stimulus-twice condition are shown for spacing and retention intervals as used in respectively the experiment of Glenberg and experiment I. The predictions for the two-stimuli-once are shown in the same kind of figure as the repeated stimuli. For the correct answer for word pair A the spacing and retention interval must be added to obtain the interval between the presentation and the test, whereas for word pair B the retention interval is the interval between

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[2] These parameters, here used for simulation purposes only, are taken from an earlier analysis of Glenberg's data and the data of experiment I but with slightly different assumptions.

presentation and test. (As described in section 2.1, the interval between the presentation of word pair A and that of word pair B is the spacing interval, and the interval between the presentation of word pair B and the testing is the retention interval.) Only the combined probability of a correct response for at least one of the word pairs is presented in the figure. In figure 8.4 the parameter values of experiment I are used to predict the probability of a correct answer in case of two-stimuli-once for the spacing and retention intervals used in experiment II.

It can be concluded from figures 8.2 to 8.4 that the SAM model using variable context encoding does not predict the spacing effect for the two-stimuli-once condition, but it does for the one-stimulus-twice condition. A slightly decreasing trend is found for at least one correct response for two-stimuli-once, due to the effects of the spacing and retention intervals on the sizes of AT, BT and ABT.

As the derivations above demonstrate, the elaboration of the SAM model for two-stimuli-once, taking the similarity in context of both presentations into account, is rather complicated. The similarity in context between both presentations (Ross & Landauer) should be responsible for any spacing effect in case of two-stimuli-once, but no spacing effect is predicted by SAM. When the context similarity is ignored it can be assumed that a correct response for pair A is independent of the response for pair B. We check if it is possible to ignore the similarity of both presentations for the prediction of a correct answer for both word pairs. In that case the probability of a correct answer to both is simply given by:

$$P(R_A \text{ and } R_B) = P(R_A)\, P(R_B), \tag{8.16}$$

where $P(R_A)$ and $P(R_B)$ are given in formulas 8.2 and 8.7. The probability of correctly given at least one of the responses is then:

$$P(R_A \text{ and } R_B) = P(R_A) + P(R_B) - P(R_A)\, P(R_B). \tag{8.17}$$

The predictions of this simplified model, using the same set of parameters as used for figures 8.2 to 8.4, are about equal to those presented in figures 8.2a, 8.3a and 8.4. Figures 8.2a, 8.3a and 8.4 are also obtained when using the simplified model. From these results we concluded that simple models, using a multiplication of the probability correct of the two word pairs and ignoring the similarity between both contexts, can be used to predict the results in the two-stimuli-once condition. It is not necessary to use the complicated model with conditional probabilities.

The value of the probability of a correct answer for two-stimuli-once as predicted with the parameters value of experiment I and shown in figure 8.4 is higher than the experimental data presented in section 3.5 for the two-stimulus-once condition. In the following section 8.4 the model using both sampling and recovery as retrieval processes is fitted to the data. The parameter values found there are used here as additional evidence to show, on simulation, that the predictions for both elaborations of the SAM model for two-stimuli-once, are about the same (except parameter s is set to .2 instead of .186). The simulations for both elaborations are equal and shown in figure 8.5. Other values of the number of active and inactive elements to those used here give a similar

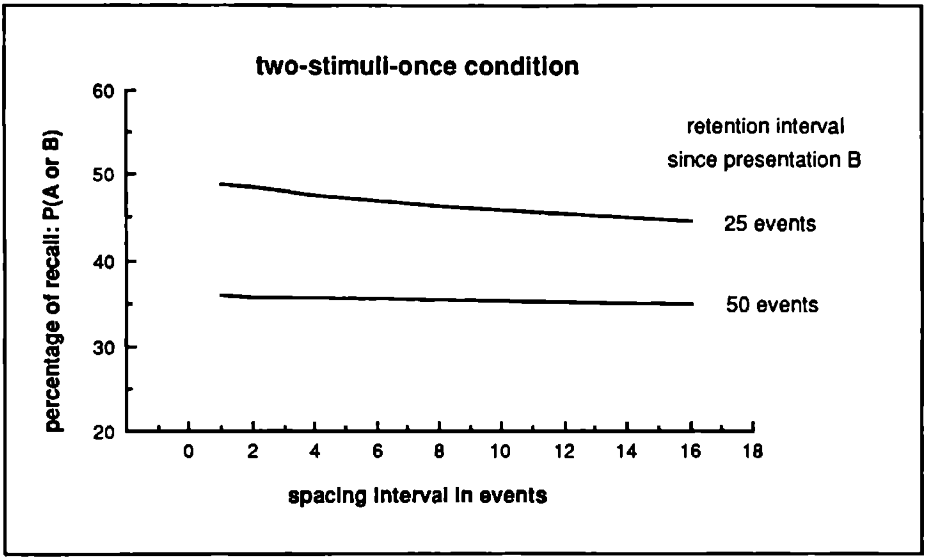

Figure 8.5. Predictions of the percentage (= probability × 100) of a correct answer for the two-stimuli-once condition for spacing and retention intervals as used in experiment II. The percentage correct as function of the spacing interval for two different retention intervals.
The parameter values used, are α=.016, s=.2, b=.39, a=3.774, Z=.277, L_{max}=3., θ_2=1., n=20 and N=80.

pattern of results: A decreasing probability correct along with increasing retention times. Using higher values for the number of elements, leads to a lower level of performance.

We conclude that we can try and fit the SAM model using the assumption that the probability of correctly responding to word pair A is independent of the response to pair B.

In the following sections, the data will be fitted to versions of the model which assume that a correct response for one pair is independent of the answer to the other pair. The probability of a correct answer (equations 2.24 and 8.16) is given by:

$$P_{CA}(t_1+t_2) \;=\; P_A(t_1+t_2) + P_B(t_2) - P_A(t_1+t_2)\, P_B(t_2). \tag{8.18}$$

The data on two-stimuli-once will be analyzed assuming sampling only, recovery only, and the combination of sampling and recovery. We will show in the next sections how the probabilities $P_A(t_1+t_2)$ and $P_B(t_2)$ must be estimated for the different version of the SAM model.

8.2. DATA FROM TWO-STIMULI-ONCE: SAMPLING ONLY

In the previous section and in section 2.5, the complete model for the two-stimuli-once condition was given. The model with only sampling as effective retrieval process will be presented in the present section. This reduction of the model is equivalent to the assumption that the image is always recovered from memory after a successful sampling phase (that is: $P_{REC}(t_1+t_2|\theta_2)=1$ and $P_{REC}(t_2|\theta_2)=1$). The probabilities of a correct response, P_A, for word pair A (equations 2.3 and 2.22, rewritten using equations 2.1, 2.6, and 5.2), or P_B for word pair B (equations 2.3 and 2.23, rewritten using equations 2.1, 2.6, and 5.2) are, respectively:

$$\begin{aligned} P_A(t_1+t_2|\theta_2) &= 1 - (1 - P_{SAM}(t_1+t_2))^{L_{max}} \\ &= 1 - \left(1 - \frac{O'(t_1+t_2)}{O'(t_1+t_2) + \frac{Z}{b\;a\;w}}\right)^{L_{max}} \end{aligned} \tag{8.19}$$

and

$$P_B(t_2|\theta_2) = 1 - (1 - P_{SAM}(t_2))^{L_{max}}$$

$$= 1 - (1 - \frac{O'(t_2)}{O'(t_2) + \frac{Z}{b\ a\ w}})^{L_{max}}, \qquad (8.20)$$

where $I(t_1+t_2)$ and $I(t_2)$ are constant in time and both equal to b (see chapter 5 "a single presentation followed by a test"). $C(t_1+t_2)$ and $C(t_2)$ are as given by equation 5.2.

Parameters s and α can be estimated from the data together with the parameter combination $\frac{Z}{b\ a\ w}$. Parameter L_{max} is fixed at 3. The parameter values of section 5.1 (table 5.1) using only sampling for reproducing the once-presented data are used as starting values. Both data sets are obtained from the same experiment and it is reasonable to expect that the parameter values for one application will also be valid in the other application. The results for these starting values are given in

Table 8.2. Parameter estimates and values of fixed parameters for the SAM model using only sampling as retrieval process to reproduce the data of the two-stimuli-once condition.

parameter	solution		
	1	2	3
s	.186*	.186*	.0524
α**	.0165*	.0165*	.0047
$\frac{Z}{b\ a\ w}$	.54*	.571	.306
L_{max}	3.*	3.*	3.*
χ^2	26.76	22.89	21.03
df	12 (−3)	11 (−2)	9

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

solution 1 of table 8.2. In the second solution only the parameter combination $\frac{Z}{b\ a\ w}$ is estimated from the data, while parameters s and α are fixed at the values found for once-presented stimuli. In the third solution of this table the estimated values of the three parameters (or parameter combination) are given. The fit in solution 3 is better than that in solution 1 and slightly better than that in solution 2 in terms of χ^2. Solution 2 is to be preferred because these parameter values can describe both the once-presented stimuli and the two-stimuli-once condition. The parameter estimates presented in solution 3 are smaller than those in solution 2, but fit equally well. The ratio between the parameters is more important than the exact parameter values in determining the probability of sampling. The effect of a lower value for s is compensated by the lower values of both parameter α and of the parameter combination

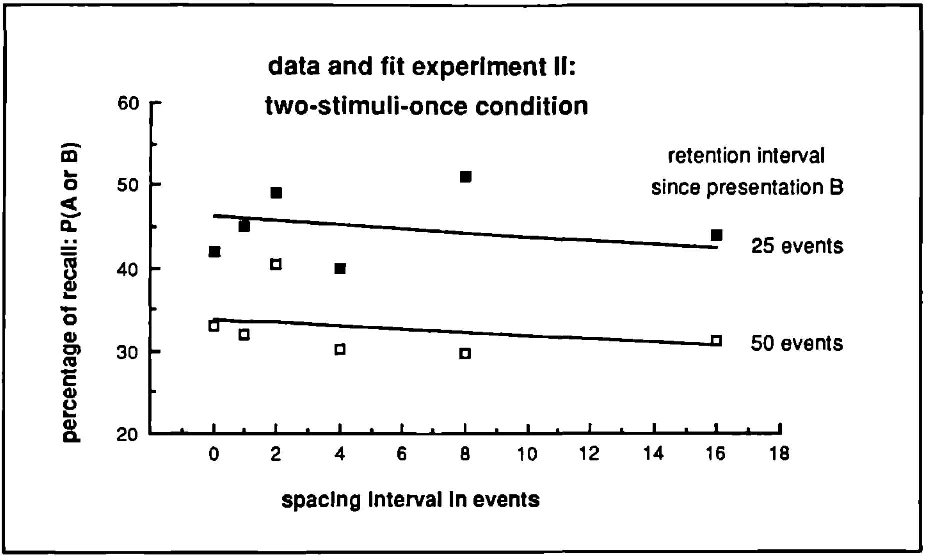

Figure 8.6. Experiment (squares) and predicted (solid lines) percentages (= probability × 100) correct for the two-stimuli-once condition using only sampling as retrieval process. The recall percentages as function of the spacing interval shown for two different retention intervals.

$\frac{Z}{b\ a\ w}$. The predicted percentage correct and the observed data for the fit in solution 2 are shown in figure 8.6.

We also attempted to fit the data with one of the context fluctuation parameters (s, α) fixed at the starting value while estimating the others. In that case the fit is about just as good as the fit presented in solution 2: The χ^2 value is between 22.72 and 22.86, but here an additional parameter must must be estimated.

The inter-item associative strength can only be estimated in combination with the parameters Z, a and w. Therefore, this strength can be eliminated without making the fit worse. We concluded that a model using only sampling (without the inter-item associative strength) can describe the data to an acceptable level.

8.3. DATA FROM TWO-STIMULI-ONCE: RECOVERY ONLY

We will now assume that only recovery is effective as retrieval process. Compared to the complete model this implies that the word pairs are always sampled (that is: $P_{SAM}(t_1+t_2)=1$ and $P_{SAM}(t_2)=1$). The probabilities of a correct response for word pair A and B (equations 2.3, 2.22, 2.23, and rewritten using equations 2.2, 2.6, and 5.2) are, respectively:

$$\begin{aligned} P_A(t_1+t_2) &= P_{REC}(t_1+t_2) \\ &= 1 - e^{-\theta_2 b - \theta_2 awO'(t_1+t_2)} \end{aligned} \tag{8.21}$$

and

$$\begin{aligned} P_B(t_2) &= P_{REC}(t_2) \\ &= 1 - e^{-\theta_2 b - \theta_2 awO'(t_2)}. \end{aligned} \tag{8.22}$$

Only the parameters s and α, and the parameter combinations $\theta_2 b$ and $\theta_2 aw$ can be estimated from the data. The parameter values (except $\theta_2 b$) as

Table 8.3. Parameter estimates and values of fixed parameters for the SAM model using recovery only to reproduce the data of the two-stimuli-once condition.

parameters	solution 1	2	3	4
$\theta_2 b$	.005	.00002	–	–
$\theta_2 aw$	4.928	7.983	5.*	6.856
s	.186*	.0599	.186*	.0701
α**	.0165*	.0046	.0165*	.0047
χ^2	22.91	21.06	22.98	21.07
df	10 (–2)	8	12 (–3)	9

Note: * The value of a fixed parameter.
** The spacing and retention intervals in seconds (number of events times presentation time) are used.

obtained from the analysis of the once-presented data with only recovery (table 5.2) have been used as starting values.

In solution 1 of table 8.3 the results are given when both $\theta_2 b$ and $\theta_2 aw$ are estimated from the data. In the second solution, the results are presented when all four parameters are estimated from the data. Both fits are acceptable in terms of χ^2. In both cases the values of $\theta_2 b$ is very small compared to $\theta_2 aw$, and the inter-item associative strength can be neglected in comparison with the context strength. In the third solution the results are presented when the inter-item associative strength is eliminated from the model and the other parameters are fixed at their starting values. Elimination the inter-item associative strength from the model has the same effect fixing the parameter combination $\theta_2 b$ at 0. In the fourth solution the results are presented when we assume that the inter-item associative strength is eliminated, but now the other three parameters are estimated from the data. All solutions describe the data to an acceptable level, but the solutions where the inter-item associative strength is eliminated from the model are to be preferred, because the same χ^2 is reached with one degree of freedom more than when the inter-item associative strength is included as a free parameter. When the parameters are fixed at the values found in section 5.2 for once-presented stimuli a reasonable fit is obtained: Estimating the parameters from the data gives a fit that is slightly better in terms of χ^2. (Note that the parameter estimates for s and α in solutions 2 and 4 are smaller than those in solutions 1 and 3, but all imply about the same probability of a correct response.) The smaller value of parameter s is compensated by a smaller value for α and a higher value for the parameter combination $\theta_2 aw$.

It can be concluded that a model using only recovery can describe the data to an acceptable level. The third solution is to be preferred because the same parameter estimates can be used for more than one set of data. The fit is just as good as for the model using only sampling presented in section 8.2. Both models (using only sampling or only recovery) can be used to reproduce the data in the two-stimuli-once condition.

8.4. DATA FROM TWO-STIMULI-ONCE: SAMPLING AND RECOVERY

In this section the complete model is used to predict the data, that is, both sampling and recovery are assumed as retrieval processes. The probabilities of a correct response to word pair A and word pair B (equations 2.3, 2.22, 2.23, and using equations 2.1, 2.2, 2.6, and 5.2 to rewrite) are respectively:

$$P_A(t_1+t_2|\theta_2) = \{1-(1-P_{SAM}(t_1+t_2))^{L_{max}}\}\ P_{REC}(t_1+t_2)$$

$$= \{1-(1-\frac{O'(t_1+t_2)}{O'(t_1+t_2)+\frac{Z}{b\,a\,w}})^{L_{max}}\}\ \{1-e^{-\theta_2 b-\theta_2 awO'(t_1+t_2)}\}$$

(8.23)

and

$$P_B(t_2|\theta_2) = \{1-(1-P_{SAM}(t_2))^{L_{max}}\}\ P_{REC}(t_2)$$

$$= \{1-(1-\frac{O'(t_2)}{O'(t_2)+\frac{Z}{b\,a\,w}})^{L_{max}}\}\{1-e^{-\theta_2 b-\theta_2 awO'(t_2)}\}.$$

(8.24)

Table 8.4. Parameter estimates and values of fixed parameters when using a model with both sampling and recovery to reproduce the data of the two-stimuli-once condition. The inter-item associative strength is not eliminated.

parameters	solution	
	1	2
$\theta_2 b$	.390	.181
$\theta_2 aw$	3.774	17.224
s	.186*	.0530
α**	.0165*	.00326
$\frac{Z}{b\ a\ w}$	.188	.167
L_{max}	3.*	3.*
χ^2	22.88	21.01
df	9 (–2)	7
C	.137 - .240	.408 - .672
sampling	.412 - .583	.330 - .469
recovery	.312 - .466	.446 - .574

Note: * The value of a fixed parameter.

** The spacing and retention intervals in seconds (number of events times presentation time) are used.

Apart from the context fluctuation parameters (s and α), the parameter combinations $\frac{Z}{b\ a\ w}$, $\theta_2 b$, and $\theta_2 aw$, can be estimated from the data. Parameter L_{max} is fixed at 3. In the first solution of table 8.4 parameters s and α are fixed at the values found in section 5.3 (table 5.3) for the once-presented data. The fit is just about as good as that for only sampling or only recovery. In this application the effect of the inter-item associative strength is not negligible when compared to the context strength. We attempted to fit the data when both s and α are also estimated from the data; the results are presented as solution 2 of table 8.4. The fit is slightly better than that in solution 1 in terms of χ^2.

In many applications of the SAM model it was either not possible to estimate the value of the inter-item associative strength from the data, or the fit of the model to the data was equally good when the inter-item associative strength was eliminated from the model. In the following discussion, the inter-item associative strength is eliminated from the model. Accordingly, the probabilities of correct responses (equations 8.23 and 8.24 after elimination of b) are:

$$P_A(t_1+t_2|\theta_2) = \{1-(1-\frac{O'(t_1+t_2)}{O'(t_1+t_2)+\frac{Z}{a\,w}})^{L_{max}}\}\,\{1-e^{-\theta_2 awO'(t_1+t_2)}\} \tag{8.25}$$

and

$$P_B(t_2|\theta_2) = \{1-(1-\frac{O'(t_2)}{O'(t_2)+\frac{Z}{a\,w}})^{L_{max}}\}\,\{1-e^{-\theta_2 awO'(t_2)}\}. \tag{8.26}$$

As before these equations can be rewritten showing that only the parameter combinations $\frac{Z}{a\,w}$ and $\theta_2 aw$ can be estimated from the data together with the context fluctuation parameters s and α. In the first and second solutions of table 8.5 the parameter values found in table 5.4 to predict the once-presented word pairs are used as starting values. In solution 1, s and α are fixed and in solution 2 they are also estimated from the data. The fit to the data is just as good as when the inter-item associative strength is not eliminated from the model.

The following procedure was used for the results presented in solutions 3 and 4. A fixed value of .0047 will be used for α (see sections 8.1 and 8.2). Parameter s is between .052 and .070 in those sections and predictions using three different values for this parameter, namely .052, .061 and .070, will be compared. When only $\frac{Z}{a\,w}$ and $\theta_2 aw$ are estimated from the data all three values of s result in fits that are equally good. In all three cases the value of $\theta_2 aw$ is very large implying that the probability of recovery is greater then .95. The χ^2 values, respectively 21.00, 20.98 and 20.97, are only slightly better than those obtained from assuming only recovery or only sampling, and are also slightly better than those presented in solutions 1 and 2. The estimates of the parameters for

Table 8.5. Parameter estimates and values of fixed parameters for the SAM model using sampling and recovery to describe the data of the two-stimuli-once condition, without the inter-item associative strength.

parameter	solution			
	1	2	3	4
$\theta_2 aw$	109.503	10.452	130.602	3.798
s	.186*	.112	.070*	.130
α**	.0165*	.00318	.0047*	.0047*
$\frac{Z}{a\ w}$	.557	.379	.413	.0496
L_{max}	3.*	3.*	3.*	3.*
χ^2	22.81	21.00	20.97	21.06
df	10 (−2)	8	10 (−2)	9 (−1)
C	.036 - .064	.055 -.085	.023 - .056	.049 - .087
sampling	.060 - .101	.127 - .184	.152 - .270	.872 - .952
recovery	.981 - .999	.438 - .589	.981 - .997	.169 - .282

Note: * The value of a fixed parameter.
** The spacing and retention intervals in seconds (number of events times presentation time) are used.

$s = .070$ are presented in table 8.5 solution 3. In this case, sampling has the most influence in determining the probability of recall, and recovery has only a small influence.

In the fourth solution of table 8.5 the results are shown when s, $\frac{Z}{a\ w}$, and $\theta_2 aw$ are estimated from the data ($s = .061$ is used as starting value). The fit is slightly worse than that presented in solution 3. If an additional parameter is estimated then the effect is that the role of sampling and recovery in predicting the probability of a correct answer is changed. Here the probability of recovery is between .17 and .28 and that of sampling between .86 and .95. The exceptional large value of the parameter combination $\theta_2 aw$ in solutions 1 and 3 imply that the probability of recovery is nearly 1, that is, the probability of a correct response is determined by the probability of sampling. In the previous sections of this chapter we explained that only the ratio between the parameters is relevant in determining the probability of sampling and that of recovery. In this section it has been shown that a model based on only sampling, a model based on only recovery or the complete model with both processes can reproduce the data equally well.

8.5. DATA FROM TWO-STIMULI-ONCE: CONCLUSIONS

We conclude that the data of the two-stimuli-once condition can be described by simplified versions of the SAM model to an acceptable level. A model assuming only the sampling process (section 8.2) or only the recovery process (section 8.3) as retrieval process can reproduce the data just as well as the complete model (section 8.4). In case of only sampling (section 8.2), it is only possible to estimate the inter-item associative strength from the data in combination with parameters Z, a and w. In case of only recovery (section 8.3), elimination of the inter-item associative strength from the model does not worsen the fit compared to a model with the inter-item associative strength included. The parameters s and α can be set at the values as obtained in chapter 5 from the analysis of the once-presented data with only sampling or only recovery. The data can be described to an acceptable level when the parameter combinations $\frac{Z}{b\ a\ w}$ (in case of only sampling) or $\theta_2 a w$ (only recovery) are estimated from the data. Estimating the parameters s and α also from the data results in a slightly better fit in terms of χ^2, but is not to be preferred because the benefit in χ^2 is small compared to the loss of degrees of freedom. It can be remarked that when s and α are estimated from the data, the values of the parameters are much lower and lead to a similar fit. The reason is that the ratio of the parameters is determining the probabilities of sampling and recovery.

9. CONTEXT FLUCTUATION OR OTHER DECAY FUNCTIONS

In the application of the model to the data it is very difficult to separate the context from the inter-item associative strength. In the previous chapters it has been shown that the experimental data can be described with simpler model versions, for which only the context strength is used and the inter-item associative strength is deleted. One might wonder whether other simpler models for the effect of context fluctuation may be more appropriate.

We will first summarize the way SAM models context strength and inter-item associative strength.

In the SAM model, as used here, the inter-item associative strength and the context strength determine the probabilities of sampling and recovery when a stimulus must be recognized at a later presentation or when the stimulus must be recalled at a test. The context strength is defined as the overlap between stored context elements and the context elements active at the moment of testing. It is calculated by means of the context fluctuation model (sections 1.3 and 2.1). The context strength can be seen as a decay function. The inter-item associative strength, on the other hand, is not elaborated by means of a decay function, but is simply a constant value which is incremented after every successful recall or recognition (using the function given in equation 2.6 based on only the number of presentations).

Section 9.1 will discuss some details of context fluctuation not previously presented, and demonstrate its similarity to a decay function.

As to an alternative, to context fluctuation we refer to Reed (1977) who used the trace strength principle of Wickelgren (1972,1974) in a theory which employs only one passive memory trace to describe the experimental data of Glenberg. It is possible to use the trace strength concept as developed by Reed in the SAM model to calculate the context associative strength. In section 9.2 the characteristics of this decay function will be given. The trace strength as developed by Reed will be incorporated in the SAM model, to reproduce the data of Glenberg's experiment and those of experiment I (these are also presented in section 9.2).

In section 9.3 the characteristics of the decay functions necessary for multiple presentations will be summarized. The context fluctuation function and the trace strength decay function conform to these requirements, but more simple decay functions that can be used to calculate the context and/or the inter-item associative strength, do not.

9.1. CONTEXT FLUCTUATION AS DECAY FUNCTION

In paragraph 1.3.1 the context fluctuation model was explained. In section 2.1 the formulae (equations 2.7 to 2.11) to derive the context associative strength for a single and for multiple presentations were given. In both sections the principles of the context fluctuation model were described. However, the exact characteristics of the context fluctuation model were not shown. These characteristics will be presented in this section.

9.1.1. Characteristics of the Context Fluctuation Function

As described before, there are active and non-active context elements, and as time passes, there are transitions of context elements from the active to the non-active state (and vice versa). A proportion of the context elements in the active state is encoded and stored in the memory trace. The overlap of the stored context elements and the context elements active at the time of retrieval is taken as a measure of the context strength. This overlap depends on the time lag between presentation and test. Four parameters were used in previous chapters to estimate the context strength. Only three parameters (s, the equilibrium value of the proportion of elements that is active; α, the rate of fluctuation between the active and non-active states; and w, the probability of being encoded) will be used here to illustrate the context fluctuation function. The fourth parameter, a, the scale parameter to transfer overlap into context strength is fixed at 1, and not discussed further in this section. This overlap will be illustrated for a single presentation and a test, as well as for two and three presentations and a test.

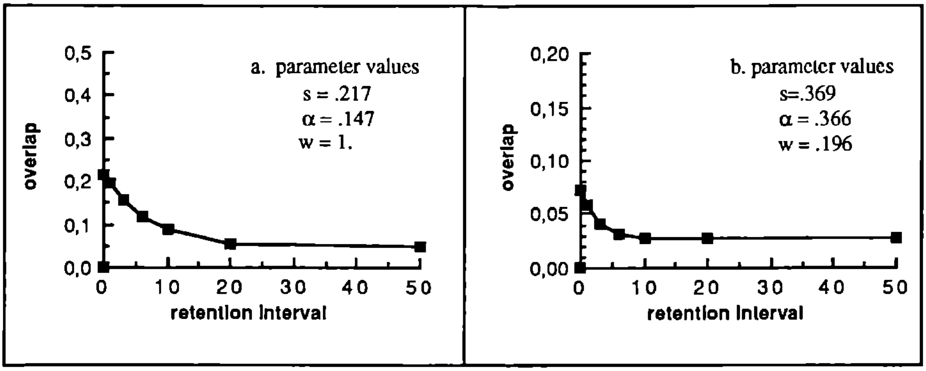

Figure 9.1. Overlap between storage after one presentation and the active elements at the time of testing as a function of the retention interval. In (a) all active elements are stored, and in (b) nearly 20% is stored. The parameter values were found in fitting a version of the SAM model to the data of Rumelhart (cf. ch. 7). The retention interval is in events.

Even after one presentation the overlap between context elements in storage and the active context at test is starting to decay to a constant value with increasing retention intervals. In figures 9.1a and 9.1b the decay of the context fluctuation function is shown for two sets of the context fluctuation parameters *s*, α and *w*, which have been found as acceptable parameter values in chapters 5 to 8. (In most of the figures in this section the same parameter values will be used.) In figure 9.1a all active elements are stored, that is, *w* = 1, and in figure 9.1b only a part of the active elements is stored (*w* = .196).

If the stimulus is recognized or recalled at the second presentation, P_2 (i.e. the strength of the trace is sufficient to retrieve the item) the strength of the trace is increased with additional context elements that are active at P_2 but not yet stored. The greater the interval between P_1 and P_2 the greater the additional storage. At P_3 or at a test after two presentations the model indicates the overlap between the stored context elements and the context elements active at that moment. This overlap depends on both spacing and retention interval in the special case of two presentations followed by a test. The resulting curves of the overlap can be represented in two ways. Firstly, overlap can be shown as a function of retention interval, with the spacing interval as a parameter. This is shown in figure

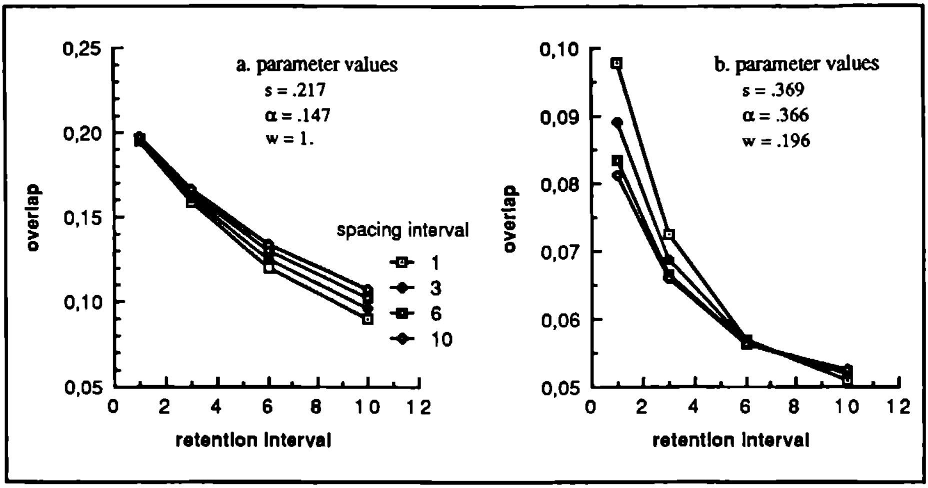

Figure 9.2. Overlap of active context at testing with stored elements after two presentations as a function of the retention interval for different constant spacing intervals. Both the spacing and the retention intervals are in events.

9.2 and shows that the proportion of overlap decreases when the retention interval increases, but that the decrease in overlap is more rapid when the spacing interval is longer. When all active elements are encoded (*w* = 1) the overlap at spacings of zero is always equal to the proportion of active elements (*s*). When only a proportion of active elements is encoded (*w* < 1) this overlap is smaller than *s*, except when all context elements are stored.

Secondly, overlap can be presented as a function of spacing interval, with retention interval as a parameter (figure 9.3). When all active elements are stored at each presentation the overlap versus retention interval curves are all steeper. When only a small proportion of the elements is stored, then an interaction is clearly seen: Small retention intervals entail a decrease in overlap, while with long retention intervals the overlap is increasing. Remember that the data of Glenberg and of experiment I described in chapter 3, were presented in the same way as in figure 9.3. The percentage of recall was presented as a function of the spacing interval for different retention intervals.

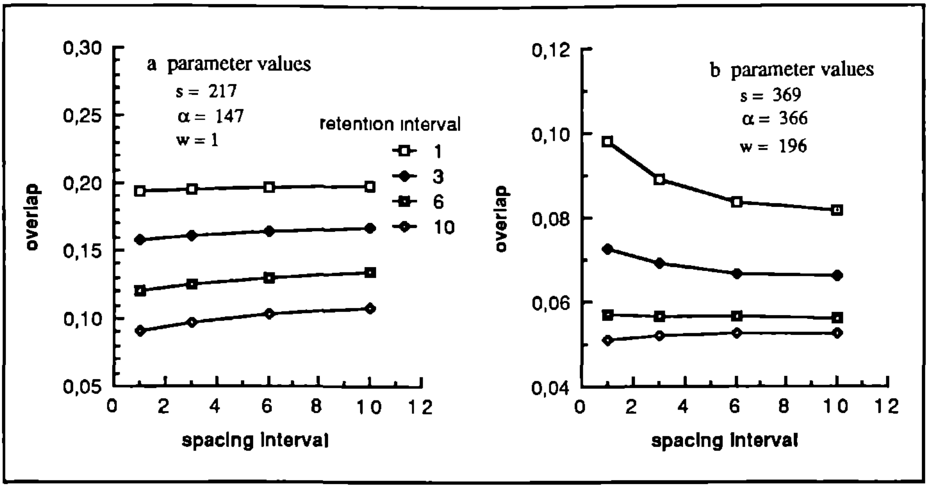

Figure 9.3. Overlap of active elements at testing with stored elements after two presentations as a function of the spacing interval for constant retention intervals. The spacing and the retention intervals are in events.

For the subsequent presentations a proportion of active context elements not stored already is always encoded in the trace. Assuming that there are i presentations with the ith presentation as a test, it is usually seen that if the total interval between the first and the i-1th presentation is constant the overlap between the total number of stored context elements and the number of active context elements at test is decreasing with an increasing retention interval. In the case that all active context elements are stored, the order of the spacing between presentations does not matter, as the overlap is reset each time to a maximum value. This is illustrated in figure 9.4a for three presentations followed by a test. Further, it is seen that after every increment of the trace strength the overlap decreases more slowly for these spacings. The overlap for the spacing of zero is, in all cases, equal to the maximal number of active context elements, i.e., .217.

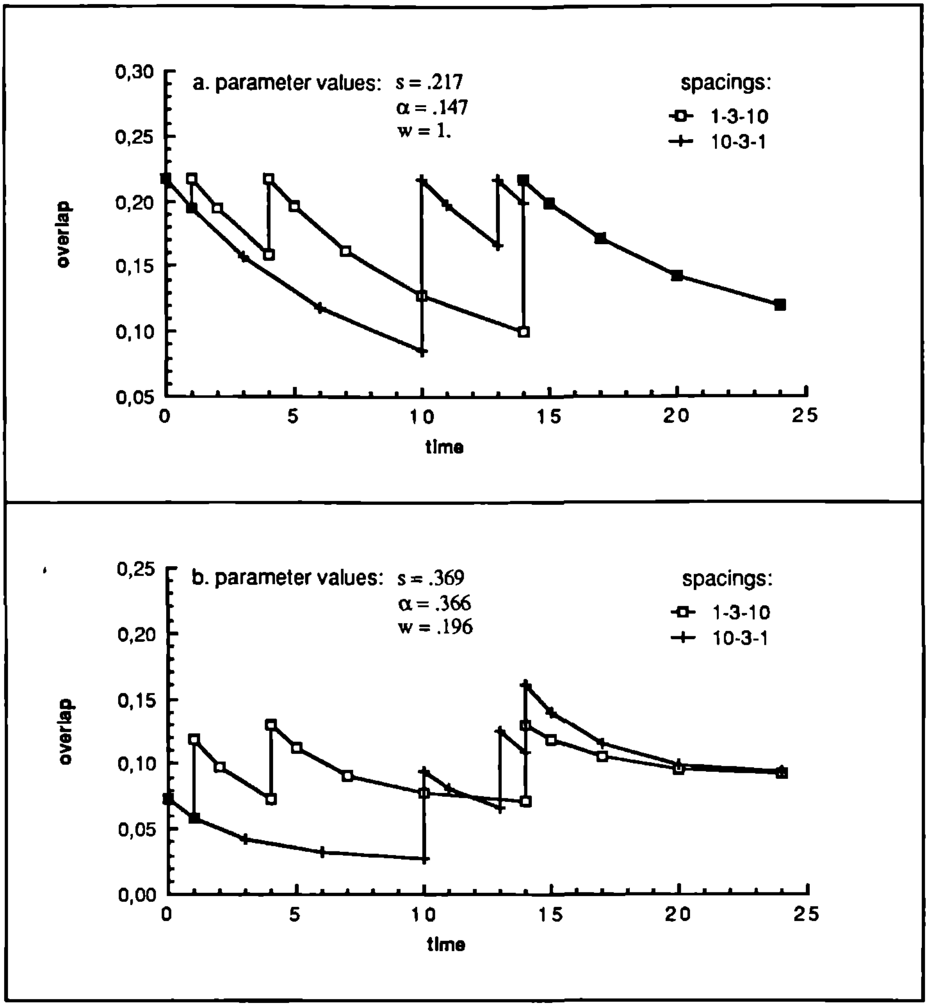

Figure 9.4. Overlap of stored and active elements as a function of the time between the first presentation and the test after the third presentation. In (a) all active elements are stored and in (b) only 19.6 %. In each panel of the figure two sets of spacings are used, namely t_1=1, t_2=3 and t_3=10 (squares: 1-3-10) versus t_1=10, t_2=3 and t_3=1 (+'s: 10-3-1). The time and the spacings are in events.

In figure 9.4b the overlaps for the same spacing as those used in figure 9.4a are shown for the other parameter set, that is, in the case that only a proportion of about 20% is stored in memory. The overlap immediately after an increment is not reset to a maximum value, but depends on the spacing before the increment and on the total number of stored context elements. In this case both the order of the separate spacings between the i-1 presentations and the length of the separate spacings determine the decay after the i-1th presentation, that is, at P_i.

One other aspect can be mentioned in case of storage of all active context elements ($w = 1$). The overlap at P_i after correct recall or recognition depends directly on the sum of the separate spacings between the first and the i-1th presentation. The greater this sum the greater the overlap.

9.1.2. Why use Context Fluctuation?

In section 1.2.2.1 the Component-Levels theory of Glenberg (1979) was reviewed. Glenberg distinguished three kind of components: descriptive, structural and contextual[1]. In SAM, all aspects not directly related to structural and descriptive aspects of the stimuli are taken together as the context. It is assumed that context is fluctuating slowly. The context elements are slowly changing from the active to the inactive state and vice versa. It is assumed that this fluctuation process is random. These context changes cannot be observed.

In the experiments presented here the context was not manipulated explicitly. At a test, the second word of a word pair must be given with the first word as retrieval cue (or, in case of Rumelhart, the response must be given with the stimulus as retrieval cue). No additional information or cues were given about how long ago the word pair was presented. The environment of the subject was kept as constant as possible. The only context information perceptible by the subject can then lie in the order of presented stimuli themselves. However, in the experimental design care has been taken to randomize the presentation order of the items or, in terms of the models, to minimize the context overlap. Mensink (1986) has assumed in his applications of the SAM model elaborated with context fluctuation that the context within one list

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[1] Remember that Glenberg uses the term contextual instead of context.

of words is constant and that the context only fluctuates between lists. At testing he presented additional information to the subjects, e.g. he tells the subjects in which list the items were presented. In the experiment of Glenberg and experiments I and II presented here a single very long list is used. The experiment of Rumelhart is also a long run of testings immediately followed by a presentation of the same pair. That is, it can be assumed that the context is constant on the average. Context fluctuations manifest themselves in these experiments at best as a consequence of an uncontrolled, random process.

The importance of context fluctuation cannot be controlled experimentally, and additional experimental evidence for the role of context fluctuation is needed. Only experiments in which the context is explicitly manipulated may give rise a definite answer.

Context is an important aspect in theories and models about memory. Although not quantifiable many context changes are clear, such as using another testing room or testing in the morning instead of the afternoon. The fluctuating context as used in the SAM model to describe the experiments is not experimentally related to context. It can therefore also be seen as some kind of decay process for the strength of the memory trace. Context fluctuation is a rather complicated decay process with 3 parameters to describe the overlap. In the following section of this chapter another decay function will be presented and compared with the context fluctuation function.

9.2. DECAY OF TRACE STRENGTH, DEVELOPED BY WICKELGREN

Wickelgren (1972,1974) has introduced the concept of trace strength in his strength-resistance theory. Reed (1977) developed the trace strength principle further to quantitatively predict the spacing effects in learning. Reed elaborated the function of Wickelgren for two presentations.

9.2.1. Mathematical Aspects of Decay of Trace Strength

Wickelgren (1972,1974) assumed that stimuli presented for the first time are stored in traces with a certain initial strength. In the course of time the trace decays, i.e. the strength of the stimulus stored in long-term memory decreases. Two processes, beginning at the moment of storage, are responsible for the decrease in strength. These are growth of resistance and decay of strength. The decay rate depends on the resistance of the trace and resistance in its turn, depends on time. The trace strength ($S(t)$) at time of retrieval, given by Wickelgren (1972, 1974) as an exponential power function, is:

$$S(t) = S_0 \, e^{-\Psi t^{\gamma}}, \tag{9.1}$$

where S_0 is the strength at storage, γ determines the growth rate of the trace resistance and Ψ is a parameter for the rate of strength decay.

The trace strength decay concept was originally used within a multiple-trace theory. Reed (1977) has used the trace strength principle in a theory which employs only one passive memory trace. Similarly, we will use only one passive memory trace. If items are repeated it is assumed by Reed (1977) that the trace strength of recognized items is enhanced. After recognition or recall of the stimulus, the strength of the trace in long-term store is reset to its strength at the first presentation (or at a somewhat higher value). Further, Reed assumed that the process of resistance growth is not restarted, but continues as if no increment of strength has taken place. The strength at time of testing (or P_3) is given by Reed (1977) as:

$$S(t_1,t_2) = S_0 \, e^{-\Psi \left((t_1+t_2)^{\gamma} - t_1^{\gamma}\right)}. \tag{9.2}$$

Therefore, it follows that after an increment of trace strength the decay of the trace strength will slow down. Remember that t_1 is the interval between P_1 and P_2, and t_2 is the interval between P_2 and P_3.

The decay of trace strength is illustrated for values of the parameters ψ and γ found in an earlier presentation of this decay function incorporated in the SAM model (van Winsum-Westra, 1987) for twice-presented stimuli. The third parameter, S_0, the strength at storage, is assumed to be constant and can be set at 1 and will be not presented in the figures at the moment. In figure 9.5 the decay of the trace after a single presentation is shown to decrease with increasing time between presentation and test. In

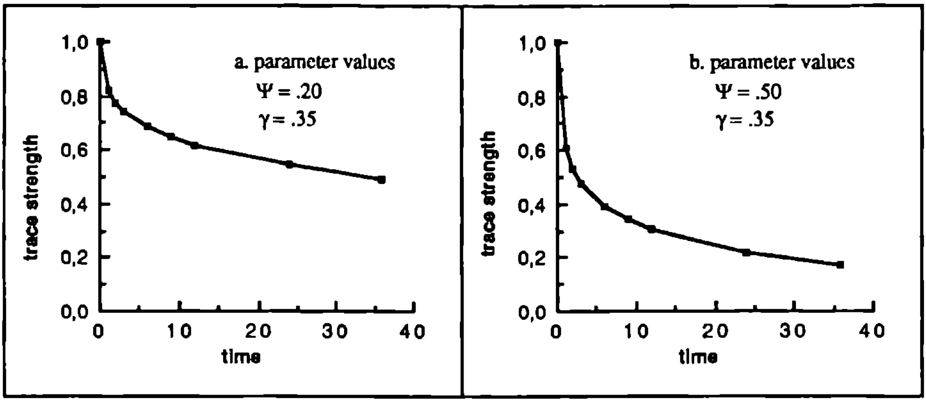


Figure 9.5. Decay of trace strength as a function of the elapsed time between presentation and test for two sets of parameter values, when the exponential power function of Wickelgren is used. In panels a and b two different sets of parameter values are used.

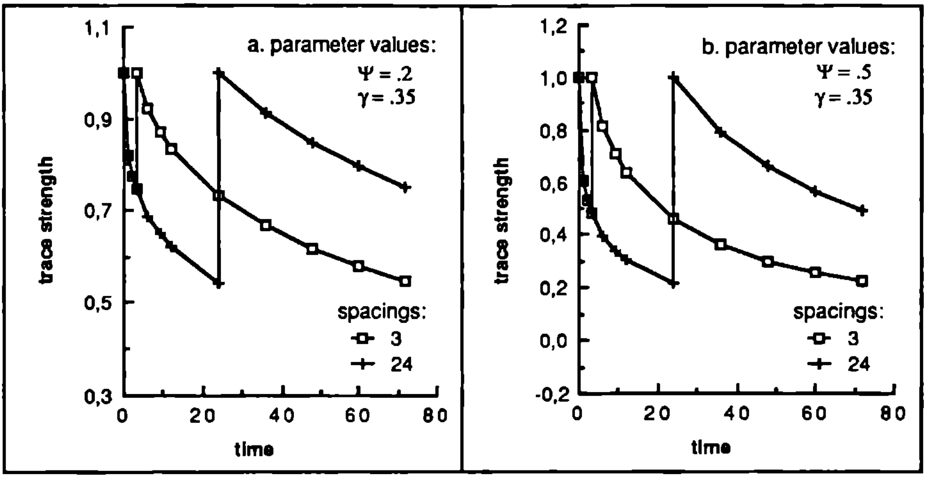


Figure 9.6. Decay of trace strength as a function of the time between the first presentation and the test after the second presentation using the exponential power function developed by Reed. In panels a and b two different sets of parameter values are used. In both panels the effect of two different spacing intervals is shown (for the squares t_1=3, and for the +'s t_1=24). The horizontal axis represents t_1+t_2 (cf. equation 9.2).

figure 9.6 the decay after two presentations is shown. The strength of the trace is incremented at the second presentation and the decay function (equation 9.2) is illustrated in figure 9.6 for two different spacing intervals (one relatively short, the other relatively long) and variable retention intervals. The strength is reset to the same initial value at the second presentation, while the growth of resistance is continued.

The strength of the trace and the decay of this strength for more than two presentations was not further developed by Wickelgren or Reed, but can be derived in different ways from equation 9.2. We will illustrate this decay function (comparable to the context fluctuation function) as follows. We assume that the strength of the trace will increase with the number of presentations. Moreover, greater time intervals between presentations will also increase their strength, as a consequence of resistance growth of the trace. We assume that the strength of the trace after more than two presentations with increment at each presentation is at time of the i+1th presentation given by:

$$S(t_1,\dots,t_i) \;=\; S_0\, e^{-\Psi\,((t_1+\dots+t_i)^{\gamma} - (t_1+\dots+t_{i-1})^{\gamma})}, \tag{9.3}$$

where t_i is the interval between P_i and P_{i+1}. In equation 9.3, it can be seen that only the sum $t_1 + \dots + t_{i-1}$ and the spacing interval t_i are relevant for the decay of trace strength after P_i. That is, the time between P_1 and P_i and the interval between P_i and P_{i+1} determine the strength at P_{i+1}. The number of presentations between P_1 and P_i (the value of i) does not matter if the interval between P_1 and P_i is constant. For every presentation P_i at a specific time after P_1, the decay after P_i is independent of the number of presentations (i). This effect is shown in figure 9.7 for three presentation. Figures 9.7a and 9.7b show the effect for two different sets of parameters. In both panels, two different spacing intervals t_1 and t_2 are used with a constant sum (for the squares t_1=3 and t_2=57, and for the +'s t_1=24 and t_2=36) Both panels show that the decay after P_3 is equal for both combinations of spacing intervals.

We have studied this decay function within the framework of the SAM model, where we used it to define the context associative strength. To incorporate the notion of strength decay in a model for retrieval it is necessary to have a model (such as the SAM model) with a recognition or

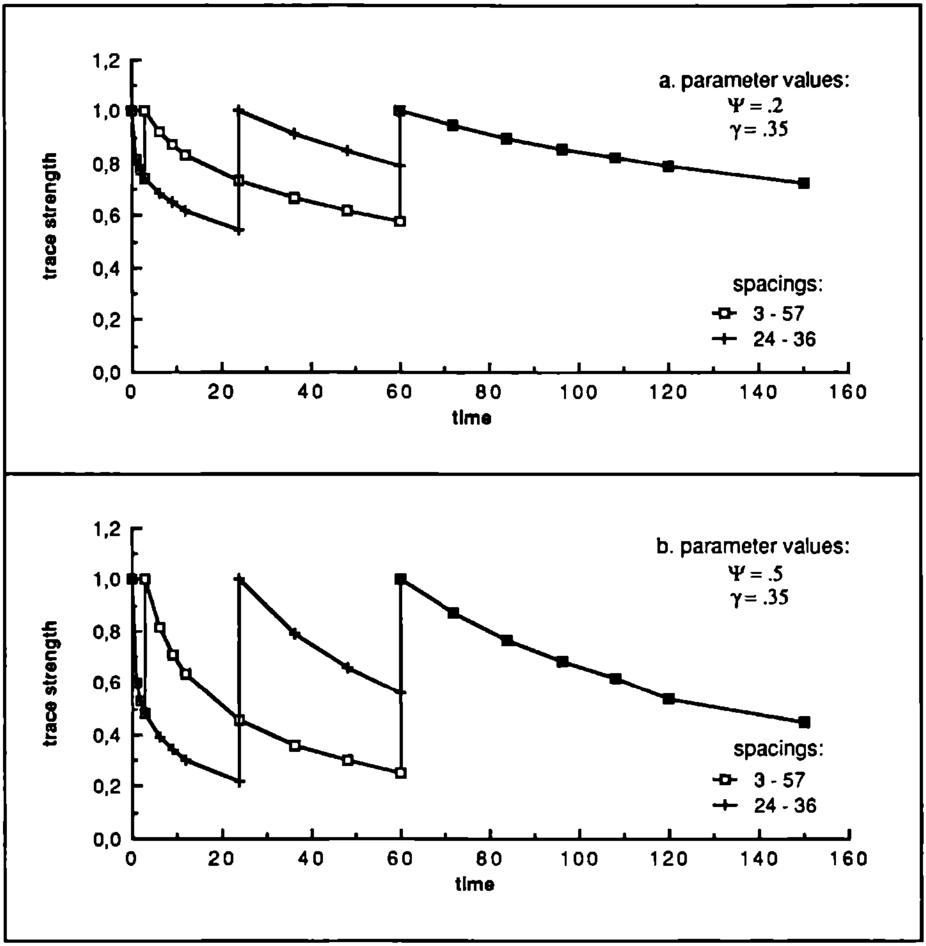


Figure 9.7. Decay of the trace strength as a function of the time between the first presentation and the test after the third presentation using of an exponential power function. In panel a one set of parameter values is used in panel b another. In both panels, two combinations of spacing intervals t_1 and t_2 with a constant sum are used. For the squares $t_1=3$ and $t_2=57$, and for the +'s $t_1=24$ and $t_2=36$. The horizontal axis represents $t_1+t_2+t_3$ (cf. equation 9.3).

recall phase (possibly implicit) at every presentation, which determines either whether a new trace is formed, or whether an old trace is incremented and the resistance growth is continued. In models without a recognition or recall phase we assume that the strength of the trace is increased at every presentation. In such models only the interval between the first and the last presentation is relevant. Models assuming that the trace is incremented at every presentation might perhaps describe data with one or two presentations followed by a test, but cannot describe data with more than 2 presentations adequately, because of the irrelevance of the number of previous presentations.

In SAM, when an item is presented the stored trace is retrieved from memory if the item is stored and the strength is great enough for successful recognition or recall. When the item is not stored or not recognized or recalled it will be treated as new. Only in the case of a successful retrieval is the trace strength reset and the resistance growth continued. For items presented only a few times (that is, with larger spacings) the probabilities of retrieval at every presentation are smaller than for item presented more often. We assume that a new trace is formed for items which are not recognized as old. A new trace is formed more often for items presented with larger spacings.

Comparing the trace decay function (of Wickelgren and Reed and the elaboration given here in equation 9.3) with the decay function following the principles of context fluctuation (section 9.1.1) the most striking differences between the two functions are:

1. The trace decay function resets the strength of the trace to the same initial value (S_0) while the growth of resistance is continued. For context fluctuation, and only if all context elements are stored, the overlap immediately after the presentations is constant and equal to the proportion of active elements (that is, reset to the same initial value). If only a proportion of the active context is stored, the reset value increases after every correct retrieval: from ws after the first presentation to s if all context elements are stored (that is, after many presentations).
2. For context fluctuation the decay depends on the number of presentations before the test. The more presentations preceding the test

the slower the decay. In case of the trace decay function the number of presentations before the test is irrelevant as the interval between the last presentation and test is constant.

3. The rate of decay for context fluctuation is discontinuous after the next recognized presentation, but in case of the trace decay function the rate is continuous. The number of stored context elements is always increased after every presentation until all elements are stored. If only a proportion of elements is stored, the overlap is at most equal to the proportion of active elements but the degree of overlap immediately after a presentation varies and depends on the actual number of presentations and the intervals between these presentations. This overlap is mostly increasing for subsequent presentations, until all active elements are stored.

It is possible to reset the trace strength again and again to a higher value after each presentation, but then it is necessary to introduce an additional parameter to restrict this increment to an asymptotic value. If this is not done a maximum asymptotic value for the reset value of the strength must be derived from the number of presentations. The exact number of presentations preceding the test and the intervals between the presentations are both relevant in this case.

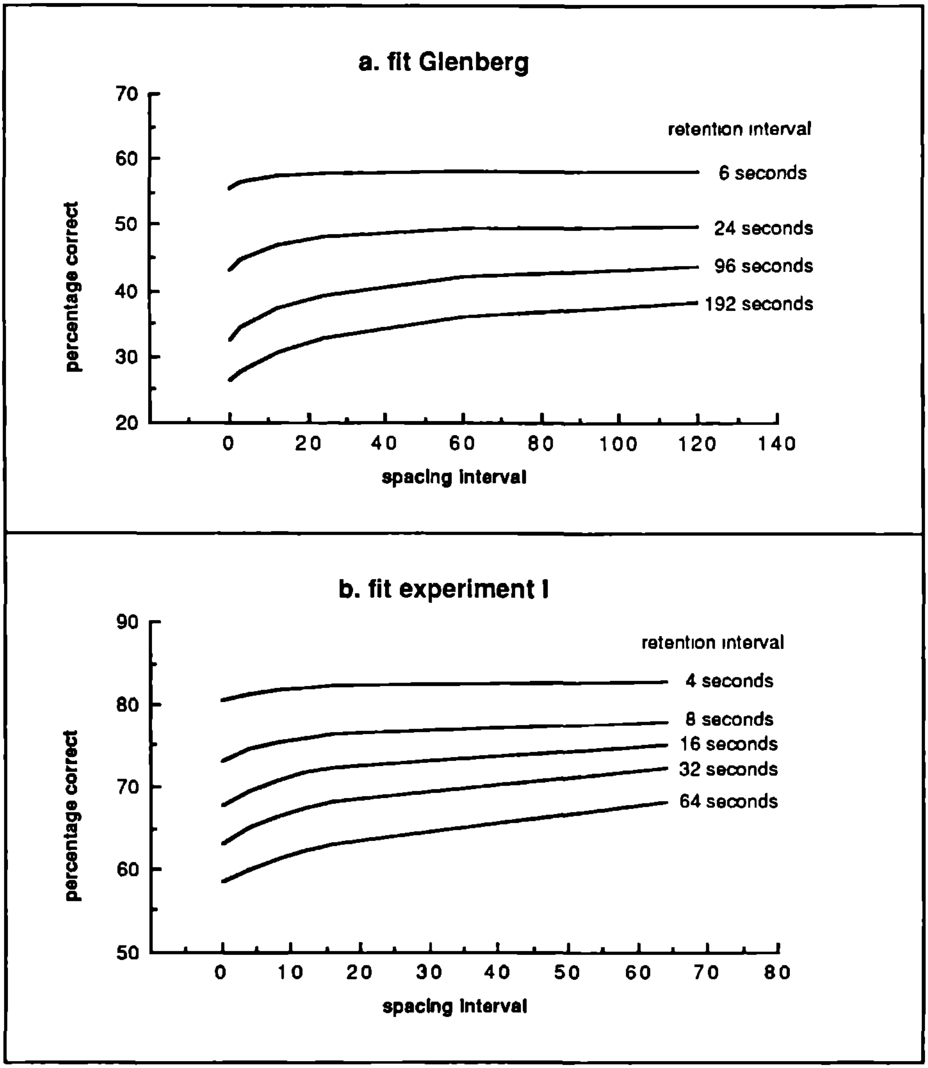
9.2.2. Application of the SAM Model with Strength Decay

We will illustrate the incorporation of the strength decay function (9.2) into SAM, by application of this model to the data of Glenberg and of experiment I, to explain the spacing and repetition effects for two presentations followed by a test. In this application the strength of the trace at the moment of test (P_2 for recognition and T for recall) is taken as a measure of the context associative strength. We assume that, at P_1, information concerning the context is stored with some "inter-item" information. What happens on P_2 depends on whether or not the memory trace stored at the P_1 is retrieved on the second presentation. Directly following each presentation the elements of the item are also held for some time in the short-term store. Items held in this STS at the moment of a following presentation are always recognized. For items not in the STS at P_2 retrieval of the episodic image of P_1 is necessary for recognition. If recognition is successful the context strength of the memory trace is reset to the original strength (equal to the strength at time of P_1), but the decay is slower than that found after only one presentation. This is equivalent to resetting the strength but with decay still as it started with the first presentation. The inter-item associative strength is in this case assumed to be constant during the experiment and is also not increased.

Hence, the memory trace of a repeated, recognized item will be stronger than the trace of an item presented once. The spacing effect found with repetitions (see figure 2.4) shows that the probability of a correct answer decreases with increasing spacing intervals for small retention intervals and increases with increasing spacing intervals for large retention intervals. This interaction can be predicted by the present version of the SAM model with strength decay. In case of a large retention interval, it is important that resetting the strength has a strong effect, this will be the case if the trace corresponds to two presentations with a long spacing interval. For small retention intervals the situation is different, because the decay in memory strength is very small. In that case, a small spacing interval will increase the similarity between storage and test, and hence also the probability of a correct answer.

The stronger the trace (the slower the decay) the greater the probability of a correct response. The probability of recognition and the various recall probabilities were given in section 2.1 by equation 2.5. Equation 9.1 must be substituted for the context associative strength to calculate the probabilities of recognition ($P_{RG}(t_1|\theta_1)$) and of recall of a trace not recognized at the second presentation (based on a single presentation), that is, when a new trace is formed at P_2, ($P_{RL}(t_2|\theta_2)$). Equation 9.2 must be used to calculate the probability of recall of a recognized, and by that strengthened trace ($P_{RL}(t_1,t_2|\theta_2)$).

In table 9.1 a set of parameter estimates with a small value for χ^2 is presented and in figure 9.8 the predicted percentages of a correct response are shown. The fit of this model (with trace strength decay) to the data is not systematically investigated. Many different parameter values lead to approximately the same values for χ^2. The parameter estimates presented in table 9.1 are presented to illustrate that this model can reproduce the data of two presentations followed by a test just as well as the SAM model with context fluctuation. The fit is acceptable for both



a. fit Glenberg

b. fit experiment I

Figure 9.8. The predicted percentage correct for the data of Glenberg and experiment I as a function of the spacing interval for the retention intervals used, when using the parameters presented in table 9.1.

Table 9.1. Parameter estimates and values of fixed parameters for the data of Glenberg and that of experiment I for the version of the SAM model with strength decay using an exponential power function (see van Winsum-Westra, 1987).

parameter	Glenberg	experiment I
Ψ**	.200	.502
γ**	.35*	.35*
S_0	7.680	8.561
b	.520	6.628
L_{max}	3.*	3.*
Z	1.*	1.*
θ_1	1.*	1.*
θ_2	.096	.100
λ**	.35	.35*
χ^2	53.0	70.3

Note: * The value of a fixed parameter.
** The spacing and retention intervals in seconds (number of events times presentation time) are used.

data sets. We found that the stimuli are nearly always sampled and also recognized. In case of experiment I, a rapid rate of decay is found. In this analysis a number of parameters is fixed arbitrarily. In this SAM model version with trace strength decay the number of parameters is greater than the minimal number of parameters necessary to describe the curves (see section 4.2). In the same manner as that illustrated in section 4.3, the model can be simplified and predict or describe the data just as well.

9.3. DECAY FUNCTIONS: CONCLUSIONS

As mentioned in the introduction (see section 1.1), after additional presentations performance increases until retention reaches an asymptotic level. The rate of decay is slower after more presentations because the trace is assumed to be stronger, therefore, functions in which the rate of decay is always the same after an increment, are not acceptable. It is necessary that the rate of decay is transmitted over the successive presentations, that is the decay, after a presentation of a repeated item that is recognized or recalled, is slower than the decay after the previous presentation. Further, the strength at an additional presentation is reset to some basic level or is increased to a higher level until an asymptote is reached. For the overlap in case of context fluctuation with all active context elements stored, and for the trace strength decay model, the strength is always reset to the basic level. When, however, only a proportion of the context elements is encoded, the strength is reset to a higher level until an asymptote is reached. For the trace strength decay function two effective parameters (ψ and γ) are involved in accomplishing this effect. For the context fluctuation function three parameters are involved (s, α, and w), one of which may be constrained (namely w=1). At this moment it is not clear what improvement the context fluctuation function with three parameters gives over that with two parameters. Both functions, context fluctuation and trace strength decay, can be used to predict the data of two presentations followed by a test (chapter 6 and section 9.2). The context fluctuation function can predict the data of Rumelhart to an acceptable level (chapter 7). However, it remains to be seen if the trace strength decay function can also be used to predict the data of Rumelhart.

We have attempted to incorporate other more simple functions in the SAM model. Functions where only one effective parameter is used together with the spacing intervals and the number of presentations. Such functions (with one effective parameter) can predict the data of single presentations, but were not useful in predicting the data with more than one presentations. Wickelgren (1972, 1974) has developed the exponential power function for decay in memory, but he has attempted also a number of other, more simple, decay functions. In these publications the following functions for decay in memory are rejected on the basis of data from a yes-no recognition experiment:

1. linear decay $l = \lambda - \Psi t$,
2. exponential decay $l = \lambda e^{-\Psi t}$,
3. logarithmic decay $l = \lambda - \Psi \log(t)$,
4. power function decay $l = \lambda t^{-\Psi}$.

Only the exponential power function

$$l = \lambda e^{-\Psi t^{\gamma}}$$

was not rejected. In these publications of Wickelgren it can be seen that all rejected decay functions have only one effective parameter (Ψ) and a start value for the decay (λ). The function not rejected on basis of the data has two effective parameters (Ψ and γ) and a start value (λ).

Comparing these conclusions of Wickelgren to the functions presented here and assuming that the initial value of decay is always 1 (that is $\lambda = 1$), it can be concluded that only functions with 2 or 3 effective parameters (s and α, and sometimes w, in case of context fluctuation and Ψ and γ in case of strength decay) are not rejected by the data. Decay functions with only one effective parameter must be rejected. Therefore, until now only decay functions as context fluctuation and trace strength decay lead to an acceptable course of decay.

SUMMARY AND CONCLUSIONS

The central theme of the present study is the SAM theory introduced by Raaijmakers and Shiffrin. The theory is elaborated with a model for context fluctuation to account for time-dependent changes. The SAM model is applied to a number of continuous paired-associate experiments. In the application problems were encountered with the identifiability of the parameters.

In chapter 1 the effects of spacing and repetition of presentations, that appear to occur in nearly all memory tasks are reviewed. Recall of repeated items is more successful than that of items presented once (the repetition effect). In general, massed repetitions lead to less durable storage, and therefore, the recall is less successful, than spaced repetitions. If the spacing between two presentations increases, the performance becomes better (the lag or Melton effect). For CPA tasks with very short retention intervals, however, the performance becomes worse when the spacing interval increases (spacing effect).

A review is given of the most important theories that account for both the effects of repetition and the differences between massed and spaced repetitions. Broadly speaking, the theories can be placed in three major classes: (a) inattention theories, (b) consolidation theories and (c) encoding variability theories. In addition there is a smaller class that combines encoding variability and consolidation theories.

Variable encoding is mostly used to explain the effects of spacing of repetitions. Encoding variability theories assume that items can be encoded in different ways, and that the representation of the item depends on the cognitive context in which it occurs. It is assumed that some cues available at presentation are recreated at retrieval. For items presented twice the chance of retrieval is higher if the item has been presented in different contexts. It is assumed that a greater spacing of presentations leads to more diversity in the encoding context and therefore, at test, there are more ways to retrieve the stimuli.

The Component-Levels theory of Glenberg proposes that spacing effects are due to variable encoding of any or all of three types of informational components. Variable encoding can reside in the semantic interpretation, in the context in which the events are encoded, and in the subjective organization in which the events are embedded. The Component-Levels theory is not mathematically elaborated. The global ideas of this theory will be incorporated in the SAM theory.

Also in chapter 1, the SAM theory, a theory for retrieval of information from memory is presented. Retrieval of information is considered a two-stage process of sampling and recovery by means of retrieval cues. In the sampling phase the information is searched in memory and after successful sampling the information is recovered (assembled and articulated into an answer) in the recovery phase. Retrieval cues are based on the context and on specific information of the stimulus, and the associative strengths between these cues and the image are respectively the context and the inter-item associative strengths. If either sampling or recovery fails a new retrieval attempt may be made until success, or a criterion of failure is attained.

The stimulus sampling theory of Estes can be elaborated into a context fluctuation model to explain spacing and repetition effects. Context elements are assumed to fluctuate between the active and non-active states. Only elements which are active at the time of a stimulus presentation can be encoded and stored in the memory trace. The overlap of stored context elements and the context elements active at the time of retrieval is taken as a measure of the context strength.

According to SAM, associations between items are formed when they are simultaneously present in a rehearsal buffer. For free recall tasks, all items present in the short-term store are assumed to be also part of the rehearsal buffer. However, in case of paired-associate tasks the rehearsal buffer and the short-term store are assumed to be non coincident. Two members of a pair are associated only to each other (during the presentation of the pair, when the items of the pair are actively rehearsed in the rehearsal buffer) and not to members of other pairs, still present in the short-term store. The short-term store here can be seen as a process that facilitates the recognition or recall of an item.

In chapter 2, the SAM model is extended to experiments with repeated paired-associates as stimuli. Mathematical details of different versions of the SAM model with context fluctuation are given. Versions of the SAM model are presented for stimuli presented once, twice and five times.

Further, the SAM model is elaborated to account for the results of the two-stimuli-once condition.

In all versions of the model it is assumed that some elements with context and other more specific information are stored at the first presentation of a stimulus. At the following presentations or tests of the stimulus, additional elements are stored in the same memory trace, if the stimulus is recognized or recalled. Stimuli are recognized or recalled when they are still present in the short-term store or when the stimuli are retrieved from LTS (a successful sampling is followed by a successful recovery). When a stimulus is not recognized or recalled, we assume that a new trace is formed.

In chapter 3, a description is given of the experiments used to test the different versions of the SAM model, and of the general data obtained from these experiments. The pattern of the data for the once-presented word pairs is that an increase in retention time leads to a decrease in recall performance toward an asymptotic level.

The continuous paired-associate experiment of Glenberg shows that for short retention intervals the curves of the recall probabilities are nonmonotonic functions of the spacing interval: An initial increase in performance is followed by a later decrease. Longer retention intervals give a monotonically increasing spacing effect with increasing spacing interval. In the data a dip is seen in the curves of recall probabilities for the short retention interval at a spacing interval of one event. Glenberg ignored this in the presentation of his results, but in a theoretical analysis of spacing effects by Reed the explanation of this dip in the observed data was one of the most crucial aspects of these data. In order to investigate the importance of the dip and its significance a new experiment was designed. In this replication only short retention and spacing intervals are used, because the dip in Glenberg's data was found for short intervals. The curves of the probability of a correct response for small retention intervals are nonmonotonic with increasing spacings and have a peak at about a spacing of three events. For the longer retention interval the curve is negatively accelerated with increasing spacing. No evidence was found for the dip observed in the results of Glenberg.

A continuous paired-associate experiment of Rumelhart with anticipation trials was used to test the model for five presentations. The most important observations are: (a) The probability of a correct answer depends on the immediate preceding lag, the longer the lag the lower the probability of a correct answer and (b) There is no effect of the preceding sequence of lags on the percentages of correct answers.

A second continuous paired-associate experiment was designed to test the SAM model for the one-stimulus-twice and the two-stimuli-once conditions. We found no spacing effect for the two-stimuli-once condition, but a small spacing effect for the one-stimulus-twice condition. In free recall experiments more pronounced lag effects (comparable to spacing effects with long retention intervals) were found for repeated items and in order to compare the effects of an increasing spacing for one-word-twice to two-words-once a free recall experiment is designed. In this free recall experiment a more pronounced and significant lag effect is observed for repeated stimuli and no lag effect is found for the two-words-once condition. SAM elaborated with context fluctuation can only be accepted when the arguments of Ross and Landauer (a theory with variable encoding always predicts a spacing effect for the two-stimuli-once condition, as for the one-stimulus-twice condition) do not hold.

In chapter 4, it is shown that in the SAM model for twice-presented word pairs that incorporates both recognition and recall, five parameters can be mathematically reduced to four. Further, an indication of the existence of other dependencies between some parameters was given, when the observed data are used to fit the model to. These dependencies are statistical in nature, because when artificial data generated with the model, are used as "experimental data" to fit the model to, the fitting procedure yielded the parameters which had been used to generate the data.

A number of problems which were encountered when the model was fitted to the data of Glenberg, are presented. Some of the sub-processes which determine the percentages of correct responses are hardly effective. Recognition turned out to be nearly always successful, as was sampling. As a consequence of an always successful recognition phase, the strength of nearly all items is increased at a second presentation and rarely is a new trace formed. The spacing and repetition effects are mostly due to the recovery of an incremented trace. Further, the inter-item associative strength appeared negligible in comparison with the context strength. Also the effect of the short-term store appeared very small.

All eight parameters cannot be estimated uniquely from the data. We tried to fit the data with simplified models derived from the SAM model, because of the problems in fitting the data with the complete model. Some of the indications for simplifications of the model were taken from the results of the analysis of Glenberg's data. Sampling only, recovery only, and a combination of sampling and recovery were tried as simplified models. Further, these simplified models, elaborated with a short-term store, were tried. For the data of Glenberg and those of experiment I, it was assumed that the recognition phase is always successful.

In chapters 5, 6 and 7, the versions of the SAM model presented in chapter 2 are fitted to the data of stimuli presented once, twice or five times. For all data, it was shown that elimination of the inter-item associative strength from the model does not make the fit worse. For the once-presented word pairs a model using sampling only or a model using recovery only can describe the data just as well as the complete model with both sampling and recovery. For the data of Glenberg and of experiment I, the reduced models using sampling or recovery both elaborated with a short-term store can describe the data just as well as the complete model. A model with sampling and recovery (without a short-term store) appeared the best to apply to the data of Rumelhart.

In chapter 8, it was shown that, when the similarity in contexts is taken into account, the SAM model does not predict a spacing effect for the two-stimuli-once condition. The argument of Ross and Landauer is that a variable encoding theory implies a spacing effect in the two-stimuli-once condition in the same way as for repeated stimuli. This argument does not hold for the SAM model. It is shown that the predictions of a model that ignores the similarity in contexts give the same probabilities of correct responses in the two-stimuli-once condition as when the similarity is taken into account. In fitting the model to the data the similarity of the contexts is also ignored. The flaw in Ross and Landauer's reasoning appears to be that they ignored that a stimulus can be recognized at a later presentation. The inter-item associative strength can be eliminated from the model without making the fit worse. The models using sampling only or recovery only can describe the data just as well as the complete model with sampling and recovery.

At this point, it is not possible to conclude which processes, sampling or recovery, must be retained to predict the data of once and twice-presented stimuli and the data of the two-stimuli-once condition. Only in the case of twice-presented stimuli does the fit improve when a short-term store is added.

For all sub-processes in the SAM model a good rationale can be given, but it appears that the combination of all sub-processes is not more successful in predicting the experimental data than a single sub-process or a combination of only two sub-processes. The experiments do not permit separation of the effects of all components.

To decide whether sampling or recovery must be retained, or whether both processes must be combined for retrieval, it is necessary to design a series of experiments that have effects on sampling, on recovery or on both. The effects of sampling and recovery must be separated experimentally. Sampling can be manipulated by experiments containing a variable number of word pairs or stimuli, to vary the size of the search set. Manipulations of the number of search cycles, (L_{max}) can lead to variations in the sampling probability. But it is not easy to manipulate L_{max} experimentally and check if the effects of these manipulations only influence the sampling process. Specific instructions about the procedure followed in search or retrieval and restrictions of the retrieval time could perhaps be compared by their effect on L_{max}.

Manipulations in the ease with which the items can be reproduced, can be used to look at recovery. When word pairs are used and when the second word of the pairs is tested, it is possible to give a number of different tests as recognition, cued recall, or free recall. In case of cued recall the first word can be given while the second must be memorized, but also a synonym or only a part of the first word can be given. The recovery parameter θ depends on the amount of information available at the moment of retrieval. θ is greater in case of recognition than in case of recall, and it can be expected that in case of recall the more information is given the greater the value of θ. To separate the effects of sampling and recovery it is necessary to design experiments that manipulate the parameters which are specially effective only in sampling or only in recovery.

Apart from the parameters used in one of the two processes, a number of parameters is used in both processes, such as all parameters determining the strengths of the image in memory. In the elaborations of the SAM model used here two different strengths, inter-item associative and context, determine the strength of the image. In the inter-item associative strength the associations between the words in a pair and all characteristics of both words are combined. The context strength is based on a background of slowly fluctuating context elements. Both strengths cannot directly be determined from the data, and it is difficult to separate them. The context strength by itself can predict the data just as well as using both strengths. The importance of the inter-item associative strength when separated from the context strength can be checked by experiments with variations in the associations between the words and variations in the retrievability of the words. It is reasonable to assume that words that can be associated easily have a greater inter-item associative strength than words that are difficult to associate. In general, it is known that concrete words are more easy to memorize than abstract words, therefore, it can be expected that they imply also a higher inter-item associative strength. The predictions about the inter-item associative strength can be checked with a series of experiments or one experiment with words easy or difficult to associate and to memorize.

The principles of context fluctuation in relation to the experiments are considered in chapter 9. It is shown that the context strength decreases as the time since the last presentation of the stimulus increases. The rate of decay after a presentation of a repeated item that is recognized or recalled is slower than the decay after the previous presentation, and the strength is reset, for a recognized repeated item, to some basic value or is increased to a higher level till an asymptote is reached.

The importance of context fluctuation cannot be controlled by the experiments presented here, and additional experimental evidence is needed. Context is an important aspect in theories and models about memory. Only experiments in which the context is explicitly manipulated may give a definite answer for the role of context fluctuation in the SAM model.

The context can be manipulated by changing aspects in the background. The rate of fluctuation (parameter α) can be manipulated by the rate in the changes in the background. Also the effect of more than one aspect of the background can be manipulated, for example the background noise and the colour of the background of the printed words.

It can be expected that manipulations of the presentation duration influence both the inter-item associative strength and the context strength.

In the context fluctuation process the percentage of active elements, s, grows the longer the duration. The effects of manipulations on the mode of the presentations are not easy to predict. The stimuli can be presented aurally or visually, words can be presented written or pictorially.

Context fluctuation can be seen as a decay process for the strength of the memory trace. Other decay processes can be assumed when context fluctuation is seen as decay process. The decay of trace strength developed by Wickelgren and elaborated by Reed can be used for the strength of the memory trace in the SAM model. Growth of resistance and decay of strength, beginning at the moment of storage, are responsible for the decrease in strength. After recognition or recall of the item the strength of the trace in long-term store is reset to its initial value at the first presentation and the process of resistance continues as if no increment of strength has taken place.

Both the context fluctuation model and the model with decay of trace strength can be used for the strength of the stimulus in the SAM model to predict spacing and repetition effects. Further, it is shown that models for decay with only one effective parameter have to be rejected. It is important to design new experiments to conclude which decay model is the more valid.

To identify all parameters of the SAM model a series of experiments must be designed manipulating only a limited set of the parameters. With the experiments presented here only a small number of parameters can be estimated from the data. For the other parameters some arbitrary values can be taken instead of having to use values estimated in other applications of the model for lack of such values. For parameter L_{max}, the number of search cycles in the sampling process, a value found by Raaijmakers and Shiffrin (1981a) was used.

Using parameters found for one version of the model in other versions, is complicated by the diversity of some aspects of the experimental designs. The presentation duration is three seconds in Glenberg's experiment and four seconds in both experiments I and II. The CPA experiment of Rumelhart uses the anticipation method, while the other experiments are of the continuous paired-associative type without anticipation trials. The exact order of the presentations and the tests is known in case of experiments I and II and for the Rumelhart experiment, but not for that of Glenberg. Further, it would be useful to determine the influence of the order of presentations and tests on the probability of a correct answer.

In general, we found that an additional presentation improves the performance. The spacing effect was more or less found for Glenberg's data: The performance improves to an asymptotic level with a growing spacing interval for long retention intervals and decreases for small retention intervals. However, this interaction (a decrease in performance for small retention intervals and an increase in performance for long retention intervals) was not found in experiment I. To understand the spacing effect it is important to investigate when this interaction is found and whether this interaction depends on experimental conditions.

A complicating matter is that the errors of sampling are, in general, not presented in the literature. In experiments I and II a relatively large sampling error is found. It is to be expected that this is also the case for the experiments presented in the literature.

In all experiments that show spacing and repetition effects as in the results presented here, the probability of a correct answer from a great number of subjects is averaged. The application of the models to the data is based on this averaged scores. It would be interesting to investigate how differences in level of performance and in variations in performance for individual subjects influence that average. It would also be interesting to know whether models based on the average subject can be applied to predict the performance of individual subjects. To investigate this an experiment must be designed for which enough data are sampled from one individual subject to test the spacing and repetition effects. A problem may be that for reliable probabilities of a correct answer in a given experimental situation a great number of observations are necessary.

APPENDIX A. EXPERIMENT I: DESIGN AND WORDS

A1. Design of Experiment I

The order of presentations and tests. The columns of the table represent:

1. The trial number
2. The number of the word pair (note: the sequence of the word pairs is randomized before presentation)
3. B: a buffer item;
   F: a filler item.
   #1: the retention interval of a word pair presented once
   #1 – #2: the spacing interval – the retention interval of a repeated word pair
4. R1: the first presentation of a repetition
   R2: the second presentation of a repetition
   RT: the test of a repetition
   O1: the presentation of a single presentation.
   OT: the test of a single presentation.

Trial	Word	Kind	
1	1	B	1
2	2	B	1
3	3	B	1
4	1	B	2
5	1	B	T
6	4	B	1
7	2	B	2
8	5	B	1
9	4	B	2
10	2	B	T
11	6	3-8	R1
12	7	1-1	R1
13	8	16-4	R1
14	7	1-1	R2
15	6	3-8	R2
16	7	1-1	RT
17	9	0-2	R1
18	9	0-2	R2
19	10	3-4	R1
20	11	1-16	R1
21	9	0-2	RT
22	11	1-16	R2
23	10	3-4	R2
24	6	3-8	RT
25	12	1-8	R1
26	13	2-1	R1
27	12	1-8	R2
28	10	3-4	RT
29	13	2-1	R2
30	8	16-4	R2
31	13	2-1	RT
32	14	16-2	R1
33	15	0-8	R1
34	15	0-8	R2
35	8	16-4	RT
36	12	1-8	RT
37	16	3-16	R1
38	5	B	2
39	11	1-16	RT
40	17	4-4	R1
41	16	3-16	R2
42	5	B	T
43	15	0-8	RT
44	18	2-16	R1
45	17	4-4	R2
46	19	F	1
47	18	2-16	R2
48	4	B	T
49	14	16-2	R2
50	17	4-4	RT
51	20	16-16	R1
52	14	16-2	RT
53	21	0-1	R1
54	21	0-1	R2
55	22	1-4	R1
56	21	0-1	RT
57	22	1-4	R2
58	16	3-16	RT
59	23	3-2	R1
60	24	0-16	R1

Trial	Word		Kind
61	24	0-16	R2
62	22	1-4	RT
63	23	3-2	R2
64	18	2-16	RT
65	25	4-2	R1
66	23	3-2	RT
67	26	8	O1
68	20	16-16	R2
69	19	F	2
70	25	4-2	R2
71	27	16-1	R1
72	28	4-1	R1
73	25	4-2	RT
74	3	B	2
75	29	4-16	R1
76	26	8	OT
77	28	4-1	R2
78	24	0-16	RT
79	28	4-1	RT
80	29	4-16	R2
81	30	2-2	R1
82	31	F	1
83	32	16-8	R1
84	30	2-2	R2
85	20	16-16	RT
86	33	2-8	R1
87	30	2-2	RT
88	27	16-1	R2
89	33	2-8	R2
90	27	16-1	RT
91	34	4-8	R1
92	35	2	O1
93	36	0-4	R1
94	36	0-4	R2
95	35	2	OT
96	34	4-8	R2
97	29	4-16	RT
98	33	2-8	RT
99	36	0-4	RT
100	32	16-8	R2
101	37	16	O1
102	38	3-1	R1
103	39	F	1
104	40	2-4	R1
105	34	4-8	RT
106	38	3-1	R2
107	40	2-4	R2
108	38	3-1	RT
109	32	16-8	RT
110	39	F	2
111	41	1-2	R1
112	40	2-4	RT
113	41	1-2	R2
114	42	4	O1
115	43	1	O1
116	41	1-2	RT
117	43	1	OT
118	37	16	OT
119	42	4	OT
120	44	F	1
121	45	2	O1
122	46	0-16	R1
123	46	0-16	R2
124	45	2	OT
125	47	1-4	R1
126	48	3-16	R1
127	47	1-4	R2
128	49	8	O1
129	50	1-2	R1
130	48	3-16	R2
131	50	1-2	R2
132	47	1-4	RT
133	51	4-4	R1
134	50	1-2	RT
135	52	16-4	R1
136	53	2-8	R1
137	49	8	OT
138	51	4-4	R2
139	53	2-8	R2
140	46	0-16	RT
141	54	3-4	R1
142	55	1-16	R1
143	51	4-4	RT
144	55	1-16	R2
145	54	3-4	R2
146	56	2-4	R1
147	48	3-16	RT
148	53	2-8	RT
149	56	2-4	R2
150	54	3-4	RT
151	57	3-2	R1
152	52	16-4	R2
153	58	2-16	R1
154	56	2-4	RT
155	57	3-2	R2
156	58	2-16	R2
157	52	16-4	RT
158	57	3-2	RT
159	59	0-1	R1
160	59	0-1	R2
161	55	1-16	RT
162	59	0-1	RT
163	60	4-2	R1
164	61	16-1	R1
165	62	3-8	R1
166	63	0-2	R1
167	63	0-2	R2
168	60	4-2	R2
169	62	3-8	R2
170	63	0-2	RT
171	60	4-2	RT
172	64	1-1	R1
173	58	2-16	RT
174	64	1-1	R2
175	65	4-8	R1
176	64	1-1	RT
177	66	1	O1
178	62	3-8	RT
179	66	1	OT
180	65	4-8	R2
181	61	16-1	R2
182	67	16-2	R1
183	61	16-1	RT
184	68	0-4	R1
185	68	0-4	R2
186	69	1-8	R1
187	70	3-1	R1
188	69	1-8	R2
189	65	4-8	RT
190	68	0-4	RT
191	70	3-1	R2
192	71	16-16	R1
193	70	3-1	RT
194	39	F	T
195	72	4-16	R1
196	73	16-8	R1
197	69	1-8	RT
198	74	2-2	R1
199	67	16-2	R2
200	72	4-16	R2
201	74	2-2	R2
202	67	16-2	RT
203	75	4-1	R1
204	74	2-2	RT
205	76	0-8	R1
206	76	0-8	R2
207	3	B	T
208	75	4-1	R2
209	71	16-16	R2
210	75	4-1	RT

Trial	Word	Kind	
211	77	2-1	R1
212	78	16	O1
213	73	16-8	R2
214	77	2-1	R2
215	76	0-8	RT
216	77	2-1	RT
217	72	4-16	RT
218	19	F	T
219	44	F	2
220	79	4	O1
221	80	F	1
222	73	16-8	RT
223	44	F	T
224	80	F	2
225	79	4	OT
226	71	16-16	RT
227	81	F	1
228	81	F	2
229	78	16	OT
230	80	F	T
231	82	3-2	R1
232	81	F	T
233	83	0-8	R1
234	83	0-8	R2
235	82	3-2	R2
236	84	16-4	R1
237	85	1-4	R1
238	82	3-2	RT
239	85	1-4	R2
240	86	8	O1
241	87	0-2	R1
242	87	0-2	R2
243	83	0-8	RT
244	85	1-4	RT
245	87	0-2	RT
246	88	16-8	R1
247	89	2-16	R1
248	90	3-8	R1
249	86	8	OT
250	89	2-16	R2
251	91	2-1	R1
252	90	3-8	R2
253	84	16-4	R2
254	91	2-1	R2
255	92	3-16	R1
256	91	2-1	RT
257	93	2-4	R1
258	84	16-4	RT
259	92	3-16	R2
260	93	2-4	R2
261	90	3-8	RT
262	94	1-1	R1
263	88	16-8	R2
264	94	1-1	R2
265	93	2-4	RT
266	94	1-1	RT
267	89	2-16	RT
268	95	0-16	R1
269	95	0-16	R2
270	96	4-4	R1
271	97	2-8	R1
272	88	16-8	RT
273	98	4-16	R1
274	97	2-8	R2
275	96	4-4	R2
276	92	3-16	RT
277	99	1-2	R1
278	98	4-16	R2
279	99	1-2	R2
280	96	4-4	RT
281	100	3-4	R1
282	99	1-2	RT
283	97	2-8	RT
284	101	2	OT
285	100	3-4	R2
286	95	0-16	RT
287	101	2	OT
288	102	0-4	R1
289	102	0-4	R2
290	100	3-4	RT
291	103	1-8	R1
292	104	3-1	R1
293	103	1-8	R2
294	102	0-4	RT
295	98	4-16	RT
296	104	3-1	R2
297	105	16-16	R1
298	104	3-1	RT
299	106	1-16	R1
300	107	2-2	R1
301	106	1-16	R2
302	103	1-8	RT
303	107	2-2	R2
304	108	16-2	R1
305	109	4-2	R1
306	107	2-2	RT
307	110	1	O1
308	111	16-1	R1
309	110	1	OT
310	109	4-2	R2
311	31	F	2
312	112	4-1	R1
313	109	4-2	RT
314	105	16-16	R2
315	113	4-8	R1
316	31	F	T
317	112	4-1	R2
318	106	1-16	RT
319	112	4-1	RT
320	113	4-8	R2
321	108	16-2	R2
322	114	16	R1
323	115	F	R1
324	108	16-2	RT
325	111	16-1	R2
326	115	F	T
327	111	16-1	RT
328	116	4	R1
329	113	4-8	RT
330	117	F	1
331	105	16-16	RT
332	117	F	2
333	116	4	OT
334	118	0-1	R1
335	118	0-1	R2
336	117	F	T
337	118	0-1	RT
338	119	F	1
339	114	16	OT
340	119	F	2
341	120	16-4	R1
342	121	0-1	R1
343	121	0-1	R2
344	122	3-4	R1
345	121	0-1	RT
346	123	2-16	R1
347	124	8	R1
348	122	3-4	R2
349	123	2-16	R2
350	125	1-2	R1
351	126	2-4	R1
352	125	1-2	R2
353	122	3-4	RT
354	126	2-4	R2
355	125	1-2	RT
356	124	8	OT
357	127	2-8	R1
358	120	16-4	R2
359	126	2-4	RT
360	127	2-8	R2

Trial	Word		Kind
361	128	0-4	R1
362	128	0-4	R2
363	120	16-4	RT
364	129	3-16	R1
365	130	4-4	R1
366	123	2-16	RT
367	128	0-4	RT
368	129	3-16	R2
369	127	2-8	RT
370	130	4-4	R2
371	131	2-2	R1
372	119	F	T
373	132	4-16	R1
374	131	2-2	R2
375	130	4-4	RT
376	133	2	O1
377	131	2-2	RT
378	132	4-16	R2
379	133	2	OT
380	134	0-8	R1
381	134	0-8	R2
382	135	1-1	R1
383	136	3-8	R1
384	135	1-1	R2
385	129	3-16	RT
386	135	1-1	RT
387	136	3-8	R2
388	137	0-16	R1
389	137	0-16	R2
390	134	0-8	RT
391	138	1-4	R1
392	139	16-8	R1
393	138	1-4	R2
394	140	F	1
395	132	4-16	RT
396	136	3-8	RT
397	141	4-8	R1
398	138	1-4	RT
399	142	16-2	R1
400	143	0-2	R1
401	143	0-2	R2
402	141	4-8	R2
403	144	4-1	R1
404	143	0-2	RT
405	145	1-16	R1
406	137	0-16	RT
407	145	1-16	R2
408	144	4-1	R2
409	139	16-8	R2
410	144	4-1	RT
411	141	4-8	RT
412	146	16-16	R1
413	140	F	T
414	147	F	1
415	148	4-2	R1
416	142	16-2	R2
417	149	F	1
418	139	16-8	RT
419	142	16-2	RT
420	148	4-2	R2
421	150	16-1	R1
422	151	2-1	R1
423	148	4-2	RT
424	145	1-16	RT
425	151	2-1	R2
426	147	F	2
427	151	2-1	RT
428	152	3-2	R1
429	146	16-16	R2
430	153	F	R1
431	154	4	O1
432	152	3-2	R2
433	155	16	O1
434	149	F	2
435	152	3-2	RT
436	154	4	OT
437	156	1-8	R1
438	150	16-1	R2
439	156	1-8	R2
440	150	16-1	RT
441	147	F	T
442	157	1	O1
443	158	3-1	R1
444	157	1	OT
445	159	F	1
446	146	16-16	RT
447	158	3-1	R2
448	156	1-8	RT
449	158	3-1	RT
450	155	16	OT
451	160	16-1	R1
542	161	2-8	R1
543	162	3-16	R1
544	163	1-4	R1
545	161	2-8	R2
546	163	1-4	R2
457	162	3-16	R2
458	164	1	O1
459	149	F	T
460	164	1	OT
461	163	1-4	RT
462	165	0-2	R1
463	165	0-2	R2
464	161	2-8	RT
465	166	16-16	R1
466	165	0-2	RT
467	167	1-8	R1
468	160	16-1	R2
469	167	1-8	R2
470	160	16-1	RT
471	168	4-4	R1
472	169	2-16	R1
473	170	3-2	R1
474	162	3-16	RT
475	169	2-16	R2
476	168	4-4	R2
477	170	3-2	R2
478	167	1-8	RT
479	171	4-2	R1
480	170	3-2	RT
481	168	4-4	RT
482	166	16-16	R2
483	172	1-2	R1
484	171	4-2	R2
485	172	1-2	R2
486	173	16-8	R1
487	171	4-2	RT
488	172	1-2	RT
489	174	0-4	R1
490	174	0-4	R2
491	175	1-16	R1
492	169	2-16	RT
493	175	1-16	R2
494	176	3-8	R1
495	174	0-4	RT
496	177	0-16	R1
497	177	0-16	R2
498	176	3-8	R2
499	166	16-16	RT
500	178	4	O1
501	179	16-4	R1
502	180	1-1	R1
503	173	16-8	R2
504	180	1-1	R2
505	178	4	RT
506	180	1-1	RT
507	176	3-8	RT
508	181	2-4	R1
509	182	16	O1
510	175	1-16	RT

Trial	Word	Kind	
511	181	2-4	R2
512	173	16-8	RT
513	183	3-1	R1
514	177	0-16	RT
515	184	4-8	R1
516	181	2-4	RT
517	183	3-1	R2
518	179	16-4	R2
519	183	3-1	RT
520	184	4-8	R2
521	185	0-1	R1
522	185	0-1	R2
523	179	16-4	RT
524	185	0-1	RT
525	186	4-1	R1
526	182	16	RT
527	187	16-2	R1
528	188	2-2	R1
529	184	4-8	RT
530	186	4-1	R2
531	188	2-2	R2
532	186	4-1	RT
533	189	4-16	R1
534	188	2-2	RT
535	190	0-8	R1
536	190	0-8	R2
537	191	2-1	R1
538	189	4-16	R2
539	192	3-4	R1
540	191	2-1	R2
541	193	8	R1
542	191	2-1	RT
543	192	3-4	R2
544	187	16-2	R2
545	190	0-8	RT
546	159	F	2
547	187	16-2	RT
548	192	3-4	RT
549	194	F	1
550	193	8	OT
551	195	2	O1
552	194	F	2
553	159	F	T
554	195	2	OT
555	189	4-16	RT
556	194	F	T
557	196	F	1
558	196	F	2
559	153	F	T
560	196	F	T

A2. Word Pairs presented in Experiment I

The sequence of the word pairs is randomized before presentation to the subjects.

Word 1	Word 2
ACCU	PUPIL
AGENT	BLOK
AMBT	STRIK
AULA	COACH
BAAL	TEST
BAND	GANS
BANK	LUCHT
BEEN	NACHT
BETON	VELD
BIER	BOOG
BLIK	VORK
BLOEM	KURK
BOEK	PIJP
BORST	DIER
BROOD	MUUR
CHAOS	TANTE
CREME	SMOEL
DAAD	BOOT
DANK	HAAST
DANS	KROT
DEEG	DWANG
DRAMA	HOND
DUIF	DRAAD
DUIM	LUNCH
EEUW	ZETEL
EIWIT	PROOI
EMMER	ROEM
ENKEL	GAST
EZEL	HORDE
FAAM	DORST
FEEST	LEER
FIETS	BOTER
FILM	ZOON
FLES	ERNST
GANG	STEEN
GEBAK	BOUT
GEEST	GRAAN
GELEI	NOOD
GEMAK	MOED
GETAL	BLOED
GIDS	HART
GRAM	BOCHT
GRAS	METRO
GROEI	GEZIN
HARK	VRAAG
HAVEN	BOOM
HITTE	ATOOM
HUIS	MELK
HUMOR	FEIT
HUUR	HALS
JAAR	RAAD
JAPON	ETAGE
JEUGD	SOEP
JURY	HOUT
KAAK	KRING
KABEL	AKTIE
KAMER	STORM
KEREL	GRAP
KETEL	DEUGD
KLAP	OVEN

Word 1	Word 2
KLAUW	MIJN
KLEUR	HOTEL
KNAAP	APPEL
KNOOP	TRAP
KOEK	CODE
KOGEL	GILDE
KOUS	DORP
KRAAG	BABY
KRANT	UNIE
KROEG	PROEF
KWART	MAGIE
KWAST	PIANO
LAARS	HUID
LAKEN	BEVEL
LAMP	GOUD
LEGER	ROEP
LIJK	INDEX
LIJM	STER
LIJST	TEKEN
LIST	STEP
LITER	BORD
LOON	PLAN
LUIER	BAAS
MACHT	BERG
MAIS	RADIO
MARKT	WACHT
MENS	TROTS
MEREL	WIJN
MIST	GAVE
MOUW	DEBAT
MUIS	SLOOT
NAGEL	KLEED
NEGER	TAAK
NEST	FLAT
OBER	STOEL
OPERA	MAAG
ORDER	TEEN
PAARD	LICHT
PATER	BEZIT
PAUZE	REGIE
PILS	KOOI
PLAK	SHOW
PLANK	KUIF
PLAS	GRAF
POORT	SFEER
POST	MODEL
PREEK	FOTO
PSALM	SPOOK
PUIN	GLAS
RAAM	RONDE

Word 1	Word 2
RACE	WERF
RAMP	EINDE
REEKS	BREUK
REGEL	ELPEE
REGIO	GRAAD
REIS	TANK
RIET	HOOP
ROMAN	ELAN
ROOK	HEMD
ROTS	DEUR
RUIT	FASE
RUST	KOERS
SAUS	KRUID
SCHIL	ADRES
SCHIM	BROEK
SCHIP	SLAK
SLAAF	LIFT
SLAAP	LINT
SLANG	FUSIE
SLOF	MOTOR
SLOK	SPOOR
SNAAR	MOORD
SNOR	VILLA
SPEL	GEUR
SPELD	GRIEP
SPIER	VLOEK
SPUIT	ERTS
SPUL	PUNT
STAAF	TROEP
STAD	CAFE
STAF	MAND
STAM	SERIE
STIER	VIRUS
STOP	TUIG
STRO	RING
TAAL	TEAM
TABAK	EEND
TABEL	BEKER
TABOE	ZAAK
TAFEL	RAKET
TAND	LEUZE
TEKST	WAND
TERM	SCHOT
THEMA	STAP
TIRAN	STOEP
TITEL	HAND
TOREN	MYTHE
TOUW	GROEP
TREIN	HOOFD
TREK	GELUK

Word 1	Word 2
TUBE	KERN
TYPE	ZOMER
VEER	AVOND
VENT	TOON
VERF	GOLF
VOCHT	STAL
VLOER	BEER
VOER	BUUR
VOET	AUTO
VOGEL	GROT
VORM	BRUID
VORST	WIEL
VROUW	SODA
VUUR	KLOMP
WAPEN	REGEN
WATER	RIJST
WEIDE	HEKEL
WENS	KILO
WEVER	PEPER
WIEG	NIER
WIEK	MOND
WIER	THEE
WIJF	ORGEL
WIJK	FIRMA
WIND	KEEL
ZAAL	PRENT
ZANG	DEKEN
ZEEF	PRIJS
ZEEP	TEGEL
ZEGEN	HAAK
ZEIL	STEEG
ZIEL	STEL
ZORG	STOET
ZOUT	KAST
ZUCHT	ECHO
ZWEET	GENIE

APPENDIX B. EXPERIMENT II: DESIGN AND WORDS

B1. Design of Experiment II

The order of presentations and tests. The columns of the table represent:

1. The trial number
2. The number of the word pair (note: the sequence of the word pairs is randomized before presentation)
3. B: a buffer item;
   F: a filler item.
   #1: the retention interval of a word pair presented once
   #1 – #2: the spacing interval – the retention interval of a repeated word pair
4. P1: the first presentation of a repetition
   P2: the second presentation of a repetition
   PT: the test of a repetition
   C1: the first stimulus in the two-stimuli-once condition
   C2: the second stimulus in the two-stimuli-once condition
   CT: the test in the two-stimuli-once condition
5. Word pairs that are combined in the two-stimuli-once condition.

Trial	Word		Kind	
1	1	B	C1	1-3
2	2	B	P1	
3	3	B	C2	1-3
4	4	B	P1	
5	2	B	P2	
6	5	B	P1	
7	6	B	P1	
8	2	B	T	
9	7	B	P1	
10	6	B	P2	
11	8	2-50	C1	8-11
12	9	8-25	C1	9-14
13	10	1-25	R1	
14	11	2-50	C2	8-11
15	10	1-25	R2	
16	1	B	CT	1-3
17	3	B	CT	1-3
18	12	0-50	R1	
19	12	0-50	R2	
20	13	4-25	C1	17-13
21	14	8-25	C2	9-14
22	15	8-25	R1	
23	16	2-50	R1	
24	6	B	T	
25	17	4-25	C2	17-13
26	16	2-50	R2	
27	18	16-50	C1	18-27
28	19	8-50	R1	
29	5	B	T	
30	20	4-25	R1	
31	15	8-25	R2	
32	21	0-50	C1	21-22
33	22	0-50	C2	21-22
34	7	B	T	
35	20	4-25	P2	
36	23	16-25	R1	
37	19	8-50	R2	
38	4	B	T	
39	24	F	P1	
40	24	F	P2	

Trial	Word		Kind	
41	10	1-25	RT	
42	25	F	P1	
43	26	F	P1	
44	27	16-50	C2	18-27
45	25	F	P2	
46	28	8-50	C1	31-28
47	9	8-25	CT	9-14
48	14	8-25	CT	9-14
49	26	F	P2	
50	29	16-50	R1	
51	17	4-25	CT	17-13
52	13	4-25	CT	17-13
53	23	16-25	R2	
54	30	F	R1	
55	31	8-50	C2	31-28
56	32	F	P1	
57	15	8-25	RT	
58	33	16-25	C1	42-33
59	30	F	P2	
60	34	F	P1	
61	20	4-25	RT	
62	35	1-25	C1	35-36
63	32	F	P2	
64	36	1-25	C2	35-36
65	8	2-50	CT	8-11
66	11	2-50	CT	8-11
67	29	16-50	R2	
68	37	F	P1	
69	38	F	P1	
70	12	0-50	RT	
71	39	1-50	C1	41-39
72	40	F	P1	
73	41	1-50	C2	41-39
74	34	F	P2	
75	42	16-25	C2	42-33
76	43	4-50	R1	
77	16	2-50	RT	
78	44	F	P1	
79	23	16-25	RT	
80	40	F	P2	
81	43	4-50	R2	
82	45	4-50	C1	47-45
83	37	F	P2	
84	21	0-50	CT	21-22
85	22	0-50	CT	21-22
86	46	2-25	R1	
87	47	4-50	C2	47-45
88	19	8-50	RT	
89	46	2-25	R2	
90	35	1-25	CT	35-36
91	36	1-25	CT	35-36
92	48	F	P1	
93	49	0-25	C1	49-50
94	50	0-25	C2	49-50
95	18	16-50	CT	18-27
96	27	16-50	CT	18-27
97	51	1-50	R1	
98	52	F	P1	
99	51	1-50	R2	
100	44	F	P2	
101	42	16-25	CT	42-33
102	33	16-25	CT	42-33
103	53	0-25	R1	
104	53	0-25	R2	
105	54	16-50	R1	
106	31	8-50	CT	31-28
107	28	8-50	CT	31-28
108	55	0-50	R1	
109	55	0-50	R2	
110	48	F	P2	
111	56	1-50	C1	56-58
112	57	F	P1	
113	58	1-50	C2	56-58
114	59	2-25	C1	61-59
115	46	2-25	RT	
116	60	F	P1	
117	61	2-25	C2	61-59
118	29	16-50	RT	
119	57	F	P2	
120	49	0-25	CT	49-50
121	50	0-25	CT	49-50
122	54	16-50	R2	
123	52	F	P2	
124	41	1-50	CT	41-39
125	39	1-50	CT	41-39
126	62	1-25	C1	62-63
127	60	F	P2	
128	63	1-25	C2	62-63
129	64	F	P1	
130	53	0-25	RT	
131	65	2-50	C1	65-67
132	43	4-50	RT	
133	66	F	P1	
134	67	2-50	C2	65-67
135	68	16-25	C1	77-68
136	69	F	P1	
137	64	F	P2	
138	47	4-50	CT	47-45
139	45	4-50	CT	47-45
140	70	1-25	R1	

Trial	Word		Kind	
141	71	F	P1	
142	70	1-25	R2	
143	61	2-25	CT	61-59
144	59	2-25	CT	61-59
145	72	0-50	C1	73-72
146	73	0-50	C2	73-72
147	74	8-25	R1	
148	75	0-25	R1	
149	75	0-25	R2	
150	51	1-50	RT	
151	76	1-50	R1	
152	77	16-25	C2	77-68
153	76	1-50	R2	
154	62	1-25	CT	62-63
155	63	1-25	CT	62-63
156	74	8-25	R2	
157	78	4-50	R1	
158	79	8-50	C1	79-84
159	80	16-50	C1	88-80
160	55	0-50	RT	
161	81	4-25	C1	83-81
162	78	4-50	R2	
163	82	16-25	R1	
164	56	1-50	CT	56-58
165	58	1-50	CT	56-58
166	83	4-25	C2	83-81
167	84	8-50	C2	79-84
168	70	1-25	RT	
169	85	F	P1	
170	66	F	P2	
171	71	F	P2	
172	86	8-50	R1	
173	54	16-50	RT	
174	87	F	P1	
175	75	0-25	RT	
176	88	16-50	C2	88-80
177	89	F	P1	
178	77	16-25	CT	77-68
179	68	16-25	CT	77-68
180	82	16-25	R2	
181	86	8-50	R2	
182	74	8-25	RT	
183	90	0-25	C1	91-90
184	91	0-25	C2	91-90
185	65	2-50	CT	65-67
186	67	2-50	CT	65-57
187	92	2-50	R1	
188	93	16-50	R1	
189	94	4-50	C1	96-94
190	92	2-50	R2	
191	95	4-25	R1	
192	83	4-25	CT	83-81
193	81	4-25	CT	83-81
194	96	4-50	C2	96-94
195	69	F	R2	
196	95	4-25	R2	
197	73	0-50	CT	73-72
198	72	0-50	CT	73-72
199	97	F	P1	
200	98	8-25	C1	98-102
201	99	F	P1	
202	100	F	P1	
203	85	F	P2	
204	76	1-50	RT	
205	93	16-50	R2	
206	82	16-25	RT	
207	87	F	R2	
208	101	F	R1	
209	102	8-25	C2	98-102
210	91	0-25	CT	91-90
211	90	0-25	CT	91-90
212	103	2-50	C1	105-103
213	78	4-50	RT	
214	104	2-25	R1	
215	105	2-50	C2	105-103
216	106	F	P1	
217	104	2-25	R2	
218	79	8-50	CT	79-84
219	84	8-50	CT	79-84
220	99	F	P2	
221	101	F	P2	
222	95	4-25	RT	
223	107	2-25	C1	107-110
224	108	4-50	C1	108-111
225	109	F	P1	
226	110	2-25	C2	107-110
227	88	16-50	CT	88-80
228	80	16-50	CT	88-80
229	111	4-50	C2	108-111
230	112	16-25	R1	
231	113	16-50	C1	121-113
232	86	8-50	RT	
233	114	0-25	C1	114-115
234	115	0-25	C2	114-115
235	98	8-25	CT	98-102
236	102	8-25	CT	98-102
237	116	2-50	R1	
238	117	F	P1	
239	118	F	P1	
240	116	2-50	R2	

Trial	Word		Kind	
241	92	2-50	RT	
242	119	16-25	C1	126-119
243	104	2-25	RT	
244	120	F	P1	
245	96	4-50	CT	96-94
246	94	4-50	CT	96-94
247	112	16-25	R2	
248	121	16-50	C2	121-113
249	122	0-25	R1	
250	122	0-25	R2	
251	100	F	P2	
252	107	2-25	CT	107-110
253	110	2-25	CT	107-110
254	106	F	P2	
255	123	F	P1	
256	93	16-50	RT	
257	124	0-50	C1	125-124
258	125	0-50	C2	125-124
259	126	16-25	C2	126-119
260	114	0-25	CT	114-115
261	115	0-25	CT	114-115
262	127	1-50	R1	
263	128	4-24	C1	128-130
264	127	1-50	R2	
265	129	4-50	R1	
266	105	2-50	CT	105-103
267	103	2-50	CT	105-103
268	130	4-25	C2	128-130
269	131	8-50	C1	131-136
270	129	4-50	R2	
271	132	F	P1	
272	123	F	P2	
273	112	16-25	RT	
274	133	F	P1	
275	134	8-50	R1	
276	122	0-25	RT	
277	135	1-25	R1	
278	136	8-50	C2	131-136
279	135	1-25	R2	
280	108	4-50	CT	108-111
281	111	4-50	CT	108-111
282	133	F	P2	
283	117	F	P2	
284	134	8-50	R2	
285	126	16-25	CT	126-119
286	119	16-25	CT	126-119
287	137	F	P1	
288	138	1-50	C1	138-140
289	139	2-25	R1	
290	140	1-50	C2	138-140
291	116	2-50	RT	
292	139	2-25	R2	
293	141	F	P1	
294	128	4-25	CT	128-130
295	130	4-25	CT	128-130
296	142	1-25	C1	144-142
297	143	F	P1	
298	144	1-25	C2	144-142
299	121	16-50	CT	121-113
300	113	16-50	CT	121-113
301	145	0-50	R1	
302	145	0-50	R2	
303	146	8-25	C1	146-151
304	147	F	P1	
305	135	1-25	RT	
306	148	1-50	C1	149-148
307	147	F	P2	
308	149	1-50	C2	149-148
309	125	0-50	CT	125-124
310	124	0-50	CT	125-124
311	150	8-50	R1	
312	151	8-25	C2	146-151
313	137	F	P2	
314	152	8-25	R1	
315	127	1-50	RT	
316	153	2-25	C1	155-153
317	154	F	P1	
318	139	2-25	RT	
319	155	2-25	C2	155-153
320	150	8-50	R2	
321	129	4-50	RT	
322	156	4-50	C1	156-158
323	152	8-25	R2	
324	144	1-25	CT	144-142
325	142	1-25	CT	144-142
326	157	4-25	R1	
327	158	4-50	C2	156-158
328	159	4-50	R1	
329	131	8-50	CT	131-136
330	136	8-50	CT	131-136
331	157	4-25	R2	
332	160	F	P1	
333	159	4-50	R2	
334	161	8-25	R1	
335	134	8-50	RT	
336	162	0-25	R1	
337	162	0-25	R2	
338	146	8-25	CT	146-151
339	151	8-25	CT	146-151
340	163	F	P1	

Trial	Word		Kind	
341	138	1-50	CT	138-140
342	140	1-50	CT	138-140
343	161	8-25	R2	
344	163	F	P2	
345	155	2-25	CT	155-153
346	153	2-25	CT	155-153
347	164	8-50	C1	164-168
348	165	16-50	C1	173-165
349	152	8-25	RT	
350	166	1-50	R1	
351	160	F	P2	
352	166	1-50	R2	
353	145	0-50	RT	
354	154	F	P2	
355	167	16-25	C1	167-178
356	168	8-50	C2	164-168
357	157	4-25	RT	
358	169	8-25	C1	175-169
359	149	1-50	CT	149-148
360	148	1-50	CT	149-148
361	170	0-25	C1	171-170
362	171	0-25	C2	171-170
363	162	0-25	RT	
364	172	F	P1	
365	173	16-50	C2	173-165
366	174	F	P1	
367	175	8-25	C2	175-169
368	176	16-25	R1	
369	161	8-25	RT	
370	177	4-25	R1	
371	150	8-50	RT	
372	178	16-25	C2	167-178
373	179	16-50	R1	
374	180	F	P1	
375	177	4-25	R2	
376	181	0-50	R1	
377	181	0-50	R2	
378	156	4-50	CT	156-158
379	158	4-50	CT	156-158
380	182	2-50	R1	
381	174	F	P2	
382	132	F	P2	
383	182	2-50	R2	
384	159	4-50	RT	
385	176	16-25	R2	
386	183	F	P1	
387	184	F	P1	
388	171	0-25	CT	171-170
389	170	0-25	CT	171-170
390	179	16-50	R2	
391	185	4-25	C1	185-188
392	186	F	P1	
393	175	8-25	CT	175-169
394	169	8-25	CT	175-169
395	187	4-50	C1	190-187
396	188	4-25	C2	185-188
397	189	8-50	R1	
398	167	16-25	CT	167-178
399	178	16-25	CT	167-178
400	190	4-50	C2	190-187
401	177	4-25	RT	
402	191	2-25	C1	191-192
403	166	1-50	RT	
404	118	F	P2	
405	192	2-25	C2	191-192
406	189	8-50	R2	
407	164	8-50	CT	164-168
408	168	8-50	CT	164-168
409	193	2-25	R1	
410	194	F	P1	
411	176	16-25	RT	
412	193	2-25	R2	
413	195	0-50	C1	195-196
414	196	0-50	C2	195-196
415	197	F	P1	
416	173	16-50	CT	173-165
417	165	16-50	CT	173-165
418	198	1-25	C1	200-198
419	199	F	P2	
420	200	1-25	C2	200-198
421	89	F	P2	
422	185	4-25	CT	185-188
423	188	4-25	CT	185-188
424	201	2-50	C1	203-201
425	202	F	P1	
426	194	F	P2	
427	203	2-50	C2	203-201
428	181	0-50	RT	
429	204	F	P1	
430	205	F	P1	
431	191	2-25	CT	191-192
432	192	2-25	CT	191-192
433	206	2-50	C1	206-208
434	182	2-50	RT	
435	207	1-25	P1	
436	208	2-50	C2	206-208
437	207	1-25	R2	
438	193	2-25	RT	
439	209	4-50	R1	
440	210	F	P1	

Trial	Word		Kind	
441	179	16-50	RT	
442	211	2-25	R1	
443	212	4-25	R1	
444	209	4-50	R2	
445	211	2-25	R2	
446	200	1-25	CT	200-198
447	198	1-25	CT	200-198
448	212	4-25	R2	
449	213	0-50	C1	213-214
450	214	0-50	C2	213-214
451	190	4-50	CT	190-187
452	187	4-50	CT	190-187
453	215	2-50	R1	
454	183	F	P1	
455	216	2-25	C1	217-216
456	215	2-50	R2	
457	189	8-50	RT	
458	217	2-25	C2	217-216
459	218	0-50	R1	
460	218	0-50	R2	
461	205	F	P2	
462	219	F	P1	
463	207	1-25	RT	
464	220	8-50	C1	226-220
465	195	0-50	CT	195-196
466	196	0-50	CT	195-196
467	221	4-25	C1	221-225
468	222	F	P1	
469	223	16-50	C1	223-231
470	224	F	P1	
471	221	2-25	RT	
472	225	4-25	C2	221-225
473	226	8-50	C2	226-220
474	212	4-25	RT	
475	197	F	P2	
476	210	F	P2	
477	227	16-25	R1	
478	203	2-50	CT	203-201
479	201	2-50	CT	203-201
480	228	F	P1	
481	229	1-50	R1	
482	230	F	P1	
483	229	1-50	R2	
484	217	2-25	CT	217-216
485	216	2-25	CT	217-216
486	231	16-50	C2	223-231
487	206	2-50	CT	206-208
488	208	2-50	CT	206-208
489	232	0-25	C1	232-233
490	233	0-25	C2	232-233
491	234	F	P1	
492	235	16-50	R1	
493	236	F	P1	
494	227	16-25	R2	
495	209	4-50	RT	
496	230	F	P2	
497	224	F	P2	
498	221	4-25	CT	221-225
499	225	4-25	CT	221-225
500	237	F	P1	
501	213	0-50	CT	213-214
502	214	0-50	CT	213-214
503	238	1-25	R1	
504	239	F	P1	
505	238	1-35	R2	
506	240	F	P1	
507	215	2-50	RT	
508	241	F	P1	
509	235	16-50	R2	
510	242	16-25	C1	242-249
511	218	0-50	RT	
512	219	F	P2	
513	243	1-25	C1	245-243
514	244	8-25	R1	
515	245	1-25	C2	245-243
516	232	0-25	CT	232-233
517	233	0-25	CT	232-233
518	241	F	P2	
519	246	F	P1	
520	227	16-25	RT	
521	246	F	P2	
522	247	F	P1	
523	244	8-25	R2	
524	226	8-50	CT	226-220
525	220	8-50	CT	226-220
526	248	1-50	C1	250-248
527	249	16-25	C2	242-249
528	250	1-50	C2	250-248
529	251	F	P1	
530	252	F	P1	
531	238	1-25	RT	
532	247	F	P2	
533	240	F	P2	
534	229	1-50	RT	
535	253	0-25	R1	
536	253	0-25	R2	
537	223	16-50	CT	223-231
538	231	16-50	CT	223-231
539	254	8-25	C1	259-254
540	255	F	P1	

Trial	Word		Kind	
541	245	1-25	CT	245-243
542	243	1-25	CT	245-243
543	256	F	P1	
544	257	F	P1	
545	255	F	P2	
546	258	F	P1	
547	228	F	P2	
548	259	8-25	C2	259-254
549	244	8-25	RT	
550	260	F	P1	
551	261	F	P1	
552	239	F	P2	
553	242	16-25	CT	242-249
554	249	16-25	CT	242-249
555	262	F	P1	
556	263	F	P1	
557	251	F	P2	
558	256	F	P2	
559	264	F	P1	
560	235	16-50	RT	
561	265	F	P1	
562	253	0-25	RT	
563	266	F	P1	
564	266	F	P2	
565	184	F	P2	
566	120	F	P2	
567	143	F	P2	
568	267	F	P1	
569	268	F	P1	
570	269	F	P1	
571	270	F	P1	
572	265	F	P2	
573	271	F	P1	
574	259	8-25	CT	259-254
575	254	8-25	CT	259-254
576	272	F	P1	
577	268	F	P2	
578	270	F	P2	
579	250	1-50	CT	250-248
580	248	1-50	CT	250-248

B2. Word Pairs presented in Experiment II

The word pairs are in a randomized sequence presented to the subject.

Word 1	Word 2
ACCENT	PAARD
ACCU	PANTY
AFLOOP	MAIS
AGENT	STEL
AKKER	MAGIE
ALINEA	ZEEP
AMBT	OCEAAN
ANGST	KETEL
ATOOM	WAGEN
AULA	HAAR
AVOND	TIRAN
BAAL	LADDER
BAARD	GEVEL
BASIS	GEMAK
BEGIN	DORST
BEURS	TONG
BEVEL	HEELAL
BEWIJS	OLIE
BILJET	KLEED
BLAD	OVEN
BLOEM	AFKEER
BLOK	WHISKY
BOEK	DUIF
BOER	TEMPEL
BOEZEM	LIJST
BOND	IJVER
BOOM	VLAG
BORREL	REGIE
BOUT	RONDE
BRAND	WALVIS
BREIN	SCHRIK
BRON	DEBAT
BROOD	NEST
BRUG	GLORIE
BURGER	MOUW
CODE	JACHT
COGNAC	GIPS
CRISIS	HALS
CULTUS	PLAK
CURSUS	HUID
DAAD	SNOEK
DATUM	KIEM
DETAIL	LIED
DIJK	POEDER
DINER	CREME
DOEL	RECEPT
DOLLAR	ENGEL
DONDER	THEMA
DORP	PUPIL
DOUCHE	MEREL
DUIM	BENDE
DUIT	TOUW
EEND	PION
EEUW	DRANK
EINDE	BRIL
EMMER	WENS
ERNST	ZOLDER
EXAMEN	TONEEL
EXPERT	PAUZE
FAAM	STRONK

Word 1	Word 2	Word 1	Word 2	Word 1	Word 2
FASE	PAND	KLOMP	STRUIK	REGIO	STIER
FIETS	CITAAT	KNAAP	TITEL	RENTE	GRACHT
FILM	RECORD	KNOOP	EUVEL	REST	PIJP
FIRMA	SMOEL	KRAAG	PIANO	RIJST	KOORTS
FLAT	KNIE	KRAAN	ADRES	RING	DEUR
FOTO	ERTS	KRUID	ADEL	ROEP	METRO
FRUIT	CIJFER	KOPIE	HEMD	ROES	TINT
GAVE	KAART	KUIL	OPGAVE	ROMAN	HAVEN
GEBAK	ONWEER	KWAST	GARAGE	SAUS	WIMPER
GEBOUW	DIER	LAKEN	STEP	SALDO	MELK
GEHEIM	MARKT	LEEK	STRAAL	SCHAAR	SNEEUW
GELD	REGEN	LEEUW	HELFT	SCHAT	GRAAN
GELEI	SPIER	LEUZE	DANK	SCHERM	MONNIK
GELUK	VORST	LEZING	STOET	SCHIL	POMP
GETAL	KERN	LICHT	EXCUUS	SCHIM	TANK
GEUR	TREDE	LIJK	TROUW	SCHOK	KOSMOS
GEVAAR	THEE	LOKET	DRAAK	SCHOP	BABY
GEWEST	SUIKER	LUCHT	MIDDEL	SCHOOL	KONIJN
GLAS	TUIN	LUNCH	BEZIT	SCHORT	BANAAN
GLOED	FLUIT	MAAND	KLOOF	SCHOT	ORGEL
GROND	STAKER	MANTEL	ROUTE	SCHUIT	STOOM
GROT	OPROEP	MINUUT	FUSIE	SERIE	KLEM
GUNST	BORD	MOED	LIJM	SHOW	INSEKT
HAAK	MUIS	MOND	ROTS	SIGAAR	RUIT
HAAST	VORK	MOSKEE	WEIDE	SIRENE	BEELD
HARING	BETOOG	NACHT	STUUR	SLAAP	BODEM
HARK	KOUS	NATUUR	NOOD	SLAK	VRAAG
HEKEL	RAAD	NEVEL	MAAG	SLOGAN	VUIL
HITTE	KILO	NEGER	STOK	SLOOT	RITME
HOEK	SOORT	NYLON	BUNDEL	SLUIER	KROT
HOOI	ECHO	OPSTEL	STAND	SNOR	CLUB
HORDE	BEUGEL	ORDER	KLAUW	SOEP	GRAM
HOTEL	BEEN	PAKKET	BETON	SPEECH	MOTOR
HUIS	SNAAR	PARK	PEPER	SPELD	GANG
HULP	ANTIEK	PATER	KOERS	SPLEET	CLIENT
HUMOR	DRUG	PEST	DRAAD	SPOT	BUREAU
IDEE	ETAGE	PLAATS	KAAK	SPRAAK	MEUBEL
IDIOOT	RADIO	PLAN	DOEK	SPUIT	GEEST
JAAR	HOUT	PLAS	VRUCHT	SPUL	MUSEUM
JUFFER	TREIN	PODIUM	BIET	STAL	KOOP
JURY	VLAKTE	POLS	BIER	STANK	PAAL
KABEL	VERSIE	POORT	REUMA	STAP	SMAAK
KAMER	GEIT	PREEK	PLOEG	STAPEL	RUIL
KANAAL	JEUGD	PRENT	HEIL	STEEG	MACHT
KEET	BLAZER	PRINS	STREEP	STEEN	NAALD
KERMIS	LUIER	PROOI	JAPON	STEM	ZWAGER
KEUKEN	SLOF	PRIJS	DIENST	STILTE	WIEK
KIND	ZONE	RAKET	GOUD	STORM	GENIE
KLEPEL	DRIFT	REDEN	FREULE	STRAAT	SCHEUR
KLEUR	DIVAN	REEKS	LEUGEN	STRAND	FOUT

Word 1	Word 2
STRO	BOORD
STOF	ZAAL
STOP	WENK
STUDIO	UNIE
SULTAN	BEDROG
TAAK	VOER
TABAK	IMPULS
TAFEL	VONDST
TEGEL	STEUN
TEKST	KLOK
TERRAS	STAAF
TEST	BEER
TRAAN	PUIN
TRAM	GANS
TROEP	HERDER
TUIG	RACE
VAKMAN	SCHETS
VEER	ZIEL
VELD	PAGINA
VERF	NAGEL

Word 1	Word 2
VETE	KUUR
VEZEL	SPEER
VILLA	KUIF
VIRUS	KOGEL
VLOEK	ROMMEL
VLOER	PREMIE
VLOOT	HEUVEL
VLUCHT	INDEX
VOCHT	PLEIN
VOET	SCHUUR
VOGEL	TUBE
VOLK	SLAAG
VRIEND	BAGAGE
VUIST	TERM
WAND	SLANG
WAPEN	MARGE
WEDUWE	KWART
WEKKER	GROEP
WERF	DEUGD
WERK	FIGUUR

Word 1	Word 2
WIEL	SCHERF
WIER	LITER
WIND	MASKER
WOEDE	KORF
WOLK	SPIJT
WONDER	POST
WORTEL	ELPEE
ZAAK	PARFUM
ZAND	VEST
ZANG	LAMP
ZEEF	REGEL
ZEGEN	STRIK
ZEIL	KEIZER
ZENDER	JURK
ZICHT	STROOK
ZIEKTE	TIJD
ZOEN	TOEVAL
ZOMER	PUNT
ZONDE	NEUS
ZORG	WOLF
ZUIL	SCHEMA
ZWAARD	MODEL

APPENDIX C. EXPERIMENT III: DESIGN AND WORDS

C1. Design of Experiment III

The two experimental lists in the one-word-twice condition, each consisting of 48 different items in 72 presentations (from left to right), were constructed as follows:

List 1:	01	02	03	04	05	06	07	08
	09	10	10	11	12	13	14	15
	13	16	17	14	18	12	19	18
	20	21	22	23	11	24	25	22
	24	26	21	17	27	28	28	29
	30	09	31	32	33	34	34	31
	15	30	35	35	36	37	38	19
	29	39	37	40	32	36	40	25
	41	42	43	44	45	46	47	48

List 2:	01	02	03	04	05	06	07	08
	09	10	11	12	13	13	14	11
	15	16	10	17	18	19	20	21
	22	09	23	22	21	18	24	25
	26	24	27	28	29	30	28	20
	31	31	30	32	12	33	34	14
	25	35	36	37	17	38	33	36
	38	39	39	23	37	40	40	34
	41	42	43	44	45	46	47	48

The two experimental lists in the two-words-once condition, each having 68 different items in 72 presentations, had the following structure:

List 3:	01	02	03	04	05	06	07	08
	09	10	11	12	13	14	15	16
	17	18	19	20	21	22	23	24
	25	26	27	25	28	29	30	31
	32	33	34	35	36	37	38	39
	40	41	42	43	33	44	45	46
	47	48	49	50	51	52	36	53
	54	18	55	56	57	58	59	60
	61	62	63	64	65	66	67	68

List 4: 01 02 03 04 05 06 07 08
09 10 11 12 13 14 15 16
17 17 18 19 20 21 22 23
24 25 26 27 28 29 30 31
32 33 34 35 32 36 37 38
39 40 41 34 42 43 44 45
46 21 47 48 49 50 51 52
53 54 55 56 57 58 59 60
61 62 63 64 65 66 67 68

C2. Words presented in Experiment III

Below are given the 232 nouns presented to the 54 subjects of the experiment:

ACCU
AFKEER
AFLOOP
AGENT
ALINEA
ANGST
ANTIEK
AVOND
BAARD
BAGAGE

BANAAN
BEELD
BEER
BEVEL
BEZIT
BIET
BILJET
BLAD
BLAZER
BLOEM

BLOK
BOER
BORD
BOUT
BRAND
BRIL
BUNDEL
BUREAU
BURGER
CIJFER

CLIENT
CODE
COGNAC
CREME
CRISIS
CURSUS
DANK
DIJK
DINER
DOEK

DOLLAR
DORP
DORST
DOUCHE
DRIFT
ECHO
EEND
EMMER
ENGEL
ETAGE

FIRMA
FREULE
FRUIT
GANS
GARAGE
GAVE
GEBAK
GEEST
GEHEIM
GELD

GELEI
GEVEL
GEWEST
GIPS
GOUD
GRAAN
GRACHT
GUNST
HAAK
HAAST

HALS
HARK
HAVEN
HEELAL
HELFT
HERDER
HOOI
HOUT
HUID
HULP

IDEE
IDIOOT
INDEX
JAAR
JACHT
JAPON
JEUGD
JUFFER
KAART
KABEL

KANAAL
KEET
KETEL
KEUKEN
KLAUW
KLEED
KLEM
KLEPEL
KLOMP
KOGEL

KONIJN
KOOP
KOORTS
KOUS
KRAAG
KUIF
KUIL
KWART
KWAST
LEEUW

LEUGEN
LEUZE
LITER
LUNCH
MAAG
MAIS
MARKT
MASKER
MELK
MEREL

METRO
MOTOR
MOUW
MUIS
NEVEL
NYLON
ONWEER
OPGAVE
ORDER
OVEN

PAGINA
PANTY
PARFUM
PARK
PEPER
PIANO
PIJP
PION
PLAN
PLAS

PODIUM
POEDER
PROOI
PUIN
PUNT
PUPIL
RACE
RADIO
RAKET
REDEN

REEKS
REGEN
REGIO
RENTE
REST
RIJST
ROEP
ROES
ROMAN
ROMMEL

RONDE
RUIL
SALDO
SAUS
SCHAAR
SCHAT
SCHOOL
SCHORT
SCHUUR
SERIE

SFEER
SIRENE
SLOF
SLOGAN
SMOEL
SNEEUW
SPEECH
SPIER
SPLEET
SPOT

SPUIT
STAL
STAPEL
STEL
STEUN
STIER
STILTE
STROOK
STRUIK
SUIKER

TAAK
TEGEL
TEMPEL
TEST
TIJD
TINT
TIRAN
TOEVAL
TRAAN
TRAM

TREIN
TROEP
TUIG
VEER
VELD
VERSIE
VEZEL
VILLA
VIRUS
VLOEK

VLUCHT
VOER
VOET
VORK
VRIEND
VRUCHT
VUIL
WALVIS
WEDUWE
WENS

WHISKY
WIEK
WIER
WIMPER
WIND
ZAAK
ZEEP
ZICHT
ZIEKTE
ZIEL

ZOEN
ZOMER

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SAMENVATTING

De SAM theorie van Raaijmakers en Shiffrin is het centrale thema van deze dissertatie. De theorie is uitgebreid met een model voor context fluctuatie om tijdsafhankelijke veranderingen te beschrijven. Het SAM model wordt toegepast op een aantal experimenten met gepaarde associaties. Tijdens deze toepassing kwamen problemen met de identificatie van de parameters aan het licht.

In hoofdstuk 1 wordt een overzicht gegeven van de effecten van repetitie en de spreiding van repetities, zoals deze in de literatuur worden beschreven voor bijna alle soorten geheugen taken. Herhaalde items worden beter herinnerd dan items die slechts één keer worden aangeboden (repetitie effect). "Gestapelde" aanbiedingen leiden in het algemeen tot een minder duurzame opslag dan meer gespreide aanbiedingen. Als het tijdsinterval tussen twee presentaties (van hetzelfde item) groter wordt, dan wordt de herinnering (recall) of de herkenning (recognitie) ook beter (lag of Melton effect). Bij continue gepaarde associatie (CPA) taken wordt de reproductie ook beter met een toenemend interval tussen beide presentaties (spreidings interval) als het retentie interval groot is. Als echter het retentie interval erg klein is, wordt de reproductie juist slechter met een toenemend spreidings interval (spreidings effect).

De belangrijkste theorieën die zowel de repetitie effecten als de effecten van spreiding van de aanbiedingen verklaren, worden besproken. Er kunnen grofweg drie klassen van theorieën worden onderscheiden, en wel: (a) inattentie theorieën, (b) consolidatie theorieën, en (c) theorieën met variabele codering (variable encoding theories). De consolidatie en de variabele coderings theorieën (en hun combinatie) worden hier uitgebreider beschreven.

De variabele coderings theorieën worden het meest gebruikt om de effecten van repetitie en van spreiding van repetities te verklaren. Alle soorten variabele coderings theorieën nemen aan dat een item op verschillende manieren kan worden gecodeerd. De representatie van het item hangt af van de cognitieve context waarin het wordt aangeboden (optreedt). Er wordt aangenomen dat enkele van de "cues" die aanwezig zijn tijdens de opslag van het item (tijdens de presentatie) weer worden omgezet tijdens het ophaal proces (retrieval). Voor items die twee keer worden aangeboden, is de kans op ophalen groter, als het item aangeboden is in twee verschillende contexts. In deze theorieën wordt aangenomen, dat een grotere spreiding van aanbiedingen tot een grotere diversiteit van de context leidt. Er zijn daarom bij een grotere spreiding meer manieren om de items op te halen.

De Component-Levels theorie van Glenberg gaat er van uit dat spreidings effecten te wijten zijn aan variabele codering van drie soorten informationele componenten (structurele, context en descriptieve). Variabele codering kan ontstaan door de semantische interpretatie, door de context waarin de items worden gecodeerd, en door de organisatie van de items door het subject. De Component-Levels theorie is mathematisch niet uitgewerkt. De globale ideeën van deze theorie zullen worden opgenomen in de SAM theorie.

In hoofdstuk 1 wordt verder een beschrijving gegeven van de oorspronkelijke SAM theorie. SAM is een theorie voor het ophalen van informatie uit het geheugen. Ophalen van informatie wordt gezien als een proces met twee stadia, namelijk selectie (sampling) en reconstructie (recovery) van de opgeslagen informatie met behulp van ophaalaanwijzingen (retrieval cues). Tijdens de selectie wordt informatie uit het geheugen geselecteerd, en na een succesvolle selectie kan deze informatie in het reconstructie stadium worden omgezet in een antwoord. Informatie van de context en specifieke informatie van de items worden gebruikt als ophaalaanwijzingen. De associatieve sterktes tussen deze aanwijzingen (cues) en de opgeslagen informatie (in het image) worden de context en de interitem associatieve sterktes genoemd. Als zowel selectie als reconstructie niet succesvol zijn, zal een nieuwe ophaal poging worden gedaan, net zolang tot er succes optreedt of tot een criterium van falen is bereikt.

De "stimulus sampling" theorie van Estes kan worden uitgewerkt tot een context fluctuatie model om de effecten van spreiding en repetitie te verklaren. Van context elementen wordt aangenomen dat ze kunnen fluctueren tussen een actieve en een niet-actieve toestand. Alleen elementen in de actieve toestand, ten tijde van een presentatie, kunnen worden gecodeerd en opgeslagen in een geheugenspoor. De overlap tussen opgeslagen context elementen en de elementen actief ten tijde van het ophalen van de informatie wordt als een meting van de context sterkte genomen.

Volgens SAM worden associaties tussen items gevormd als items gelijktijdig in een zogenaamde buffer (rehearsal buffer) aanwezig zijn. Voor vrije reproductie taken wordt aangenomen dat alle items die aanwezig zijn in het korte-termijn geheugen (STS) ook deel uit maken de buffer. Voor taken met gepaarde associaties echter, wordt aangenomen dat de buffer en het korte-termijn geheugen niet samengaan. De twee items van een paar worden alleen met elkaar geassocieerd (tijdens de presentatie van het paar, als de items actief herhaald worden in de buffer) en niet met items van andere paren, die nog in het korte-termijn geheugen aanwezig zijn. Het korte-termijn geheugen kan in dit geval gezien worden als een proces dat de herkenning of de herinnering van een item gemakkelijker maakt.

In hoofdstuk 2 wordt het model uitgewerkt voor het verklaren van de resultaten van CPA experimenten. Er worden mathematische details gegeven voor verschillende versies van het SAM model met context fluctuatie. Er worden model versies gepresenteerd voor stimuli die eenmaal, tweemaal en vijfmaal worden aangeboden. Verder wordt het SAM model uitgewerkt om de resultaten van de zogenaamde twee-stimuli-eenmaal conditie te kunnen verklaren.

In alle versies van het model wordt aangenomen, dat een deel van de actieve context elementen en meer specifieke informatie wordt opgeslagen tijdens de eerste presentatie van een stimulus-response paar. Bij een volgende presentatie of bij een test wordt extra informatie opgeslagen in het geheugenspoor als het paar wordt herkend of herinnerd. Paren worden herkend of herinnerd als ze nog aanwezig zijn in het korte-termijn geheugen of als ze opgehaald worden uit het lange-termijn geheugen (via selectie en reconstructie). Als een paar niet wordt herkend of niet wordt herinnerd dan nemen we aan dat er een nieuw geheugenspoor wordt gevormd.

In hoofdstuk 3 wordt een overzicht gegeven van de experimenten en de experimentele resultaten die worden gebruikt om de verschillende versies van het SAM model te toetsen. De experimentele resultaten van de woordparen die eenmaal worden aangeboden laten een verlaging van de verrichting zien bij een toenemend retentie interval tot een asymptotische niveau.

Het CPA experiment van Glenberg laat zien dat voor korte retentie intervallen de curves van de reproductie kansen niet-monotone functies van het interval tussen beide aanbiedingen (spreidings interval) zijn: een aanvankelijke verhoging van de reproductie wordt gevolgd door een latere verlaging. Lange retentie intervallen geven een monotoon stijgend spreidings effect te zien met een toenemend spreidings interval. In de gegevens van Glenberg is een dip te zien in de curves met korte retentie intervallen bij een spreidings interval van één gebeurtenis (event). Glenberg negeerde deze dip bij de presentatie van zijn resultaten. Maar in een theoretisch analyse van spreidings effecten door Reed wordt de verklaring van deze dip in de geobserveerde gegevens één van de meest cruciale aspecten van deze gegevens. Om het belang en de betekenis van deze dip te onderzoeken werd een nieuw onderzoek opgezet. In deze replicatie zijn alleen korte retentie en spreidings intervallen gebruikt, omdat de dip in Glenberg's gegevens voor dit soort intervallen werd gevonden. De curves voor de kansen op een correct antwoord voor korte retentie intervallen in deze replicatie zijn niet monotoon stijgend met een toenemend spreidings interval en hebben een piek bij een spreidings interval van ongeveer drie gebeurtenissen. De curves voor langere retentie intervallen zijn negatief versneld met een toenemend spreidings interval. Er is geen bewijs gevonden dat de dip in Glenberg's gegevens van belang is voor het spreidings effect.

Een experiment van Rumelhart met gepaarde associaties met de anticipatie methode wordt gebruikt om het model voor vijf aanbiedingen van een paar te toetsen. De belangrijkste resultaten van Rumelhart zijn: (a) De kans op een correct antwoord hangt af van de "lag" (interval tussen twee opeenvolgende aanbiedingen van één paar) die er onmiddellijk aan voorafgaat. Hoe langer de "lag" hoe kleiner de kans; (b) Er is geen effect van de volgorde van de voorafgaande "lags" op deze reproductie kansen.

Een tweede CPA experiment wordt opgezet om het SAM model voor de twee-stimuli-eenmaal conditie te toetsen. In de twee-stimuli-eenmaal conditie wordt gekeken naar de reproductie kans van tenminste één van beide stimulus-response paren (kortweg: stimuli). Deze reproductie kans wordt vergeleken met de reproductie kans van één stimulus die tweemaal wordt aangeboden. We vonden geen spreidings effect voor de twee-stimuli-eenmaal conditie, maar wel een klein spreiding effect voor de één-stimulus-tweemaal conditie. In experimenten met vrije reproducties worden echter duidelijker "lag" effecten (vergelijkbaar met het spreidings effect voor lange retentie intervallen) gevonden voor herhaalde stimuli. Om de effecten van een toenemend spreidings interval voor beide condities te kunnen vergelijken wordt een experiment met vrije reproductie opgezet. In dit experiment wordt een duidelijk en significant "lag" effect gevonden voor de herhaalde stimuli, maar geen "lag" effect voor de twee-stimuli-eenmaal conditie. SAM uitgewerkt met het context fluctuatie model kan alleen worden geaccepteerd als de argumenten van Ross en Landauer (namelijk: een theorie met variabele codering voorspelt altijd een spreidings effect voor de twee-stimuli-eenmaal conditie net zoals voor de één-stimulus-tweemaal conditie) niet opgaan.

In hoofdstuk 4 wordt aangetoond dat in het SAM model voor tweemaal aangeboden paren, waar zowel herkenning als herinnering de reproductie kans bepalen, vijf parameters mathematisch gereduceerd kunnen worden tot slechts vier parameters. Een indicatie wordt gegeven voor het bestaan van andere afhankelijkheden tussen parameters, wanneer de geobserveerde gegevens gebruikt worden om het model te fitten. Deze afhankelijkheden zijn statistisch van aard, omdat als artificiële data gegenereerd met het model, gebruikt worden als "experimentele" data om het model te fitten, de fit procedure de parameters, die gebruikt zijn om de data te genereren, oplevert.

Een aantal problemen komen aan het licht als het model gefit wordt op de data van Glenberg. Niet alle sub-processen, die de kans op een correct antwoord bepalen blijken effectief. Er wordt gevonden dat recognitie bijna altijd succesvol is, net zoals selectie. Als een consequentie van een bijna altijd succesvolle recognitie fase, wordt de sterkte van bijna alle geheugensporen vergroot bij de tweede aanbieding. Slechts zelden wordt een nieuw spoor gevormd. De spreidings en repetitie effecten zijn grotendeels het gevolg van de reconstructie van een versterkt spoor. Verder, wordt een interitem associatieve sterkte geschat die verwaarloosbaar klein is ten opzichte van de context sterkte. Ook het effect van de STS blijkt slechts miniem.

Niet alle acht parameters kunnen onafhankelijk van elkaar worden geschat. Ook is het moeilijk om de effecten van de verschillende sub-processen te onderscheiden. Om de problemen die optreden bij het fitten van het complete model te ondervangen, zullen wij de gegevens tevens fitten met versimpelde modellen afgeleid van het SAM model. Enkele indicaties voor versimpeling van het model zijn af te leiden uit de resultaten van de analyses van Glenberg's data. Als versimpelde modellen zullen alleen selectie, alleen reconstructie en een combinatie van selectie en reconstructie worden uitgeprobeerd. Verder wordt het effect van de uitbreiding van deze versimpelde modellen met een STS bekeken. Voor de analyses van de data van Glenberg en die van experiment I wordt tevens aangenomen dat recognitie altijd succesvol is.

In de hoofdstukken 5 t/m 7 worden de versies van het SAM models zoals in hoofdstuk 2 gepresenteerd op de data gefit. Voor alle data wordt aangetoond dat als de interitem associatieve sterkte uit het model geëlimineerd wordt, de fit niet verslechtert. Voor de eenmaal aangeboden stimuli voldoen de twee modellen, met alleen selectie en met alleen reconstructie, even goed als het complete model met zowel selectie als reconstructie. Voor de gegevens van Glenberg en die van experiment I voldoen een model met selectie uitgebreid met een STS en een model met reconstructie uitgebreid met een STS even goed om de data te beschrijven als het complete model. Een model met selectie en reconstructie (zonder een STS) blijkt het beste voor toepassing op de data van Rumelhart.

In hoofdstuk 8 wordt aangetoond dat het SAM model geen spreidings effect voorspelt voor de twee-stimuli-eenmaal conditie als rekening wordt gehouden met de gelijkenis in context. De argumenten van Ross en Landauer dat een theorie met variabele codering altijd een spreidings effect voor de twee-stimuli-eenmaal conditie impliceert net zoals voor de één-stimulus-tweemaal conditie, gaan niet op voor het SAM model. Er wordt verder aangetoond dat de predicties van een model dat de gelijkenis in context negeert dezelfde predicties oplevert voor de twee-stimuli-eenmaal conditie als wanneer rekening gehouden wordt met de gelijkenis. De fout in Ross en Landauer's redenering lijkt te zijn dat ze niet onderkennen dat een stimulus herkend kan worden bij een latere presentatie. Bij het fitten van het model op de data is de gelijkenis in context dan ook genegeerd. De modellen met alleen selectie en alleen reconstructie kunnen de data net zo goed beschrijven als het complete model met zowel selectie als reconstructie. De interitem associatieve sterkte kan ook hier geëlimineerd worden uit het model zonder dat de fit slechter wordt.

Op dit moment is het niet mogelijk een conclusie te trekken welk proces, selectie of reconstructie, aangenomen moet worden om de data van eenmaal en tweemaal aangeboden stimuli en de data van de twee-stimuli-eenmaal conditie te voorspellen. Voor de tweemaal aangeboden stimuli verbetert de fit als een STS wordt toegevoegd aan het model.

De principes van context fluctuatie in relatie tot de experimenten wordt bekeken in hoofdstuk 9. Er wordt getoond dat de context sterkte vermindert als de tijd sinds de laatste presentatie van het paar groter wordt. De snelheid van dit verval van een herhaald paar, dat herkend of herinnerd wordt, is langzamer dan het verval van eenmaal aangeboden paar. Het verval na elke volgende aanbieding van een paar is langzamer dan het verval na de daaraan voorafgaande presentatie. Verder wordt de sterkte teruggezet op de begin sterkte of op een steeds iets hogere sterkte (tot een asymptotisch niveau) als het paar wordt herkend of herinnerd.

Het belang van context sterkte kan niet worden gecontroleerd met de gepresenteerde experimenten, extra experimenteel bewijs voor het belang van context fluctuatie bij CPA taken is nodig. Context is een belangrijk aspect in theorieën en modellen van geheugen. Maar alleen experimenten waarin de context expliciet wordt gemanipuleerd kunnen een definitief uitsluitsel gegeven over de rol van context fluctuatie in het SAM model.

Context fluctuatie kan gezien worden als een verval proces van de sterkte van het geheugenspoor. Andere processen van verval kunnen worden verondersteld als context fluctuatie als verval proces wordt gezien. De verval van spoor sterkte (decay of trace strength) ontwikkeld door Wickelgren en verder uitgewerkt door Reed kan gebruikt worden voor het bepalen van de sterkte van het geheugenspoor in het SAM model. Groei van weerstand en verval van sterkte vanaf het moment van opslag zijn verantwoordelijk voor de vermindering van sterkte. Na herkenning of herinnering van een paar wordt de sterkte van een spoor in LTS terug gezet op zijn begin waarde bij de eerste presentatie, maar het process van weerstand gaat door alsof er geen verhoging van de sterkte heeft plaats gevonden.

Beide modellen, het context fluctuatie model en het model met verval van spoor sterkte kunnen worden gebruikt voor de sterkte van een spoor in het SAM model om spreidings effecten te voorspellen. Het is belangrijk om nieuwe experimenten op te zetten om te kunnen concluderen welk model voor verval meer valide is.

In de Engelse samenvatting en conclusies worden de problemen met de identificatie van de parameters en met het bepalen van het belang van de sub-processen in het SAM model besproken. Mogelijke experimentele manipulaties om meer vat te krijgen op de parameters en de sub-processen van SAM worden kort beschreven.

Ten slotte kan gesteld worden, dat voor alle sub-processen in het SAM model een goede reden kan worden aangegeven. Het lijkt er echter op dat de combinatie van alle sub-processen niet meer succes heeft in het voorspellen van de experimentele resultaten dan een enkel sub-proces of een combinatie van slechts twee sub-processen. De effecten van alle componenten van het model kunnen niet gescheiden worden door de experimenten die in deze studie gepresenteerd worden.

CURRICULUM VITAE

Marijke Westra werd geboren op 29 september 1954 te Steenwijk.
In 1972 legde zij met succes het eindexamen HBS-B af aan de Rijksscholengemeenschap te Steenwijk. Meteen daarna heeft zij met minder succes twee jaar natuurkunde gestudeerd aan de Rijksuniversiteit te Groningen. In 1974 begon zij aan de psychologie studie aan de Rijksuniversiteit te Groningen. In september 1977 haalde zij het kandidaatsexamen psychologie. Tijdens de doctoraal fase deed zij onderzoek op het gebied van verrichtingsleer en psychofysiologie onder begeleiding van Dr. Mulder. Haar stage en scriptie op het gebied van besliskunde werd verricht onder begeleiding van Professor Molenaar. In juni 1982 studeerde zij af als functieleer psycholoog met wiskundige methoden als bijvak.
Van augustus 1983 tot augustus 1989 werkte zij als junior wetenschappelijk medewerkster bij de vakgroep Mathematische Psychologie aan de Katholieke Universiteit te Nijmegen. Haar onderzoekstaak bestond uit het toepassen van het SAM model op de effecten van repetities en van spreiding van deze repetities. De verslaglegging van het onderzoek vond plaats in de vorm van een proefschrift. Het voorstel voor dit onderzoek werd door Dr. Raaijmakers geformuleerd. Het proefschrift werd onder begeleiding van Professor Roskam geschreven. Naast dit onderzoek gaf zij tijdens de aanstelling bij deze vakgroep doctoraalcursussen in Methoden en Technieken.

STELLINGEN

1. Het SAM model met context fluctuatie is een combinatie van consolidatie en rehearsal theorieën enerzijds en theorieën met variabele codering anderzijds, en kan daardoor veel effecten van repetities en van spreiding van deze repetities verklaren.

2. "Gedifferentieerde opslag" verwijst naar de positieve correlatie tussen de spreiding van repetities en het aantal verschillende, in het geheugenspoor opgeslagen, elementen en niet naar de opslag in verschillende sporen.
(*Glenberg, A.M. Memory and Cognition, 1979, 7, 95-112.*)

3. De aanname dat een woordpaar in één spoor wordt opgeslagen in plaats van in twee verschillende sporen (voor elk woord één) is zuiver een kwestie van voorkeur; beide versies geven equivalente voorspellingen.
(*Raaijmakers, J.G.W. & Shiffrin, R.M. Attention and Performance IX, 1981, 403-415.*)

4. De psychologische plausibiliteit van een model is de intuïtieve aannemelijkheid van de empirische implicaties (of consequenties) ervan.

5. Het korte termijn geheugen speelt geen rol wanneer het tijdsinterval tussen de presentaties of tussen presentatie en test langer is dan circa 15 seconden.

6. De effecten van context op geheugen processen kunnen beter bestudeerd worden door context experimenteel te manipuleren dan door random context fluctuatie aan te nemen.

7. De volgende uitspraak over natuurkunde van de fysicus Ad Lagendijk tijdens zijn inaugurale rede gaat ook op voor psychologie: "Indien de hypothesen niet testbaar zijn of indien de theorie eigenlijk een verzameling van theorieën is die zeer flexibel aangepast kunnen worden aan het experiment, dan hebben we niet meer te maken met natuurkunde maar met Spielerei."

8. De argumenten die Ross en Landauer geven om te bewijzen dat een theorie met variabele codering een "spacing effect" voorspelt voor de een-stimulus-tweemaal conditie net zoals voor de twee-stimuli-eenmaal conditie, berusten op de onjuiste veronderstelling dat bij tweede aanbieding de stimulus niet herkend wordt.

9. SAM biedt pas een verklaring voor het feit dat het geheugen na een beroerte beter functioneert in een constante omgeving als het effect van afleiding door veranderingen in context opgenomen wordt.

10. Decoratieve cosmetica kunnen gezien worden als mooimakerij in de vorm van een chemische cocktail van veelal onbekende (aan de consument althans), soms giftige, ingrediënten.

11. Het ziekenfonds zou zichzelf, andere uitkerende instanties en de patiënt heel wat tijd en kosten kunnen besparen door bij verstrekkingen waarvan de ziekenfonds arts zelf zegt: "Het zal niet vergoed worden, maar gaat u maar in beroep dan komt het wel goed" meteen een zorgvuldiger afweging te maken en een positieve beslissing te nemen.

12. De overheidscampagne "Kies Exact" heeft duidelijk gefaald bij psychologie studentes die het onvoorstelbaar vinden dat je als vrouw bij de vakgroep mathematische psychologie werkt.

13. Het is maar goed dat het geheugen gebruikt kan worden zonder de werking precies te begrijpen.

Stellingen behorende bij het proefschrift van
Marijke van Winsum - Westra,
Spacing and Repetition Effects in Human Memory,
Nijmegen, 13 december 1990.