Updating of Representations in Working Memory

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To Saber and Yazan

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The term “updating of representations” describes the process of replacing no longer relevant mental contents with new, now relevant contents. In daily life, updates of mental contents occur very often. For example when somebody wants to calculate how much money he/ she spent for his/ her last holiday. He/ she may start with the price for the flight ticket. By adding the hotel costs, the representation of the initial number in working memory is replaced by the sum of the two factors. The further addition of the costs for museum tickets results in another updating of his/ her working memory content.

Working memory is conceived to be responsible for the temporary storage of information, holding contents accessible for current processing, and for the control of this information. Since updating involves the manipulation of stored information, it can be regarded as one of the main processes in the functioning of working memory. The limited capacity of working memory forces people to discard old contents from working memory (De Beni & Palladino, 2004). To keep an unlimited amount of information in a highly activated state is not possible and would be a waste of resources. By replacing no longer relevant contents, working memory capacity can be used in the most efficient way.

The detailed procedure of the updating process is not yet completely investigated and different conceptions about it exist: Whereas Morris and Jones (1990) consider the updating process as a simple replacement, Palladino, Cornoldi, De Beni, and Pazzaglia (2001) assume it to be a complex process of gradually regulating the activation level of representations. This view corresponds to a model with different activation levels of the elements of memory. According to it, updating and inhibition processes determine the activation level of the elements in working memory and the strength of incoming information.

The investigation of the procedure of the updating process requires the distinction between two aspects: An updating process involves the creation of a new representation and the suppression of the old representation. Efficient suppression of the working memory representations which are replaced is necessary to avoid proactive interference. Old contents which are not completely suppressed can interfere with the contents which are relevant at that time. Another possibility is that “temporal tagging” provides the basis for the differentiation between old and new information (Jonides & Smith, 1997).

Currently relevant contents of working memory have to be protected not only by suppression of old and no longer relevant representations, but also by inhibition of incoming irrelevant information. The following problem emerges: Sometimes a representation has to be robust against distracting new inputs to working memory, while at other times, an updating of a current representation is necessary. Consequently, a dynamic regulation system is necessary for switching between maintenance and updating.

Such a dynamic regulation system can be found in neuropsychological literature, where the updating process has been discussed on a neural level. O'Reilly and Munakata (2000) provide a detailed overview of the updating problem on this level. They assume the prefrontal cortex to be responsible for robust and rapid updates of the contents of working memory. The neuromodulatory substance dopamine seems to be important for the regulation of the frontal memory system (O'Reilly, Braver, & Cohen, 1999, Cohen & O'Reilly, 1996) by its capability to potentiate both afferent excitatory and inhibitory signals (Chiodo & Berger, 1986, Penit-Soria, Audinat, & Crepel, 1987). Midbrain nuclei under control of descending cortical projections might send dopamine to the frontal cortex (the ventral tegmental area) enabling it by this way to actively regulate the updating of its representations (Cohen & O'Reilly, 1996). Afferent connections into the frontal cortex from other brain systems are usually relatively weak compared to stronger recurrent excitation within the frontal cortex (maintenance of contents), but dopamine might enhance the strength of these afferents for rapid updating. O'Reilly and Munakata (2000) assume that dopamine could serve as a dynamic gating mechanism: When dopamine is firing, the "gate" into working memory is open (rapid updating of representations), otherwise it is closed (robust maintenance). This mechanism could operate through the dynamic regulation of the relative strength of input versus recurrent maintenance connections.

An alternative hypothesis is that the basal ganglia are important for the control of frontal working memory. Concerning the dynamic gating mechanism, basal ganglia firing may initiate the gating of memories in the frontal cortex. This could be effected by the disinhibition of cortico-thalamic loops via the connections from the basal ganglia to the regions of the thalamus that are interconnected with the frontal cortex. This alternative mechanism has the potential for finer resolution than the mechanism described before concerning which regions of the frontal cortex are updated and which are not updated.

Besides the need to further investigate the detailed procedure of the updating process, there are many other open questions. Two of these are addressed here: The first part concerns the question if it is possible to update several representations in parallel. In the second part, experiments are presented investigating if representations of elements which were replaced in an updating disappear directly or interfere with the representations of the new elements.

Before describing the experiments I conducted I will present some studies of other authors. Studies investigating the working memory updating process are few until now and deal with different aspects of this cognitive process. No experiments at all have been conducted concerning the same or similar questions like the experiments reported here. Therefore, the following report does not give a clear and consistent picture of the working memory updating process and is not directly related to the present experiments.

In the influential working memory model of Baddeley and Hitch (1974), a component called “central executive” is responsible for the controlled, attention demanding aspects of information processing, while the “phonological loop” and the “visuospatial sketchpad” hold information accessible for processing. Miyake et al. (2000) refer to this model when they describe “information monitoring and updating” as one of the most frequently postulated executive functions besides “mental set shifting” and “inhibition of prepotent responses”. A confirmatory factor analysis of these authors revealed that these three executive functions are not completely different from each other, but they can not be regarded as aspects of one unitary executive function either.

Furthermore, Miyake et al. (2000) conducted a latent variable analysis to investigate the influence of the three target processes on some executive tasks often used in cognitive and neuropsychological studies. They found updating to have a major influence on the operation span task and, besides the inhibition process, on producing sequences of random numbers. In the operation span task, which is assumed to measure verbal working memory capacity, participants had to read aloud a simple mathematical equation and to verifiy it, followed by the presentation of a word which had to be remembered. After passing through a set of equation-word pairs, participants had to recall all words presented in the current trial.

It has to be noted that possibly not all kinds of updates involve the central executive: Palladino et al. (2001) distinguish between an automatic updating, for example the automatic encoding of information, and a more controlled updating resulting from conscious processing of information.

Postle, Berger, Goldstein, Curtis, and D’Esposito (2001) investigated if updating-related processes are separable on the neural level from simple encoding and maintenance processes in working memory. If updating is an executive function, a dissociation should be found. In their experiment, a running memory span task, first introduced by Morris and Jones (1990), was used, in which subjects were presented successively 4, 8, or 12 consonants. In a recognition test at the end of a trial, the 4 most recently presented items had to be remembered. Since subjects did not know after how many consonants a list will end, they had to update continuously their working memory contents. While trials with list length 4 required no updating, longer list length did so. The presentation of the fifth item should have resulted in discarding the first presented item from working memory, repositioning the second, third, and fourth item, and adding the fifth item. Every further presented item should have resulted in another updating. The fMRI-data of this experiment revealed that the same brain areas are active during updating and non-updating processes, though with quantitative differences. Postle et al. (2001) concluded from these data that they failed to find a clear dissociation.

Ruiz, Elosúa, and Lechuga (2005) criticized the implicit assumption that subjects apply an updating strategy in the running memory span task. They hypothesized that subjects might not apply an active updating processing strategy in this task, but try to remember the recent items at the end of a trial. By this way, no item would be discarded from working memory. The results of their experiments with consonants and disyllabic words and a recall test at the end of a trial supported this hypothesis: Subjects often reported by mistake items from positions just preceding the target items which had to be reported. According to the updating assumption, items preceding the target items should have been already discarded from working memory. Furthermore, recency effects were found, which might be the final portion of the serial position curve of the whole list.

The results of Ruiz et al. (2005) offer a new explanation for the failure of Postle et al. (2001) to find a neural dissociation between updating and non-updating processes in working memory. Probably no updating took place in the running memory span task used in their experiments.

Oberauer (2003) conducted experiments with an arithmetic memory task in different forms. In the Experiments 1 a and 1 b, subjects had to remember 1, 2, 3, or 4 digits. While each digit was associated with a frame on the screen in Experiment 1 a, in Experiment 2, each digit was associated with a color. Subsequently, an arithmetic operation was presented in one of the frames or in one of the colors. This operation, for example “+2” or “-4”, had to be applied by the participant to the digit in the respective frame or to the digit with the corresponding color. The result had to be typed as quickly as possible. One trial consisted of nine operations. When there was more than one digit to remember, an operation could be applied to the same digit as the previous operation (no object switch) or to a new one (object switch). The initial digits were not updated by the results of the operations, but remained the same until the end of a trial. While this task did not require memory updating, a similar task with memory updating, but without retrieval of previous memory contents, was used in Experiment 2. This task started again with the presentation of digits associated with frames on the screen. Participants had to remember the digits and their corresponding positions. Equations like “5-2” or “2+3” in individual frames followed, which had to be solved. The initial digits had to be replaced by the results of the corresponding equations. It was possible that the result of an arithmetic operation had to be updated again, because one trial contained 1 to 10 updating operations. At the end of a trial, participants had to recall the final digits of each frame. Like in Experiment 1a and 1 b, object switches as well as no object switches were realized.

By isolating the updating component from the component of selective access to items in working memory, Oberauer (2003) showed that both processes are causes of object switch costs. The object switch effect consists of longer reaction times for operations applied to a new item compared to operations applied to the same item as before during a task.

Since updating involves the suppression of the replaced representation, another aspect for future research could be to examine how groups that have problems in ignoring interfering/ distracting information like schizophrenics, Alzheimer’s patients, children, or elderly people (Cohen & Servan-Schreiber, 1992, Dempster, 1992, Hasher & Zacks, 1988, Simone & Baylis, 1997) handle updating tasks.

Differentiating between age groups within the category of old people, De Beni and Palladino (2004) showed that working memory updating performance decreases through ageing. They used the Semantic Updating Task (SUT), constructed by Palladino et al. (2001), which required the participants of their first experiment to remember the three smallest items (animal nouns, object nouns, or two-digit numbers) of a list of 10 sequentially presented items and to recall them at the end of a trial. In this task, subjects have to start remembering the first three items. If the fourth item is smaller than one of the first three, an update is necessary replacing the biggest item of the set of memorized items with the fourth item. Every following item has to be compared with the items memorized until that point and an update is necessary if the new item is smaller than one of the remembered items. Items which seemed to be relevant until a certain point in a trial, but were replaced later, had to be suppressed to avoid intrusions. Intrusions were defined here as items of the same trial as the target items, which were incorrectly recalled. The group of oldest participants recalled less items correctly and produced a higher number of intrusions than the other two groups of old people. The effect concerned intrusions of items which should have replaced bigger items at a certain point in a trial but should then have been replaced by smaller items.

In the second experiment with animal/ object nouns as relevant information, filler items (abstract nouns) were introduced into the task to vary the number of relevant but non-target items in a trial (two/ five items, factor Updating: high and low suppression demands). The number of items to be recalled was varied, too (three/ five items, factor Maintenance: high and low memory demands in loading and retrieval operations). In this experiment, a group of young people was tested besides three groups of old people. Analysis of the percentage of correctly recalled items revealed a significant interaction between the factors Age and Maintenance. With high maintenance demand, a decline was observed between young and all three groups of old participants and between the group of the youngest old people and the other two groups of old people. With low maintenance demand, the group of oldest participants produced a significantly lower percentage of correctly recalled items than all other groups. Analysis of a certain kind of intrusions (non-target items recalled that were present in the previous lists) showed a significant interaction between the factors Age and Updating. With low suppression demand, no differences were observed, while high suppression demand led to significant differences between the group of young people and all three groups of old people. De Beni and Palladino (2004) interpreted their results as a reduction in memory capacity besides an impairment in the suppression mechanisms of irrelevant information for old people compared to younger people. They concluded that elderly people seem to be more resistant to memory updating and tend to maintain old information which has become irrelevant.

Contrary to these results, Verhaeghen and Basak (2005) found item updating to be age invariant when general slowing effects were taken into account. They conducted an experiment with a modification of the N-back task. In this kind of task, numbers are presented serially and subjects have to answer if a number is identical to the number N presentations back. For example, in the 4-back version, four numbers are presented and then, the fifth number presented requires the subject to judge if it is the same as the first number. After that, the sixth number has to be judged for identity with the second number and so on. Unlike in the original N-back task, Verhaeghen and Basak (2005) presented the numbers which had to be compared with each other in the same column and color to minimize extraneous control demands. This task requires the subject to remember the last N numbers presented. After the identity judgement, an updating of the number in the Nth position back is only necessary when the judgement is negative and a “no”-answer has to be given. The authors interpreted differences in reaction times between “yes” and “no” responses as primarily caused by the updating process. They neglected other processes besides the updating process because

Sternberg (1969) found no reaction time differences between “yes” and “no” responses in working memory access experiments that require no updating under corresponding conditions. Furthermore, they supposed that the updating process is completed before the answer is given.

Passolunghi, Cornoldi, and De Liberto (1999) suggest that individual differences in working memory span might result from differences in the efficiency of an inhibition/ suppression mechanism eliminating irrelevant/ no-longer-relevant information from working memory instead from differences in the amount of information that can be held in working memory at the same time. Contrary to this view, Oberauer, Süß, Wilhelm, and Sander (in press) argue that working memory capacity can not be reduced to the efficiency of executive functions and that working memory capacity and executive functions should be seen as different constructs.

Passolunghi et al. (1999) found evidence for their hypothesis that poor problem solvers have the same working memory capacity as good problem solvers, but do not use this capacity as efficiently as good problem solvers because of deficient inhibition mechanisms. They conducted a longitudinal study with nine year old school children, in which they formed a group of poor problem solvers and a group of good problem solvers according to criteria like performance in arithmetic word problem solving. Results of a word span test showed that poor problem solvers did not differ significantly from good problem solvers in working memory storage capacity. This test started with the auditory presentation of three familiar words (successively), which had to be repeated by the subject immediately after presentation. The number of presented words increased every second trial by one word up to eight words. A trial was stopped when a subject failed to recall all words of both trials with a certain number of words in correct order. Furthermore, both groups were able to differentiate between relevant and irrelevant information in a task that required them to underlie the most relevant information in problems presented in written format.

Passolunghi et al. (1999) adapted the listening span test of Daneman and Carpenter (1980) according to age and native language (Italian) of the subjects. In each trial of this task, 2, 3, or 4 sentences were presented successively. Each sentence had to be judged if it was true or false before the presentation of the next sentence. Besides this judgement, the last word of each sentence had to be remembered for a recall test at the end of a trial. Good problem solvers performed significantly better in the recall of the sentence-final words. The bad performance of poor problem solvers was attributed by the authors to deficient inhibition mechanisms because this group erroneously remembered significantly more non-sentence-final words than good problem solvers. In a further experimental phase with auditorily presented arithmetic word problems, poor problem solvers recalled less relevant information and more irrelevant information than good problem solvers and solved fewer problems perfectly than good problem solvers. However, Passolunghi et al. (1999) mention that their results could be explained in terms of a selective attention deficit instead of a deficit in inhibiting irrelevant information.

Problem solving requires the construction of an adequate mental model of the problem, and construction of a mental model involves the recall of relevant information presented before. Furthermore, high updating ability is useful for problem solving, because part of the information processed has to be inhibited while other representations have to be enhanced. Depending on the problem, it may be useful to construct several mental models, and switching between the models requires updating of the contents of working memory. Passolunghi and Pazzaglia (2004) showed that working memory updating abilities influence problem solving using an individual differences approach. They selected children with high and low updating abilities by the updating task of Palladino et al. (2001). Subjects were also tested for working memory span (digits and words), computation performance, and verbal intelligence. No difference was found in verbal intelligence and in digit and word spans between the two groups, but in the computation test. The group with high updating ability showed better results than the group with low updating ability. In the following experiment, subjects had to solve arithmetic word problems and to recall relevant information from another set of problems. The group with high updating ability obtained better results in problem solving, as well as in recalling text problems, than the group with low updating ability.

In the arithmetic word problem task, the amount of irrelevant information presented in the description of the problem was varied. In accordance with the hypothesis that inhibiting irrelevant information is important for problem solving, performance of the subjects was better when little irrelevant information was presented.

Updating processes are involved in other higher cognitive tasks besides problem solving, for example in reading comprehension. During reading, it is necessary to hold some of the information processed in working memory and use this information later for understanding a following sentence/ passage. Since cognitive resources are limited, it is not possible to be aware of the whole text and the reader has to replace working memory contents continuously during reading comprehension. A mental representation of the contents of the text has to be constructed by the integration of information from the text with knowledge obtained before (Gernsbacher, 1993). This representation is continuously updated during the comprehension process.

Palladino et al. (2001) conducted several experiments to investigate the relation between working memory updating ability and reading comprehension. The authors selected a group of good comprehenders and poor comprehenders on the basis of their results in the MT battery (Cornoldi, Rizzo, & Pra Baldi, 1991). The groups did not differ substantially in age and general logical intelligence.

They showed that the updating performance of poor comprehenders is worse than the performance of good comprehenders in a modification of the working memory updating task of Morris and Jones (1990) as well as in the Semantic Updating Task (first and second experiment). Subjects of the first experiment were tested for word span, so that it could be excluded that the poor performance in the updating test resulted from generally poor working memory capacity.

Another experiment with the Semantic Updating Task was conducted in order to examine the effect of memory request (number of target items which had to be remembered) and suppression request (number of relevant, but non-target items in lists of fixed length) like described before in the study of De Beni and Palladino (2004). From this experiment, it can be concluded that an increase in the number of items to be remembered has the same effect on good and poor comprehenders, whereas an increase in items to be suppressed was especially difficult to manage for poor comprehenders.

2 Feature updating experiments

Two experiments of the first series conducted here address the following question: When several features of an object have to be updated, how is this process accomplished? The last experiment of this series, described later, investigates the updating of whole objects with a varying number of objects to be updated.

It was assumed that the latencies for updates are indirect measurements of the processes of interest. Differences in latencies were interpreted as differences in the underlying updating processes. There are different options how these processes could work:

First, it may be possible that the duration of updating the features of one object is independent from the number of changed features. Constant reaction times over the number of updated features would be the result of this kind of processing. This pattern of results would be expected for constant updating durations as well as for randomly varying updating durations.

In the visual domain, this hypothesis corresponds to results from Luck and Vogel (1997) indicating that integrated objects are stored in visual working memory. In their experiments, a change-detection-paradigm was used, where test stimuli were presented at the end of a trial and had to be compared with stimuli presented before. They found the same performance (accuracy in change detection) when two, four, or six objects with two features respectively were presented compared to two, four, or six objects with one feature respectively. The same results were obtained when features from different dimensions (color and orientation) and from the same dimension (color) were used. They extended their finding for features from different dimensions to objects with four features (color, orientation, size, and the presence or absence of a gap). When integrated objects are stored in visual working memory, it may be possible that representations of objects are replaced as a whole during an updating, even when only single features have to be changed. Luck and Vogel (1997) compare their results with verbal working memory where the number of chunks limits performance.

Wheeler and Treisman (2002) failed to replicate the results of Luck and Vogel (1997) when the features were from the same dimension (color). Furthermore, in experiments with color and location as features, they found that binding information was lost while feature representations remained. They tested for binding information in conditions where the test stimuli had the same feature values as the stimuli presented first, but re-paired in different combinations. According to these results, Wheeler and Treisman (2002) proposed a framework in which feature values from different dimensions are stored in parallel in dimension-specific stores with competition for limited capacity only within the stores, but not between. Binding information can be maintained if necessary in their framework and maintenance of bindings depends on other limited attentional resources than maintenance of features.

The conclusions of Wheeler and Treisman (2002) are supported by a series of experiments conducted by Xu (2002). Like in the studies described before, she investigated object-based feature encoding in visual short-term memory with the change-detection-paradigm. In these experiments, an object-based benefit was only observed when the two features of each object were from different dimensions (color and orientation), but not when they were from the same dimension (color or orientation).

The alternative hypothesis for the present experiments is that representations of objects are not replaced as a whole when a certain number of features changes with an updating. This hypothesis can be further divided into different forms. The features of one object could be updated in parallel or serially. Under the condition that the reaction time for the updating of one feature is a constant, parallel updating would result in the same pattern of reaction times as predicted from the first hypothesis. It seems more realistic to consider the reaction time for the updating of one feature as a random variable. When more than one feature of an object has to be updated, the entire updating process will be finished when the longest of the single updating processes (updating of single features) is completed. These assumptions lead to the prediction of increasing reaction times the more features have to be updated, but in a negatively accelerated form. This pattern of reaction times was derived from the results of simulations conducted with the corresponding assumptions. In these simulations, the latency for updating a single feature and the latency for the motor part of the reaction were assumed to be gamma distributed.

In contrast, serial updating would result in linearly increasing reaction times the more features are updated (both for constant and randomly varying feature updating latencies).

In the first experiment, visual material (geometrical objects consisting of different features) was used, and in the second verbal material (consonant-vowel-consonant-vowel-consonant-conjunctions).

2.1 Experiment 1: Updating of visual features

2.1.1 Method

2.1.1.1 Participants

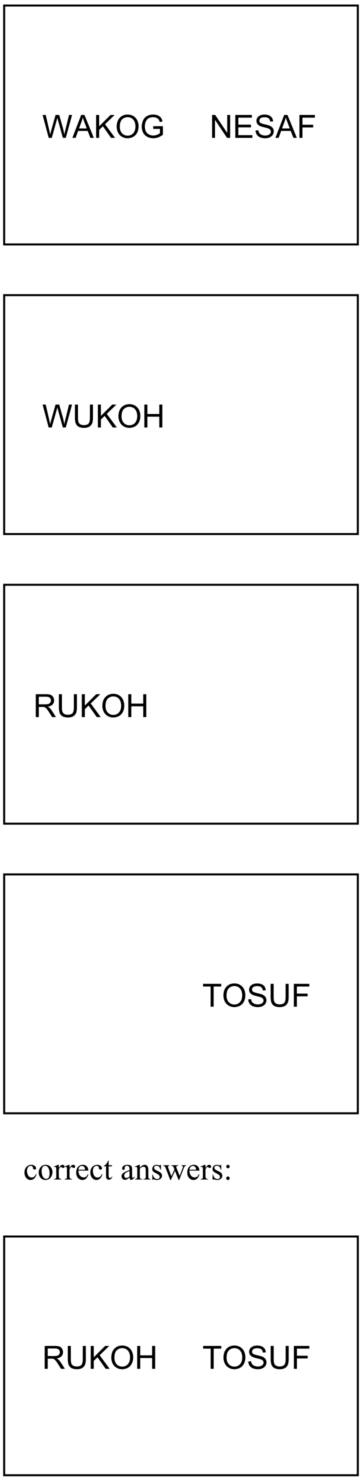
The original sample consisted of 25 adults, but the data of four persons were discarded. Two of them did not meet the criterion of at least 16 % trials with completely correct answers, the other two did not follow the instruction carefully in drawing the objects at the end of a trial with the result of unusable data. The mean age of the remaining persons was 24.1 years (SD 2.91; ranging from 20 to 30 years), 16 of them were female and 5 male. Every person received course credit or 6 Euro in return for participating in a one-hour session.

2.1.1.2 Apparatus, Stimuli, and Procedure

This and the following experiment were conducted in a quiet room on a Macintosh G 3 desktop computer with a Mac OS 9 operating system. Participants were tested individually. As stimuli, objects with four features, shape, size, color, and texture, were used. The shape could be a circle, a square, or a triangle. There were two different sizes, small and big. The colors used were yellow, pink, purple, and blue-green. They were chosen so that most people are able to distinguish these colors. The textures (in black) were dots, horizontal stripes, and crossed stripes. Furthermore, it was possible that an object had no texture.

At the beginning of each trial, two objects were presented on a black background, one on the left half of the screen, the other on the right half. The size of a small square was 3 × 3 cm, the size of a big square 6 × 6 cm. The radius of a small circle was 1.5 cm, the radius of a big circle 3 cm. A small triangle had a length and height of 3 cm, a big triangle had a length and height of 6 cm. The distance between two big stimuli was 8 cm, between two small stimuli 12 cm, and between a big and a small stimulus 10 cm. The features of the two objects were chosen randomly. Participants were instructed to look at these objects and remember them until an updating occurs. The presentation time was determined by the participant, pressing a key resulted in the presentation of an object on one of the halves of the screen, while the other half was black like the background. The object could be a different one or the same as the object presented before on the same position. The participant had to update his/ her memory representation by the current object, while for the other side, the object presented before still had to be kept in memory. In every updating cycle, it was determined randomly if the left or the right object had to be updated. It was also determined randomly if no, one, two, three, or four features changed with an updating cycle, which of the features changed, and which were the new values. The number of updating cycles in one trial varied between one and twenty. Within this range, the probability for another updating cycle was .9 after every updating cycle. At the end of a trial, subjects had to draw the last object from the left side and the last object from the right side on paper. They always started with the item from the left side. The procedure of this experiment is illustrated in Figure 1.

Every participant was tested on 32 trials, the first 4 trials were practice trials. The trials were separated by the trials of another experiment using verbal material, in a way that one trial of the feature updating experiment was followed by one trial of the other experiment. Verbal proactive interference/ proactive facilitation were investigated in the other experiment. This kind of combination should minimize proactive interference, if present, between the trials of one experiment.



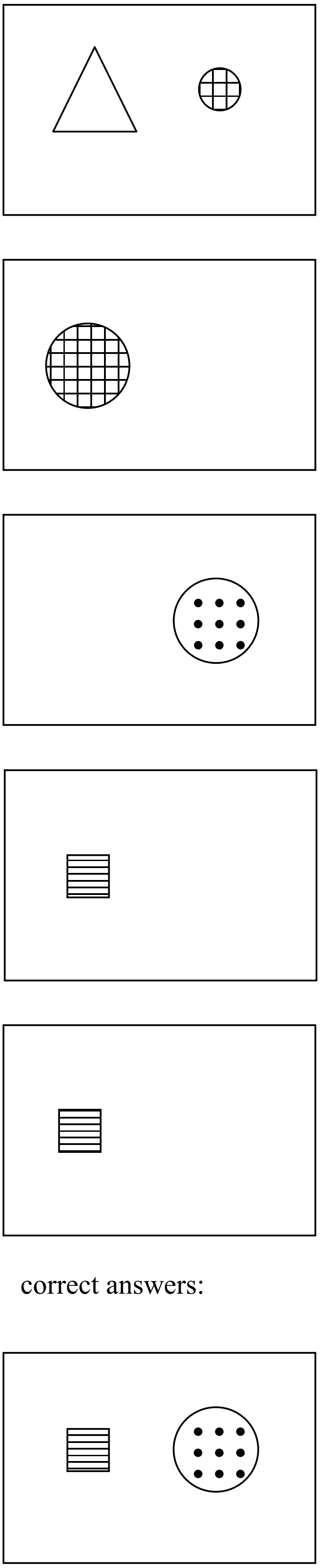


Figure 1. Procedure of the feature updating experiments (example of a trial with CVCVC-conjunctions on the left side, one with geometrical objects on the right side). Successive items presented on the computer screen can be seen here from top to bottom. Correct answers which had to be produced by the subjects are shown here at the end of an example.

2.1.2 Results

It is possible that there are some trials in which subjects did not work carefully, for example in which they did not pay attention to some updated items but continued to press a key to start the next updating. To exclude these trials from the analyses, only trials with completely correct answers were analyzed in this and in the following experiments. Subjects reached on average a level of 45.07 % completely correct trials, with a range from 17.86 % to 96.43 %. Additionally, analyses of all trials, including trials with errors, were conducted. The results of these analyses are only reported when they differ in respect of the significance decision from the results of the analyses of trials with completely correct answers.

Furthermore, reaction times shorter than 200 ms and reaction times longer than an individual's mean plus three standard deviations were excluded from the analyses. 1.6 % of the data were excluded as outliers.

All significance tests in this and in the following experiments were conducted with an alpha level of .05. In all experiments, error bars were computed according to Bakeman and McArther (1996) with an adjustment for between-subjects variability in a within-subjects design. The deviation of a subject's mean across repeated measures from the grand mean for all scores was subtracted from the raw scores of that subject. These error bars are based on separately computed confidence intervals for every cell mean.

Figure 2 illustrates the resulting reaction times as a function of the number of updated features. Repeated contrasts were conducted to compare the reaction times between two successive conditions respectively. Reliable differences appeared between the latencies for the condition with no feature updated and one feature updated, $F(1, 20) = 11.06$, $p < .01$, partial $\eta^2 = .36$, and between the latencies for the condition with one feature updated and two features updated, $F(1, 20) = 18.22$, $p < .01$, partial $\eta^2 = .48$. There was no other significant difference, neither between the latencies for the condition with two features updated and three features updated, $F(1, 20) = .81$, $p = .38$, partial $\eta^2 = .04$, nor between the latencies for the condition with three features updated and four features updated, $F(1, 20) = .90$, $p = .35$, partial $\eta^2 = .04$.

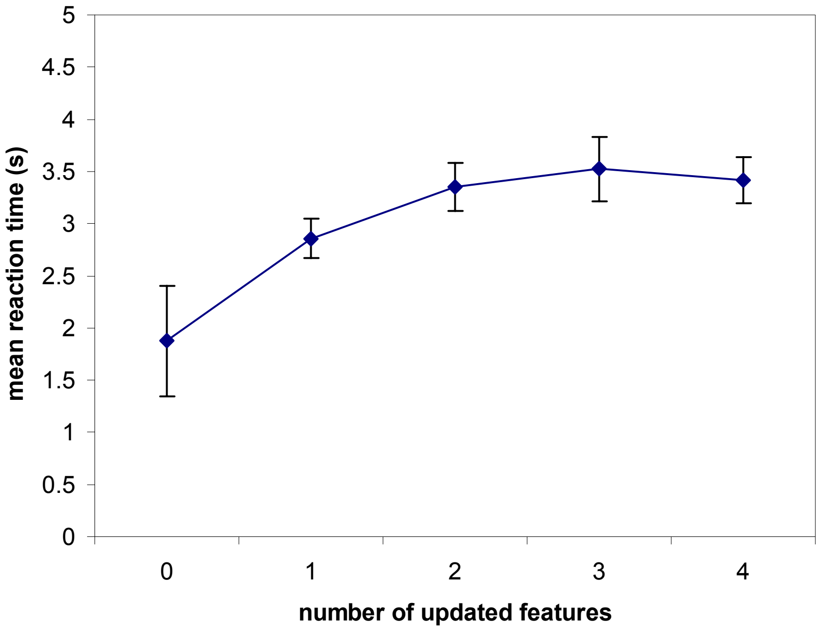


Figure 2. Effect of number of updated features on latencies, first feature updating experiment. Error bars represent 95 % confidence intervals.

Results of the analyses of all trials, including trials with errors, were consistent with the results reported before, except that latencies for the condition with two features updated were reliably shorter than latencies for three features updated, $F(1, 20) = 5.67$, $p < .05$, partial $\eta^2 = .22$.

2.2 Experiment 2: Updating of verbal features

2.2.1 Method

2.2.1.1 Participants

20 adults with a mean age of 23.45 years (SD 2.7, ranging from 20 to 29) participated in the experiment, 16 of them were female and 4 male. The original sample consisted of 2 more persons, but their data were excluded because of performance below the criterion of at least 16 % trials with completely correct answers. Subjects received course credit or 6 Euro in return for their participation in an one-hour session.

2.2.1.2 Apparatus, Stimuli, and Procedure

The stimuli of this experiment were consonant-vowel-consonant-vowel-consonant-conjunctions (CVCVC-conjunctions), selected for presentation in the following way: The first consonant was chosen randomly from a set of four consonants: W, T, N, R. For the second consonant, this set consisted of the letters S, K, M, L and for the last consonant, the set contained the letters F, G, H, and P. Both vowels were chosen randomly from the same set, A, E, O, and U. The selection of these sets of consonants and vowels resulted in very few conjunctions similar to real words, so that only six conjunctions had to be excluded because of similarity to real words.

At the beginning of each trial, two conjunctions were presented, one on the left half of the screen, the other on the right half. The text size of the conjunctions was 2.8 cm and the text font was Arial. The pair of stimuli was centered on the screen with a distance of 3.5 cm between them. The color of the letters was white on a black background.

The procedure of this experiment was the same as in the first feature updating experiment (see Figure 1, left side), only the reproduction of the latest items from both sides differed. The CVCVC-conjunctions had to be typed, first the one from the left side, then the one from the right side.

It has to be noted that the number of features of one item was four in the experiment with geometrical objects and five in the experiment with CVCVC-conjunctions. These numbers were also the maximum numbers of features that could change in one updating cycle. They were chosen to adjust the difficulty of the tasks with different materials.

Again, every participant was tested on 32 trials with the first 4 of these as practice trials. This time, the experiment was combined with a spatial proactive interference/ proactive facilitation experiment (one trial from the CVCVC-experiment was followed by one trial of the other experiment) for the same purpose as before, minimizing proactive interference between the trials of one experiment, if present.

2.2.2 Results

Like in the visual feature updating experiment, in the first analysis, only trials with completely correct answers were analyzed. On average, these were 46.25 % of all trials, ranging from 17.86 % to 75.00 %. Outliers were determined according to the same criteria as before, resulting in an exclusion of 1.6 % of the data.

As can be seen in Figure 3, the results of the repeated contrasts conducted to compare reaction times between two successive conditions mirrored the results of the experiment with geometrical objects. The difference between latency for the condition with no feature updated and one feature updated was significant, $F(1, 19) = 26.68$, $p < .01$, partial $\eta^2 = .58$, as well as the difference between latency for the condition with one feature updated and two features updated, $F(1, 19) = 17.46$, $p < .01$, partial $\eta^2 = .48$. All other results were far from significance, the difference between latency for the condition with two features updated and three features updated, $F(1, 19) = .22$, $p = .65$, partial $\eta^2 = .01$, the difference between three features updated and four features updated, $F(1, 19) = .40$, $p = .54$, partial $\eta^2 = .02$ and the difference between four features updated and five features updated, $F(1, 19) = .53$, $p = .47$, partial $\eta^2 = .03$.

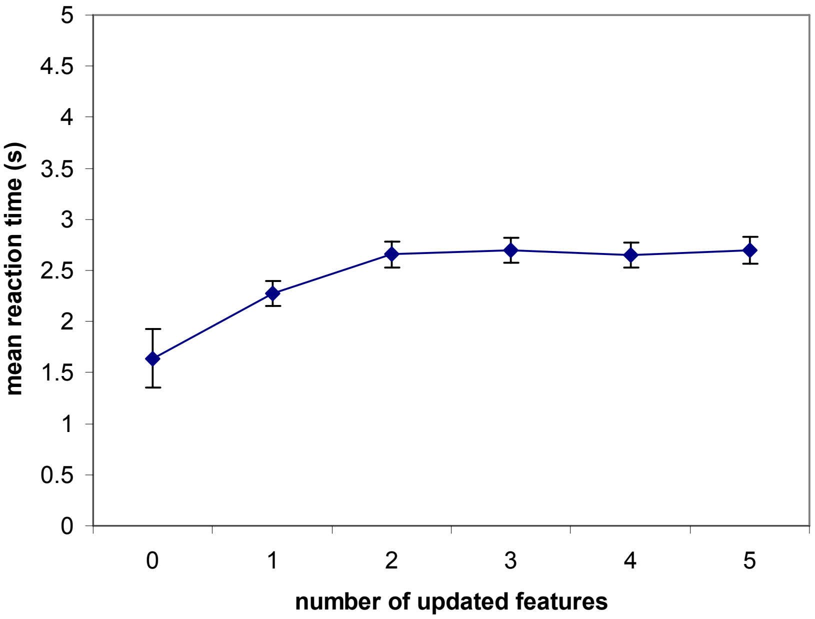


Figure 3. Effect of number of updated features on latencies, second feature updating experiment. Error bars represent 95 % confidence intervals.

2.3 Discussion Experiments 1 and 2

In both experiments, neither a linear trend, predicted by the hypothesis of sequential feature updating, nor a flat line, predicted by the hypothesis of parallel feature updating with a constant duration of every single feature updating process and by the hypothesis of integrated object updating, emerged. The process of updating one feature of an object compared to no feature updating resulted in longer latencies and the updating of two features needed more time than the updating of one feature. Reaction times for higher numbers of features to be updated did not increase further. The results can be best explained by assuming parallel updating of the object features, with a randomly varying duration of every single feature updating process. Another possible explanation for the results is that when two features or more had to be updated, an object/ CVCVC combination was replaced as a whole instead of the replacement of single features.

No material specificity of the process of feature updating was found here, the results with features of geometrical objects to be updated were almost perfectly echoed by the results of the second experiment with verbal material. It is possible that the features of the geometrical objects were encoded verbally, for example an object could have been represented as a “big, yellow circle with no texture”. In this case, results from the two feature updating experiments would be a replication within the same domain.

One problem concerning all updating experiments of this kind is that correct answers at the end of a trial are possible even when the subject did not pay attention/ did not devote enough time for complete updates in some updating cycles/ cycles before. Some of the correct answers may result by chance obscuring that the subject was not attentive in these trials to some or all of the features/ objects to be updated. However, the resulting latencies for this case should not depend on the number of features/ objects to be updated and therefore diminish the systematic effects found here. The strategy to include only the completely correct trials is already conservative, because it can be assumed that subjects made complete updates almost all the time but failed to remember all features/ objects at the end of a trial. The probability that a trial stops was a constant at every point in the trial, so that subjects should have been motivated to pay attention to every new stimulus.

3 Experiment 3: Updating of verbal and spatial objects

In the last experiment of this series, whole objects had to be updated. Two different kinds of material were used, verbal and spatial. The design was the same as in the two feature updating experiments, except that now whole objects took the role of the features in the previous experiments. The goal of this experiment was to investigate if feature and object updating are similar processes or differ from each other. One hypothesis was that whole objects can not be updated in parallel in contrast to features because they are more complex than single features. The contrary hypothesis seems plausible, too, because an arrangement of several objects could be perceived as a whole like a single object with features.

3.1 Method

3.1.1 Participants

Fifteen female undergraduate students took part in the experiment which was divided into two one-hour sessions on different days. For the analysis of spatial material, the data of two participants were excluded because of very poor performance (less than 16 % of the trials with completely correct answers). The mean age of the whole sample was 25.33 years (SD = 3.66, ranging from 20 to 32 years), the mean age of the reduced sample was 25.69 years (SD = 3.79, ranging from 20 to 32 years). Participants received course credit or were paid 12 Euro.

3.1.2 Apparatus, Stimuli, and Procedure

Participants were tested individually in a quiet room on a Macintosh G 4 computer with a Mac OS 9 operating system.

The verbal items consisted of 20 German words from five categories, kinds of fruits, tools, furniture, clothes, and animals. All words consisted of two syllables and were chosen by the constraint that every syllable appeared only once in the whole set of 20 words. As spatial material, 16 objects were constructed from a three x three dot arrangement, in which three dots were connected by lines, resulting in simple drawings of two connected lines. These spatial objects were classified into four categories depending on shape. The angle between the two lines (one vertical and one horizontal) was 90° for all objects of the first category. The second category contained objects with an angle of 45° between the two lines (one vertical or horizontal and one diagonal). The third category consisted of objects with an angle of 135° between the two lines (one vertical or horizontal and one diagonal). The angle between the two lines (both diagonal) was 90° for all objects of the fourth category. The color of all presented items was white and they were presented on a black background.

The procedure of this experiment is illustrated in Figure 4. Each trial with verbal material started with the presentation of five words, one word from every category. The five words were arranged equidistantly on a centered virtual circle with a radius of 7.5 cm. The size of one word was 4-6 cm × 2 cm, depending on its length. Participants determined the presentation time by pressing a key when they were ready for an updating cycle. With every updating cycle, again five words from the five categories were shown. Words from one category always appeared on the same position. Every word could be the same or different from the word shown on the same position in the previous updating cycle. By this way, the stages of the independent variable, number of updated objects, were realized. The stages of the independent variable varied from no object to be updated to five objects to be updated. At the end of every trial, the whole set of 20 words appeared on the screen and participants had to indicate the five words which were presented in the last updating cycle by clicks with the computer mouse. For this presentation of the whole set of words, the categories were separated corresponding to their positions on the virtual circle before during the updates, and the words of one category were presented in smaller form than before line by line.

Words were chosen randomly for presentation, and the number of words to be updated in every updating cycle was also determined at random. The number of updating cycles in one trial varied between 1 and 20 and was determined again randomly. Like in the previous experiments, participants had to pay attention to the items of all updating cycles because they did not know after which updating cycle the trial ended and which items had to be recalled.

The procedure in the trials with spatial material was the same as in the trials with verbal material, but only four spatial objects were presented instead of five words. These different set sizes were chosen because Oberauer, Lange, and Engle (2004) found approximately the same percent correct rates for these different set sizes in a memory recall task with similar materials. Spatial objects were presented equidistantly on a centered virtual circle with a radius of 7.5 cm. The size of one pattern was 3.3 cm × 3.3 cm. At the end of a trial, the whole set of spatial objects was presented and subjects had to reproduce the latest items from every position through clicks with the computer mouse. The four items of one category were presented in smaller form than before in two lines on the position corresponding to that category during the updating cycles.

One trial with verbal material was followed by one trial with spatial material. Each session consisted of 32 trials with verbal material and 32 trials with spatial material. For verbal and spatial material respectively, trial one to four from the first session were training trials which were not included in the data analysis.

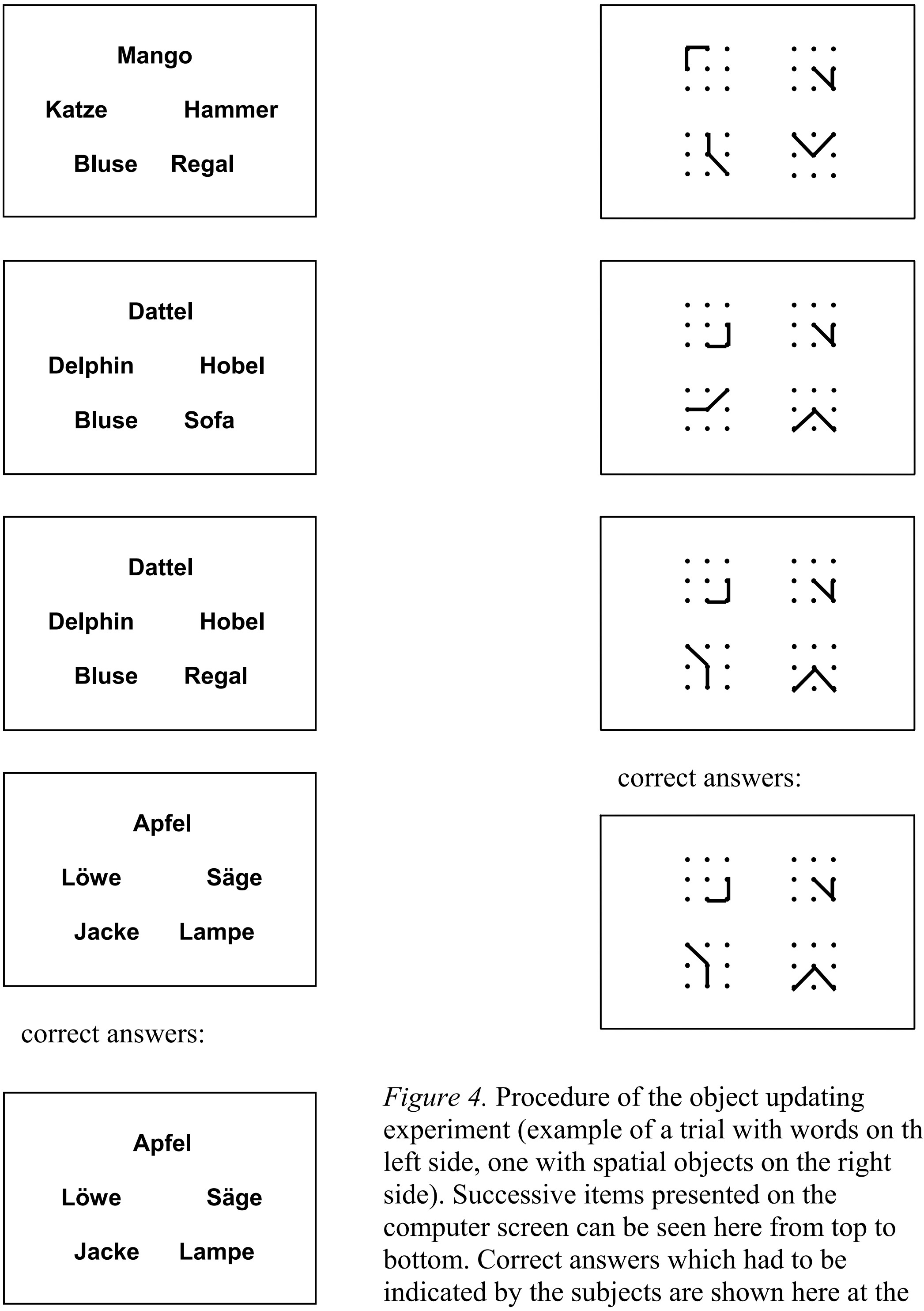


Figure 4. Procedure of the object updating experiment (example of a trial with words on the left side, one with spatial objects on the right side). Successive items presented on the computer screen can be seen here from top to bottom. Correct answers which had to be indicated by the subjects are shown here at the end of an example.

3.2 Results

For the same reason as in the experiments before, only trials with completely correct answers were included in the first analyses. In this experiment, subjects reached on average a level of 74.67 % completely correct trials, with a range from 33.33 % to 93.33 %, concerning verbal material. With spatial material, mean performance was 43.97 % completely correct trials, ranging from 16.67 % to 78.33 %.
Like in the feature updating experiments, reaction times shorter than 200 ms and reaction times longer than an individual's mean plus three standard deviations were excluded from the analyses. The percentages of outliers were 1.7 % for verbal data and 1.9 % for spatial data.

The results of the repeated contrasts between the latencies of two successive conditions are illustrated in Figure 5. With verbal material, the first three contrasts were significant, the difference between the latency for the condition with no object updated and one object updated, $F(1, 14) = 26.68$, $p < .01$, partial $\eta^2 = .66$, the difference between one object updated and two objects updated, $F(1, 14) = 16.50$, $p < .01$, partial $\eta^2 = .54$, and the difference between two objects updated and three objects updated, $F(1, 14) = 14.51$, $p < .01$, partial $\eta^2 = .51$. No reliable difference could be found between three and four objects updated, $F(1, 14) = .35$, $p = .56$, partial $\eta^2 = .03$. The difference between four and five objects updated was not significant either, $F(1, 14) = 1.34$, $p = .27$, partial $\eta^2 = .09$.

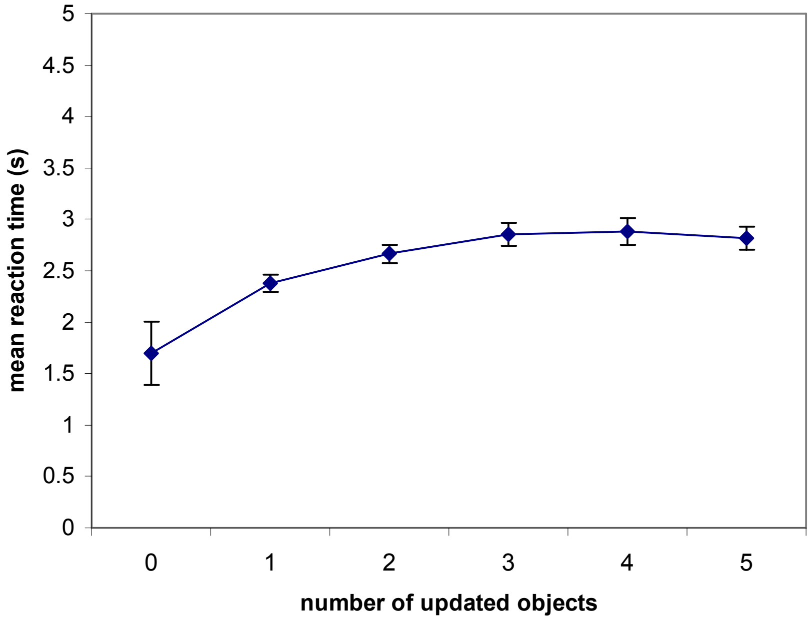


Figure 5. Effect of number of updated objects on latencies, verbal material. Error bars represent 95 % confidence intervals.

The results of the repeated contrasts conducted to compare reaction times between two successive conditions for spatial material (see Figure 6) are consistent with the results obtained for verbal material. The first three contrasts were significant, the difference between latency for the condition with no object updated and one object updated, $F(1, 12) = 51.32$, $p < .01$, partial $\eta^2 = .81$, the difference between one object updated and two objects updated, $F(1, 12) = 7.03$, $p < .05$, partial $\eta^2 = .37$, and the difference between two objects updated and three objects updated, $F(1, 12) = 11.74$, $p < .01$, partial $\eta^2 = .50$. No reliable difference emerged between three and four objects updated, $F(1, 12) = .11$, $p = .75$, partial $\eta^2 = .01$.

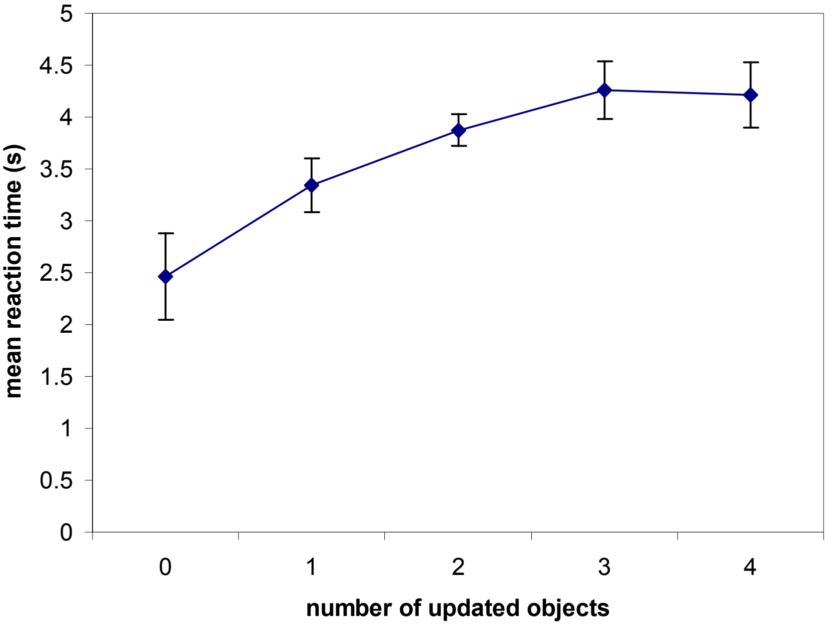


Figure 6. Effect of number of updated objects on latencies, spatial material. Error bars represent 95 % confidence intervals.

3.3 Discussion

The results with spatial material mirror those with verbal material. Furthermore, these results are very similar to those from the feature updating experiments with the difference that reaction times for three objects to be updated were reliably longer than reaction times for two objects to be updated. Like the process of updating object features, the updating of whole objects seems to be executed in parallel with a randomly varying duration of a single object updating process. The alternative explanation, replacement of the whole arrangement of objects for higher numbers of objects to be updated, has to be considered here, too. This process might be easier/ more economic when a higher number of single updates have to be made, but it is unlikely that people are able to make such complex replacements like the replacement of an arrangement of five words or four spatial objects at once. Such a cognitive process would require that people have long-term-memory representations consisting of five randomly selected words/ four randomly selected spatial objects which can be positioned in working memory as a whole.

The results of this experiment seem to reflect basic cognitive processes valid for different (at least two) kinds of material. A verbal encoding of the spatial objects was unlikely, because it is not easy to name these objects.

The experimental design of the object updating experiment differed from those of the feature updating experiments in the following points: In the experiments with updating of object features, two objects had to be remembered, each consisting of four or five features. One updating cycle involved a certain number of features of one object. In the object updating experiment, four or five objects had to be remembered and one updating cycle involved a certain number of these objects. Furthermore, in the feature updating experiments, subjects had to reproduce (drawing or typing) the latest items for each position, while in the object updating experiment, all possible answers were presented on the screen and subjects had to indicate their answers through clicks with the computer mouse. I assume that these differences did not influence the results in a significant way and that the results of both designs are comparable with each other. This assumption is supported by the similarity of the data across all experiments.

4 General Discussion Experiments 1, 2, and 3

The present series of experiments was designed to examine an aspect of the working memory updating process which had not been considered before. While the first two experiments addressed the question if several features of objects are updated in parallel or serially, or if they are upated by a replacement of the whole object, the last experiment investigated the same question with whole objects now taking the role of the features in the experiments before. Results from all experiments supported two different hypotheses, the hypothesis of parallel feature/ object updating with randomly varying single updating latencies, as well as the hypothesis of whole object/ whole arrangement replacement (the latter only for higher numbers of features/ objects to be updated). Although no clear interpretation in favor of one hypothesis was possible, the present findings provide strong evidence that the hypothesis of serial feature/ object updating can be ruled out. This is an important step in the investigation of the process of updating several features/ objects. In future research, results which can decide between the two remaining hypotheses would be useful.

Further progress in the investigation of the binding issue, the question how features are bound together to one object when they are encoded and stored in working memory, may help to develop precise hypotheses about how single feature representations as part of whole object representations are replaced by newer ones. Raffone and Wolters (2001) suggest that synchronized oscillations of groups of neurons, each group coding one feature, could be the mechanism in visual cortex which accomplishes the binding of features to one object in working memory. Updating a single object feature would require that the oscillations of the neuron group coding the feature which has to be replaced are desynchronized from the oscillations of the neuron groups coding the other object features, while the oscillations of the neuron group coding the new feature are synchronized with them.

Another important point to note is that feature and object updating seem to be very similar cognitive processes. One reason for this finding could be that an arrangement of objects is perceived as a chunk of objects corresponding to an object as a chunk of features. It was already discussed before that an arrangement of five words/ four spatial objects like in the experiment described here seems to be too complex for such an integrated replacement.

The stagnation of reaction times from three objects to be updated onwards instead from two features to be updated onwards could have resulted from a greater variance in single object updating latencies compared to single feature updating latencies, as can be shown in simulations.

Results were also consistant over different kinds of material (verbal and visual features, verbal and spatial objects), indicating that they addressed a basic aspect of the cognitive process of updating contents in working memory. In future research, it would be interesting to see if the consistency of these results can be extended to other updating tasks/ paradigms.

Altogether, the results of the present experimental series are a further step in the investigation of the working memory updating process. When other aspects of this cognitive process will be examined, a model of working memory updating could be constructed and incorporated in established working memory models. By this way, more precise predictions about the relation of updating to other working memory processes and about its role in higher cognitive processes could be made.

A connectionist model may help to understand how the feature updating process itself works. Connectionist models are a method of simulating complex cognitive processes by implementing assumptions about how the processes function and by comparing the results of the model behavior with empirical data.

This point is illustrated in a simplified form in Figure 7. One feature is represented by one node in the feature layer, one object by one node in the object layer, and an object position is represented in the position layer. Encoding an object presented on one side of the screen would result in an activation of the corresponding feature, object and position nodes (black nodes), which provokes a strengthening of all connections between two nodes activated at the same time. When the next object with some features differing from the previous object is encoded for the same position, the corresponding nodes are activated in this model. Connections which are now between two activated nodes would be strengthened, all other connections would loose strength. A connection to be strengthened would reach a given strength threshold after a certain (randomly varying) time interval (dotted lines), whereas the strength of the connections relevant at the encoding of the first and the second object would remain above this treshold. When the strength of all currently relevant connections is above the threshold, the updating process would be completed. The final model state is illustrated in Figure 8. In both figures, only relevant and excitatory connections are represented.

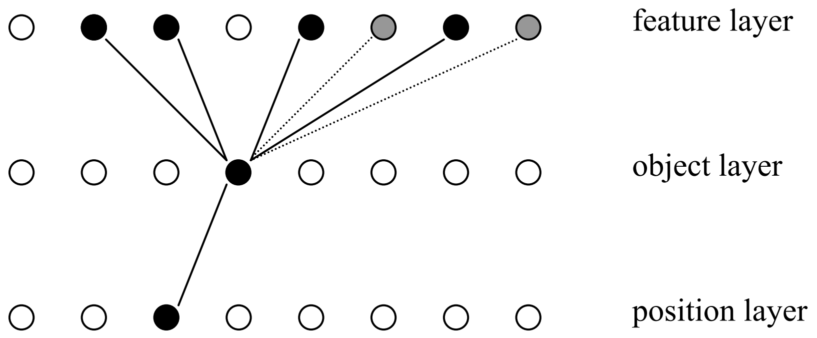


Figure 7 . Scheme of a connectionist network modelling the updating of features in an object representation.

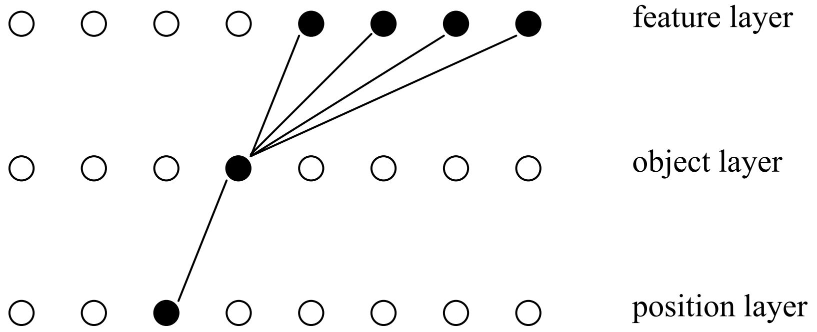


Figure 8 . State after the updating of two features of the object representation.

5 Proactive interference in working memory- new aspects within a new paradigm

The cognitive operation of updating memory representations is closely related to the phenomenon of proactive interference: Updating a representation involves replacing a representation which is no longer relevant, so that the success of an updating process can be defined by the extent of proactive interference originating from the old representation. Proactive interference means that learning/ memory contents are negatively influenced by prior learned material.

Wickens, Born, and Allen (1963) used the Brown-Peterson-Paradigm with lists composed of consonant-trigrams and lists composed of digit-trigrams. Every trial consisted of one trigram which had to be recalled after presentation. Independent variables were immediate recall versus a retention interval of 11 s and change of material versus repetition of material. Immediate recall did not result in a performance difference between the conditions with material repetition and material change. With recall after a retention interval of 11 s, during which participants had to name colors, proactive interference occurred after repetition of material but not after change of material. Assuming a short duration (some seconds) of short–term-memory, this result can be interpreted as evidence for the hypothesis that the contents of short-term-memory are not influenced by proactive interference of older, now irrelevant representations. Since there are different conceptions about the duration of short-term-memory, it is debatable if the items to be remembered were not in short-term-memory anymore after the retention interval of 11 s.

Cowan, Johnson, and Saults (2005) found evidence for the same hypothesis in a speeded recognition task. They used the Sternberg-task with lists of words, each list contained words from one category. In every trial, one list had to be stored in memory and subsequently, a probe item was presented. Subjects had to judge whether the probe item had been shown before in the list. Cowan et al. (2005) realized a condition with a high amount of proactive interference (the same category used in successive lists) and a condition with a low amount of proactive interference (no repetition of categories in successive lists). Presentation mode (sequential versus concurrent) and the number of words in a list were also varied, there were lists with three, four, six, and eight words. Proactive interference appeared mainly in target absent trials and when working memory capacity was exceeded (lists with more than four words). These results appeared in the analysis of percent correct responses, as well as in the analysis of reaction times. It has to be noted that ceiling effects concerning the percentage of correct responses occurred with list lengths three and four.

In an earlier experiment, Halford, Maybery, and Bain (1988) made a similar high/ low amount of proactive interference manipulation (semantic and rhyming categories in different experiments) and found proactive interference effects for lists of ten items but not for lists of four items. Monsell (1978) and McElree and Dosher (1989) found some proactive interference on target-absent trials with set sizes of two and three items. Presentation rate and mode of presentation (sequential/ concurrent) differed between the Halford et al. (1988) experiments on one side and the experiments of Monsell (1978) and McElree and Dosher (1989) on the other side. Presentation rates were similar in the experiments of Halford et al. (1988) (1.2 s / 1.5 s per item in the list, plus 1 s more per list) and Cowan et al. (2005) (1.5 s), but shorter in the other experiments (.5 - .7 s per item).

Contrary to the results reported above, evidence for proactive interference in working memory comes from an experiment of Lustig, Hasher, and May (2001). Using the reading span task, they found better performance of subjects when another task with different material was done between the trials of the reading span task. The reading span task requires subjects to read some unrelated sentences and recall the final words of the sentences at the end of a trial, whereby the number of sentences in one trial increases during the task. The interpretation of the results is controversial, too, it can be argued that information is partly recalled from long-term-memory in the reading span task. The duration of reading some sentences may exceed the time contents remain in working memory.

When the results of different experiments are compared with each other, it has to be considered that authors may have different theoretical conceptions of working memory duration and capacity and that the interpretation of the experimental results depends on their conceptions.

Another problem has to be considered using the term proactive interference: The definition of this term does not specify when the effect occurs. It could occur when information is encoded, when it is stored, or when it is recalled (Dillon, 1973).

Bellezza (1982) investigated the updating of temporary bindings between list words which had to be remembered and peg words given as part of a mnemonic device. Once a binding has been updated and is not relevant anymore, it could be dissolved or it could still provoke proactive interference with a negative effect on recall of the new binding between a peg-word and a list word. In this case, the new bindings have to be differentiated from older ones.

The author found that the time of occurrence of an event is an important factor in memory search and retrieval and that the temporal distinctiveness of the item presentation predicts recall success. In one of his experiments, subjects had to use the peg-word mnemonic for learning the same set of 16 words in three different orders (list 1 to list 3). After presentation of the last peg-word and the last item of a list, a test of that list followed. A peg word was presented and subjects had to answer with the list word most recently paired with the peg word. Bellezza (1982) supposed that the time of learning a certain list is encoded and serves as a cue which enables subjects to give the correct answer and not the answer corresponding to a previous list.

In the experimental condition, presentation and testing of the third list was divided into four parts. This mode of presentation was supposed to disrupt a temporal organization and therefore make subjects more susceptable to proactive interference from older bindings which are not relevant anymore than the normal presentation mode in the control condition. Mean retention interval and number of new pairings were equated for control and experimental group. No difference in the proportion of correctly recalled words was found between experimental and control group for the lists 1 and 2. In both groups, a significant decrease in performance occurred from list 1 to list 2. For list 3, performance was significantly worse in the experimental than in the control condition.

Kane and Engle (2000) compared high and low working memory span participants concerning susceptibility to proactive interference in conditions with and without attentional load. The task measuring susceptibility to proactive interference consisted of recalling words of different lists. The first three lists in one trial contained words from the same category, whereas the words from the last list belonged to another category than the first three. A retention interval of 16 s, during which participants had to perform a combined letter-number counting task, preceded the recall phase. Subjects were required to complete a tapping task simultaneously with the proactive interference task. The tapping task was complex in the load condition and simple in the no load condition. While low spans showed greater proactive interference than high spans in the no load condition, no difference occurred in the load condition. The authors conclude from these results that high spans used attention to avoid proactive interference in the no load condition, which is not possible when attention is already consumed by a complex second task (load condition).

The hypothesis that subjects are able to make updates of their working memory contents without much interference from older representations, at least as long as working memory capacity is not exceeded, can be applied to temporary bindings in working memory, too. Temporary bindings play an important role in a framework for the architecture of working memory of Oberauer (2002). According to this framework, working memory consists of three components, the activated part of long-term memory, the region of direct access, and the focus of attention. The first component contains those representations which are activated above baseline through perceptual input or through spread of activation from other representations. A subset of these representations is bound to positions in a mental coordinate system. This subset is described as the region of direct access. The focus of attention is embedded within the region of direct access and holds only that representation which is needed next for a current cognitive operation. In long-term memory, we speak of associations in contrast to bindings in working memory, because they may differ from each other. Building, consolidation, and updating of a representation in long-term-memory needs time and proactive interference is found (Ericsson & Kintsch, 1995). Proactive interference in long-term memory is due to the amount of similar contents from which a certain representation has to be differentiated for retrieval.

In contrast, some authors assume working memory contents to be protected from proactive interference of long-term structures. Such protection would offer the possibility to build new structures in working memory which differ from contents already in long-term memory. Another difference to long-term memory is that working memory tasks require fast manipulations and updates of representations/ bindings. Consequently, these should be fast and easily executed, without proactive interference from irrelevant representations/ bindings, which have been in working memory before the updating. A part of this hypothesis is supported by experiments of Oberauer (2001, 2002) which show that contents can be quickly removed from the region of direct access, probably through dissolution of the bindings.

6 Conception Experiments 4 and 5

The experiments reported here used the memory-updating paradigm, originally introduced by Yntema and Mueser (1962), which offers the possibility to investigate proactive interference between temporary bindings with a new method. In the memory-updating task, elements have to be updated, which are bound on locations. With reaction time for an updating cycle as dependent variable, it is possible to test if the bindings between a stimulus and the corresponding location are directly and completely dissolved when an updating occurs.

If a binding stays for a while even when an updating already occurred, a new presentation of the same stimulus on the same location should result in shorter reaction times compared to the presentation of a stimulus never presented before. The more time elapses between the previous occurrence and the later repetition of a certain stimulus on a certain location, the more the represented binding from the first presentation should lose strength and updating times should be less shortened. Shortened updating times caused by the repeated presentation of a stimulus on the same position can be termed proactive facilitation, indicating a positive effect of previously memorized information on performance contrary to the negative effect of proactive interference.

No difference between updating times for new stimuli and already presented ones would be evidence for direct and complete dissolution of temporary bindings through updating.

We must distinguish two cases here, the repeated presentation of a stimulus on the same location as before or on another location. If the effect of shortened updating times occurs for both of these cases, it would indicate residual activation of the representation of that stimulus, independent of the binding to a certain location. This case could be designated as repetition priming. Repetition priming can be described as a facilitation of performance on a stimulus (for example reaction times for naming words) which has been already presented before. This effect can even be unconscious to the subject (see Ashcraft, 2006).

Different effects for the same location and another location would indicate that temporary bindings in working memory stay, at least for a while, even when they are not relevant anymore. Different effects could be reduced reaction times with repetition of a stimulus on the same location, combined with increased reaction times for repetition relative to another location, as well as reduced reaction times with repetition on the same location, combined with no effect for repetition relative to another location. No effect for repetition relative to another location would mean that representations on another location do not influence processing on the current location at all because of the maintained bindings, whereas increased reaction times for repetition relative to another location would indicate proactive interference, caused by a binding representing conflicting information relative to the binding representation which has to be constructed at that moment.

The working memory task used in the present experiments has advantages compared to the tasks used before in other studies. Proactive facilitation/ interference can be investigated directly when temporary bindings are built and dissolved thus clearly locating the effect to the encoding stage. It has to be noted that previous studies focused on proactive interference on individual contents, whereas the present experiments examine proactive facilitation/ interference on temporary bindings between a stimulus and a location representation. The proactive facilitation/ interference effects investigated here should take place within a short time interval, because repetitions of stimuli are considered which are separated in time by zero to three updates. Therefore I suppose that recall from long-term memory has no or less influence than in tasks used in previous studies.

6.1 Experiment 4

6.1.1 Method

6.1.1.1 Participants

The sample consisted of 22 adults (mean age = 24.18 years; SD = 2.87; ranging from 20 to 30 years; 17 females and 5 males). Three additional persons belonged to the initial sample, but they did not meet the criterion of at least 35 % completely correct trials and therefore, their data were discarded. Subjects received course credit or 6 Euro for their participation in a one-hour session.

6.1.1.2 Apparatus, Stimuli, and Procedure

This and the following experiments were conducted in a quiet room on a Macintosh G 3 desktop computer with a Mac OS 9 operating system. Participants were tested individually. The consonants B, C, D, F, G, presented as capital letters, formed the stimulus set. At the beginning of each trial, two consonants were presented, one on the left half of the screen, the other on the right half. The distance between the two stimuli was 8 cm. Distances between a stimulus and upper and lower edge of the screen were equal, and distances between the left stimulus and the left side of the screen and between the right stimulus and the right side of the screen were equal. Text font was Arial and text size 4 cm.

The procedure of this experiment is illustrated in Figure 10. The two initially presented consonants were chosen randomly. Participants had to remember these consonants until an updating occurred. When participants pressed a key, one consonant appeared on one of the halves of the screen, while the other half was black like the background. The consonant could be different or the same as the consonant presented before on the same position. Participants had to update their memory representation by the current consonant, while for the other side, the consonant presented before still had to be remembered. The number of updating cycles in one trial varied randomly between one and twenty to assure that subjects did not know when a trial finished and consequently paid attention from the beginning of a trial. In every updating cycle, it was determined randomly if the left or the right consonant had to be updated. A successive updating on the same side for at least two times was distinguished from a switch of the side on which the updating occurred (independent variable object switch vs. no object switch).

At the end of a trial, subjects were instructed to type the last consonant presented on the left side and the last consonant presented on the right side.

Another independent variable of this experiment was lag to the same position on the screen, measured in number of updating cycles between the presentation of a certain consonant and the last updating cycle in which the same consonant was represented in working memory for the same side. The last updating cycle in which the same consonant was represented in working memory can differ from the last updating cycle in which the same consonant was presented on the screen because a certain consonant representation has to remain in working memory until an updating is required by the task on the corresponding side.

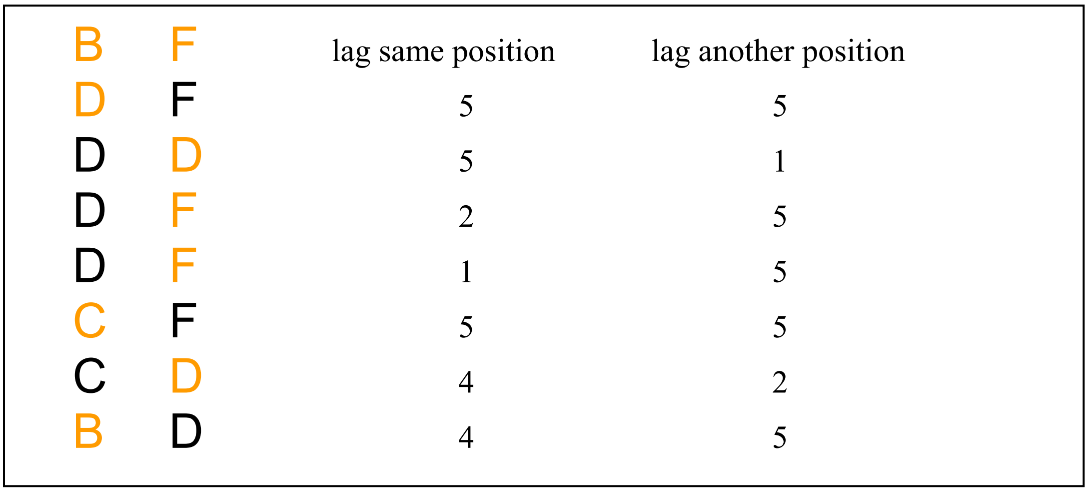
The third independent variable was lag to another position on the screen. In this and in the following experiment, there was only one other position, in the last experiment, there were more than one other position. In all experiments, the variable will be called lag to another position on the screen to have the same name across experiments. Within the independent variables lag to the same position on the screen and lag to another position on the screen, five categories were differentiated: Lag 1 to the same position describes the case that the actual consonant is still represented in working memory for the same position. Lag 2 to the same position occurs when a certain consonant was represented in working memory for the same position before the last two updating cycles, that means the representation has been replaced for one cycle by the representation of another consonant. In the case of lag 3 to the same position the representation of the actual consonant was the same on the same position three updating cycles before and has been replaced two times by the representation of another consonant. Lag 1 to another position on the screen means that the actual consonant is the same as the one still represented in working memory for another position since the last updating cycle (this one was not updated during the last cycle because only one consonant is updated in every cycle). The lag 4 categories (to the same position and to another position) include higher lags, too, because higher lags do not occur very often. When a consonant is presented for the first time in a certain trial, lag category 5 is assigned (again separately for the same position and another position).

The assignment of the different lag categories is described in Figure 9. The light consonants are those which are actually presented, whereas the dark ones are working memory representations. The first line contains the two consonants shown together at the beginning of a trial, in this example B for the left side and F for the right side. In the first updating cycle of this example, the B on the left side has to be replaced by a D, for the right side the working memory representation stays the same. On the right side of the figure, the values of the two kinds of lags can be seen. They always refer to the letters actually presented. In the first updating cycle, the letter D presented on the left side has a lag of 5 to the same position on the screen as well as to the other position on the screen. In the second updating cycle of this example, the letter D presented on the right side has a lag of 5 to the same position and a lag of 1 to the other position.

In the case of an object switch, lag 2 to the same position can not occur, in the case of no object switch, lag 2 to the other position can not be realized. Furthermore, a combination of lag 2 to the same position with lag 2 to the other position is impossible, as well as lag 3 to the same position combined with lag 3 to the other position (both kinds of lag 4 include higher lags, too, so that the problem does not occur there).

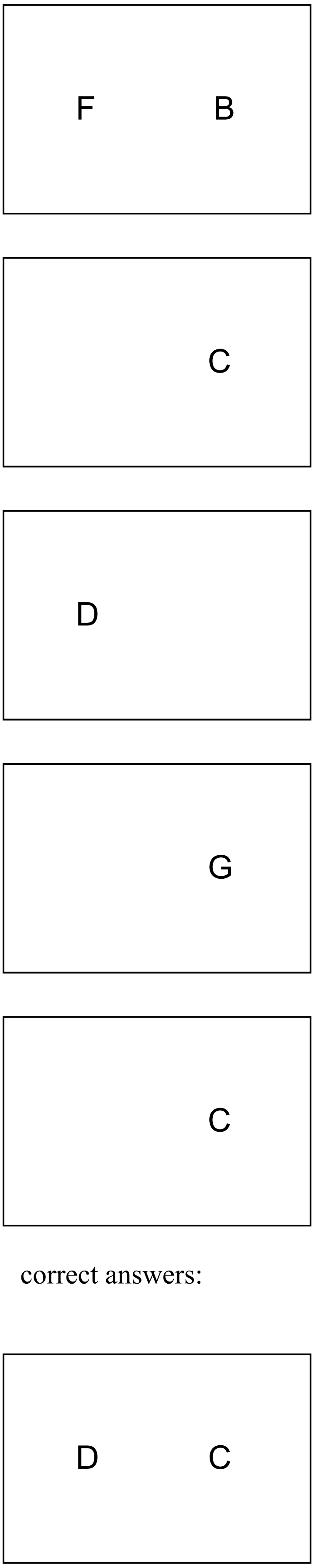
The frequencies in the categories one to four of lag to the same position on the screen were counterbalanced. First, a consonant was selected randomly. If the corresponding lag to the same position category was the one which occurred most frequently until that point in a trial, a new consonant was chosen which again was only presented when its lag was not the most frequent lag and so on. If a new consonant had to be selected 20 times by this algorithm, the last one was presented regardless of its lag. Frequencies of the categories of lag to the other position on the screen were not counterbalanced to avoid a selection procedure of the consonant to be presented which is too restricted.

The whole experiment consisted of 32 trials, the first 4 of these were practice trials. The experiment was combined with the first feature updating experiment (Experiment 1 reported above). One trial from the feature updating experiment was followed by one trial of the consonant updating experiment and so on. The combination of the two experiments was assumed to minimize proactive interference, if present, between the trials of one experiment.



		lag same position	lag another position
B	F		
D	F	5	5
D	D	5	1
D	F	2	5
D	F	1	5
C	F	5	5
C	D	4	2
B	D	4	5

Figure 9. The assignment of the different lag categories. Actually presented consonants are the light ones and working memory representations are the dark ones.



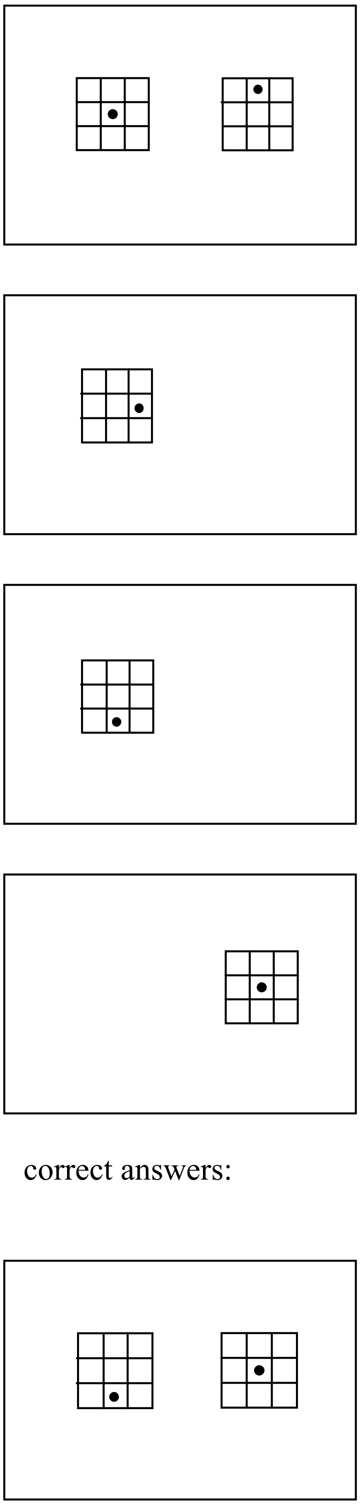


Figure 10. Procedure of the proactive facilitation/ interference experiments (example of a trial with consonants on the left side, one with spatial positions on the right side). Successive items presented on the computer screen can be seen here from top to bottom. Correct answers which had to be produced by the subjects are shown here at the end of an example.

6.1.2 Results

For the reason discussed above, only trials with completely correct answers were included in the first analyses in this and in the following experiments. Subjects reached on average a level of 89.61 % completely correct trials, with a range from 75.00 % to 96.43 %. Additionally, analyses of all trials, including trials with errors, were conducted. The results of these analyses are only reported when they differ in respect of the significance decision from the results of the analyses of trials with completely correct answers.

Furthermore, reaction times shorter than 200 ms and reaction times longer than an individual's mean plus three standard deviations within each condition of the factor object switch/ no object switch were excluded from analyses. By these criteria, 2.1 % of the data were excluded as outliers. The data of one person were excluded before the analyses of a part of the data (see below) because of empty design cells.

In this and in the following experiments, significance tests were conducted with an alpha level of .05 and error bars were computed according to Bakeman and McArther (1996) with an adjustment for between-subjects variability in a within-subjects design. These error bars are based on separately computed confidence intervals for every cell mean. In this and in the following experiment, error bars were computed separately for switch and no-switch conditions.

In Figure 11, mean reaction times for the stages of the factor lag to the same position on the screen and for the stages of the factor lag to another position on the screen are displayed for the case of no object switch, while Figure 12 shows the effects for the cases with an object switch. All these mean reaction times include only a part of the data, namely those data points with a lag 5 to the position not of interest (lag 5: a new consonant). For example, mean reaction time for lag 3 to the same position only includes reaction times resulting from a lag 3 to the same position and a lag 5 to the other position. Mean reaction time for lag 3 to the other position only includes reaction times resulting from a lag 3 to the other position and a lag 5 to the same position. This kind of data selection had to be made to avoid a confounding between the 2 kinds of lags, because the combinations of the two kinds of lags were not equally distributed. It has to be noted, that lag 5 to the same position and lag 5 to the other position coincide (a completely new item in that trial) in these partial data sets.

The results from the whole data sets are presented in the Appendix. These results have to be regarded with caution for the reason explained before, but they are added to see if the results from the whole data sets roughly equal those from the partial data sets.

Mean reaction times for lag 3 to the same position and lag 3 to the other position were compared with each other conducting a t-test, as well as lag 4 to the same position and lag 4 to the other position. No latency difference between the representation of the currently presented stimulus three (four) updating cycles before in working memory for the same position and for another position would indicate that the corresponding old bindings do not exist anymore. A latency difference between these two conditions would be evidence for the existence of old bindings between a stimulus and a position representation.

Furthermore, a difference contrast comparing the reaction times of lag 5 (new stimulus) to the same position with the mean reaction times of lag 2 to lag 4 (for object switch conditions: lag 3 to lag 4) to the same position was calculated, as well as a difference contrast comparing lag 5 (new stimulus) to the other position with lag 3 to lag 4 (for object switch conditions: lag 2 to lag 4) to the other position. These comparisons reflect the effects on reaction times of stimuli which have been already presented before compared to stimuli never presented before in that trial. A latency difference between these two cases would indicate that old working memory contents are still activated, whereby differential effects for same and another position would indicate the existence of old bindings and effects in the same direction the existence of old stimuli without bindings to a position.

Object switch and no object switch conditions were separated for all analyses.

An ANOVA with the factors lag to the same position on the screen and lag to another position on the screen could not be computed because of the lack of certain lag categories/ combinations of lag categories.

Figure 11 shows the results for the cases with no object switch. Reaction times for lag 3 to the other position were significantly longer than reaction times for lag 3 to the same position, $t(20) = 2.68$, $p < .05$, partial $\eta^2 = .26$. The difference between lag 4 to the other position and lag 4 to the same position was far from significance, $t(20) = -.09$, $p = .93$, partial $\eta^2 = .00$. Reaction times for lag 5 to the same position were not significantly different from reaction times for lag 2 to lag 4 to the same position, $F(1, 20) = 3.32$, $p = .08$, partial $\eta^2 = .14$. The difference between reaction times for lag 5 to the other position and reaction times for lag 3 and lag 4 to the other position was not significant either, $F(1, 20) = .27$, $p = .61$, partial $\eta^2 = .01$.

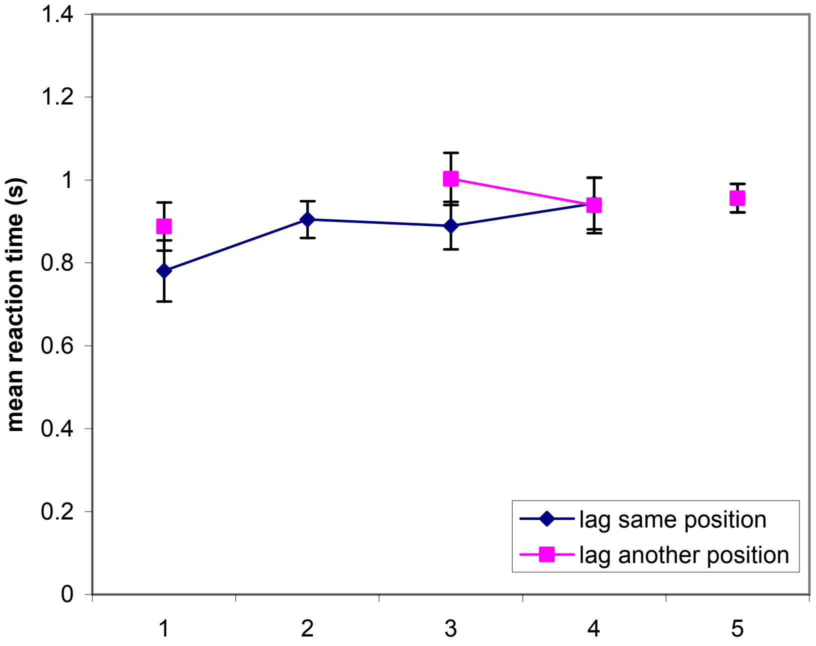


Figure 11. Effects of lag to the same position on the screen and lag to another position on the screen, cases with no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

Results for the cases with an object switch are presented in Figure 12. There was no significant difference between reaction times for lag 3 to the other position and reaction times for lag 3 to the same position, $t(20) = 1.15$, p = .26, partial $\eta^2 = .06$. The difference between lag 4 to the other position and lag 4 to the same position was not significant either, $t(20) = .07$, p = .95, partial $\eta^2 = .00$.

Reaction times for lag 5 to the same position were not reliably different from reaction times for lag 3 to lag 4 to the same position, $F(1, 20) = 3.48$, p = .08, partial $\eta^2 = .15$. In contrast, reaction times for lag 5 to the other position were reliably shorter than reaction times for lag 2 to lag 4 to the other position, $F(1, 20) = 18.97$, p < .01, partial $\eta^2 = .49$.

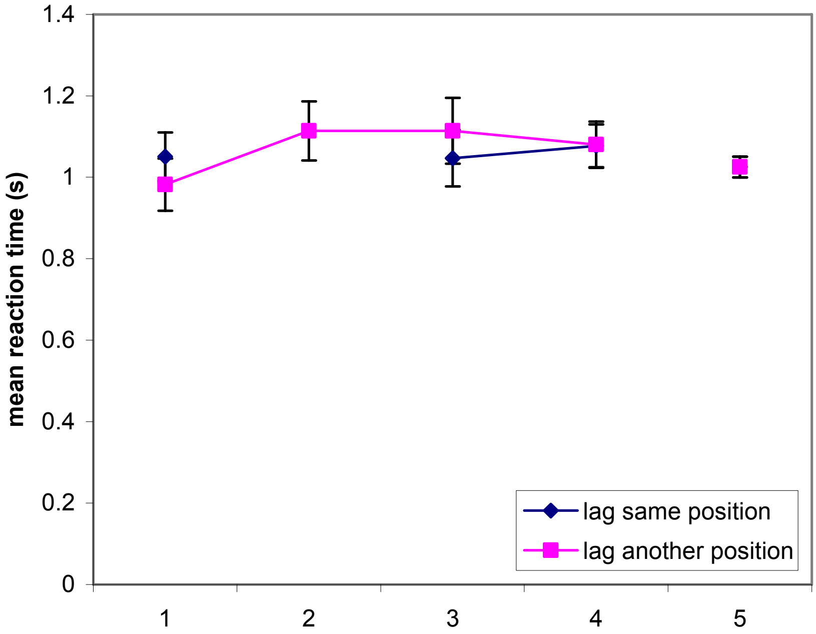


Figure 12. Effects of lag to the same position on the screen and lag to another position on the screen, cases with an object switch. Only that part of the data is included for which lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

In the analyses of all trials, reaction times for lag 3 to the other position were significantly longer than reaction times for lag 3 to the same position, $t(20) = 2.60$, $p < .05$, partial $\eta^2 = .25$.

6.1.3 Discussion

For the cases with no object switch, that means when the updating of a consonant representation occurs on the same side as the last updating before, there is clear evidence that the temporary bindings of a consonant representation to a position representation (left side/ right side) remain present, at least for a short time, even when they are not relevant anymore. When the same consonant as the actual one was represented in working memory for the other side three updating cycles before, reaction time for the actual updating is slowed down in comparison for the case that the same consonant was presented on the same side three updating cycles before. A difference between same position and another position can only be explained by the existence of bindings between stimulus and position representations. The effect seems to have disappeared for lag 4, where reaction times for the same and the other position did not differ reliably from each other.

The proactive facilitation hypothesis concerning the bindings between a stimulus and a position representation predicts shorter reaction times when a stimulus was already shown on the same position in comparison to a new stimulus. This effect could not be found here, although it was not very far from significance.

For the cases with an object switch, a significant effect was found for lag to another position, when reaction times for an updating with a new stimulus were compared to reaction times for an updating with a stimulus already shown before. The direction of this effect, longer latencies for stimuli already presented than for new stimuli, indicates the occurrence of proactive interference. Together with the lack of an effect for lag to the same position, it is further evidence for the existence of temporary bindings between a consonant and a position representation at a time when they were already updated and thus not relevant anymore.

When the consonant to be updated was not on the same side as the previous consonant to be updated, latencies were generally longer than without a switch of this kind. Although object switch costs appeared in different working memory studies before (Garavan, 1998, Oberauer, 2003), the effect was not expected here. The stimulus from the side where no updating occurred had to be remembered, too, so it seemed more likely that this side was the last one on which a cognitive operation was performed (rehearsal in this case). It was assumed that the stimulus which was presented resulted in an updating of the corresponding representation and then, the stimulus from the other side was rehearsed. Possibly this rehearsal was followed by a rehearsal/ a second encoding of the stimulus presented in the current updating cycle, offering a potential explanation for the object switch effect found here.

6.2 Experiment 5

6.2.1 Method

6.2.1.1 Participants

After the exclusion of two persons whose performance was below the criterion of at least 35 % trials with completely correct answers, the sample consisted of 20 persons. They were adults with a mean age of 23.5 years (SD = 2.69; ranging from 20 to 29 years). Sixteen of them were female and 4 male.

Every person received course credit or 6 Euro for participating in the experiment which lasted about 1 hour.

6.2.1.2 Apparatus, Stimuli, and Procedure

Each stimulus was a square, divided into 9 inner cells of equal size. One of the inner cells contained a point in the middle. The stimuli consisted of white lines and white points with a black filling and were shown on a black background. There were nine different stimuli, differing by the cell containing the point. Like that, each stimulus corresponded to a certain position: left up, middle up, right up, left middle, middle, right middle, left down, middle down, right down. For each trial of the experiment, five of the nine different stimuli were randomly selected and only these five stimuli were presented in that trial. Thereby, the number of different stimuli per trial was equal to the number of stimuli used in each trial of the consonant updating experiment.

The procedure of this experiment is illustrated in Figure 10. At the beginning of each trial, two squares were presented, one on the left half of the screen, the other on the right half. The distance between the squares, each with a size of 7 × 7 cm, was 6 cm. The two stimuli were chosen randomly for presentation. Participants had to look at these stimuli and keep the indicated positions in memory until an updating occurred. The following procedure was the same as in the consonant updating experiment. At the end of a trial, subjects reproduced the latest positions from both sides, first the left one, then the right one. The numbers of the nine keys from the number block on the keyboard were covered by pictures of all stimuli which were used in the experiment. Subjects had to press the key which corresponded to their answer.

For the updating cycles one to eight in one trial, the presented stimuli were chosen randomly. For the other updating cycles, the stimuli were chosen by an algorithm assuring that the frequencies in the lag categories were roughly equally distributed. It was tried to construct a better algorithm than the one used in Experiment 4. The algorithm here operated in the following way: When a stimulus randomly selected for the next updating cycle was not the optimal solution (did not correspond to the least frequent lag category), the algorithm tried to find an optimal solution by randomly choosing a stimulus again and again. When it was not possible to find an optimal solution within 30 attempts, the algorithm tried to find the second best solution with a maximum of 30 attempts and after that, if failing again, the third best solution and so on.

In half of the trials, lag to the same position on the screen was controlled, in the other half lag to another position on the screen (alternatively), because otherwise the selection of the stimuli would have been too restricted. The algorithm was not used for the first eight updating cycles because this would result in a reduced number of different stimuli presented in a trial. Despite the use of this algorithm, the resulting frequencies in the lag categories differed. A trade-off had to be made between the objective to equate these frequencies and the objective to determine as randomly as possible task characteristics like object switch/ no object switch or the stimulus which is presented for the next updating cycle.

An alternative procedure to the algorithm constraining the random processes of stimulus selection used here is the systematic construction of all task characteristics instead of random processes. But this alternative procedure would face the same problem that constructing a certain lag value implies the creation of other lag values inevitably. No other option was found than accepting different frequencies in the lag categories or using only a part of the data. The first alternative was regarded as the better one here.

Every subject completed 32 trials, the first 4 of these were practice trials. To minimize potential proactive interference effects between the trials, the experiment was combined with the verbal feature updating experiment (Experiment 2 above) in a way that one trial from the fifth experiment was followed by one trial from the second experiment and so on.

6.2.2 Results

In this experiment, mean performance level of the participants was 73.93 % completely correct trials, with a range from 57.14 % to 82.14 %.

One data point longer than 25 s was removed from the data before the regular outlier analysis. Reaction times exceeding this criterion were regarded to be irregular long because of any disturbing influences besides the cognitive processes of interest. The following outlier analysis was the same as already described for the consonant updating experiment, resulting in an exclusion of 1.9 % of the data. In the no object switch conditions of the partial data set, three persons were excluded because of empty design cells. For the case of an object switch in the partial data set, there were even more empty design cells, so that these data were not analyzed at all.

The same analyses were conducted like in Experiment 4. Results for the partial data sets are presented here, results for the whole data sets can be seen in the Appendix. Figure 13 shows the results for the cases with no object switch. Reaction times for lag 3 to another position were significantly longer than reaction times for lag 3 to the same position, $t(16) = 3.52$, $p < .01$, partial $\eta^2 = .44$. The difference between reaction times for lag 4 to another position and reaction times for lag 4 to the same position was not significant, $t(16) = 1.24$, $p = .23$, partial $\eta^2 = .09$.

Reaction times for lag 5 to the same position were reliably longer than reaction times for lag 2 to lag 4 to the same position, $F(1, 16) = 10.93$, $p < .01$, partial $\eta^2 = .41$. The difference between reaction times for lag 5 to another position and reaction times for lag 3 and lag 4 to another position was far from significance, $F(1, 16) = .70$, $p = .42$, partial $\eta^2 = .04$.

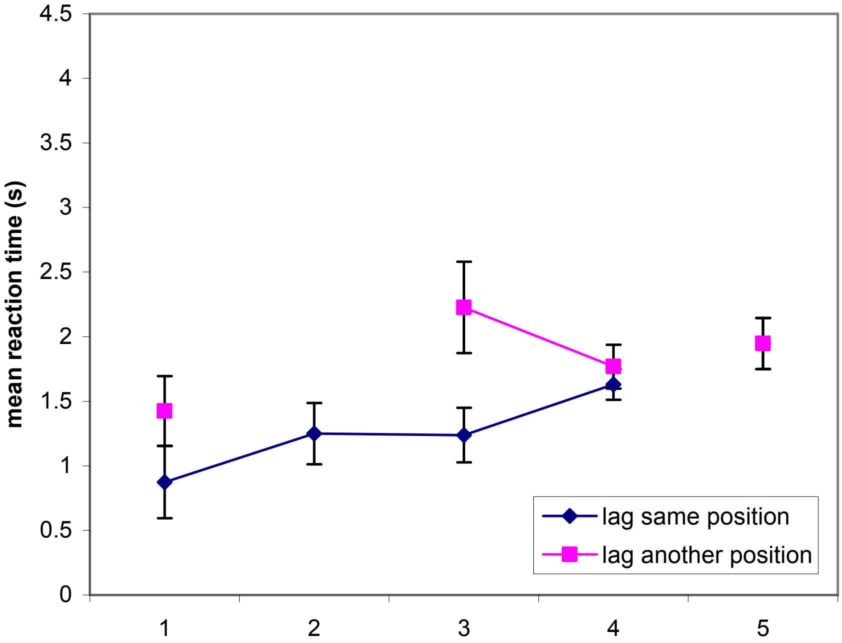


Figure 13. Effects of lag to the same position on the screen and lag to another position on the screen, cases with no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

6.2.3 Discussion

The updating of temporary bindings between two positions (left/ right side of the screen and one of the nine cells of the square as the stimulus) like in this experiment seems to be more difficult than the updating of consonant-position bindings like in Experiment 4, as is indicated by longer latencies. Apart from this difference, the results of Experiment 5 mirror the results of Experiment 4 approximately. The comparison between reaction times for lag 3 to another position and lag 3 to the same position clearly indicated the existence of bindings which should have been updated already and are thus not useful anymore. This effect seemed to last only until lag 3, like in the previous experiment with verbal material. The reliable difference between lag 5 (new stimulus) and lag 2 to 4 for the same position was further evidence for the existence of the bindings between a stimulus and a position representation for the time after their relevance. This difference can only be explained by the existence of previously constructed bindings, and not by residual activation of stimulus representations, because of the lack of an effect for lag to another position. Residual activation of stimulus representations independently from bindings would produce the same effects for lag to the same position and lag to another position.

It is possible that the spatial positions of the points in the squares were verbally encoded. In this case the results for consonant updating and for the updating of spatial positions would concern the same domain and could be regarded as a replication with the disadvantage of less general results.

6.3 General Discussion Experiments 4 and 5

The evidence for the occurrence of proactive facilitation/ interference in a working-memory task contradicts some of the results from other authors discussed before. The results of Wickens et al. (1963), the results of Cowan et al. (2005), and the results of Halford et al. (1988) indicated that working memory contents are protected from proactive interference, contrary to contents which are not in working memory anymore. A possible explanation for this inconsistency could be the use of a different paradigm here, which may be more sensitive to the effects of interest. Furthermore, it has to be noted that the present experiments investigated proactive facilitation/ interference between temporary bindings in working memory, whereas the other experiments concerned working memory contents.

Another possible reason for the diverging results is that working memory capacity was probably not exhausted with two stimulus-position bindings. It might be possible that elements inside working memory remain there until they have to be replaced by newer elements because of capacity limits. A working memory capacity of about four elements (Cowan, 2000) would offer the possibility to hold the stimulus-position bindings of about three updating cycles. This assumption requires a temporal mechanism providing the information which bindings are the newest ones. A working memory system functioning like supposed here seems to work uneconomically, because resources are bound to hold information which is not relevant anymore. On the other side, it might be parsimonious to update an element/ binding in working memory only when this is really necessary because it can be assumed that the updating process consumes cognitive resources, too.

7 Experiment 6

To test the hypothesis that the effects found in Experiments 4 and 5 are the result of free working memory capacity, Experiments 4 and 5 were replicated together with additional conditions of higher memory loads, realized through set sizes higher than 2. If this hypothesis is true, the effects of interest should only appear in the low memory load (set size 2) conditions. Furthermore, a high/ low memory load variation can be compared with the results from Cowan et al. (2005) concerning the list length variation. They concluded from their results that proactive interference only occurs when working memory capacity is exceeded. According to them, proactive facilitation/ interference are expected only for the high memory load conditions in this experiment.

7.1 Method

7.1.1 Participants

Subjects of this experiment were recruited from the undergraduate students of the University of Potsdam. The mean age of these 12 persons was 23.67 years (SD= 3.06, range from 20 to 29 years), 10 of them were female and 2 male. Every subject participated in six sessions on different days and received 6 Euro for every session (duration of about one hour). Two other persons took part in a first session but did not come to complete the whole experiment, so that their data had to be excluded.

7.1.2 Apparatus, Stimuli, and Procedure

This experiment corresponds to the two proactive interference/ facilitation experiments reported before except that set size (memory load) was varied, resulting in a 2 × 2 × 2 design with the factors set size (memory load), kind of material, and object switch/ no object switch. Verbal material (consonants) as well as spatial material (squares divided into 9 inner cells of equal size with a point in the middle of one inner cell) was used. There was a condition with low memory load, containing two consonants/ two positions. The high memory load condition contained five consonants/ three positions. Pilot testing showed that with the different kinds of material, difficulty of the task in the high set size condition was nearly the same with these different numbers of items presented.

In this experiment, stimuli were chosen from a pool of nine different stimuli. The nine consonants were B, C, D, F, G, H, J, K, L and the nine positions resulted from the nine inner cells (point left up, middle up, right up, left middle, middle, right middle, left down, middle down, right down). Text font of the consonants was Arial and text size was 2.8 cm. The size of one spatial item was 4.5 cm × 4.5 cm. Items were arranged on a centered virtual circle with a radius of 7.5 cm.

Every session consisted of 32 trials, half of the trials contained verbal material, the other half spatial material. The kind of material was changed from trial to trial, set size of each trial was determined randomly with the constraint that trials with high set size occurred as often as trials with low set size for every kind of material. The first four trials of the first session were practice trials to make the participant familiar with the task. In these four practice trials, every combination of kind of material with set size occurred once (verbal material and low set size, verbal material and high set size, spatial material and low set size, spatial material and high set size).

The algorithm roughly equating the frequencies in the different lag categories was the same as in the experiment reported before, but some parameters were adapted in a way that produced the best equating results. The number of times the algorithm tried to find an optimal solution before turning to the next optimal solution was increased to 50. With the greater number of different stimuli used in this experiment (nine instead of five), it was possible to start the equating algorithm from every fifth updating cycle in a trial onwards. Further optimizing the algorithm compared to the experiment described before led to the effect of inequality of the number of object switches and no switches (more no switches than switches).

7.2 Results

Subjects reached on average a level of 96.73 % completely correct trials, with a range from 92.86 % to 100.00 %, on trials with set size 2/ verbal material, and 71.73 % completely correct trials on average, with a minimum of 47.62 % and a maximum of 91.67 %, on trials with set size 5/ verbal material. Average performance with set size 2 and spatial material was 94.64 %, ranging from 82.14 % to 98.81 %, and with set size 3 and spatial material, mean accuracy was 70.83 %, with a range from 35.71 % to 95.24 %.

Like in the previous experiments, reaction times shorter than 200 ms and reaction times longer than an individual’s mean plus three standard deviations within each condition resulting from the combination of the factors kind of material, set size, and object switch/ no object switch were removed from analyses. One value of the set size 5, verbal data points, which was longer than 50 s, was excluded before the regular outlier analysis. Two percent of the data with set size 2 and verbal material, 2.2 % of the data with set size 5 and verbal material, 2.4 % of the data with set size 2 and spatial material, and 2.2 % of the data with set size 3 and spatial material were discarded as outliers.

In the verbal material/ set size 2/ object switch conditions for the analysis of a part of the data, one person was excluded because of empty design cells. For the same reason, the data of two persons were excluded in the verbal material /set size 5/ no object switch conditions for the analysis of a part of the data and the data of one person in the verbal material/ set size 5/ object switch conditions for the analysis of all data.

Furthermore, in the spatial material/ set size 2/ object switch conditions, two persons were excluded for the analysis of a part of the data and one person for the analysis of all data.

The same analyses were conducted like in the Experiments 4 and 5, separated by kind of material, set size, and no object switch/ object switch. Results for the partial data sets are presented here, results for the whole data sets can be seen in the Appendix.

Figure 14 shows the results for the cases with verbal material/ set size 2/ no object switch. Reaction times for lag 3 to another position were significantly longer than reaction times for lag 3 to the same position, $t(11) = 2.89$, $p < .05$, partial $\eta^2 = .43$. Reaction times for lag 4 to another position were significantly longer than reaction times for lag 4 to the same position, $t(11) = 3.66$, $p < .01$, partial $\eta^2 = .55$.

The difference between reaction times for lag 5 to the same position and reaction times for lag 2 to lag 4 to the same position was not significant, $F(1, 11) = .15$, $p = .70$, partial $\eta^2 = .01$. Reaction times for lag 5 to another position were reliably shorter than reaction times for lag 3 and lag 4 to another position, $F(1, 11) = 24.17$, $p < .01$, partial $\eta^2 = .69$.

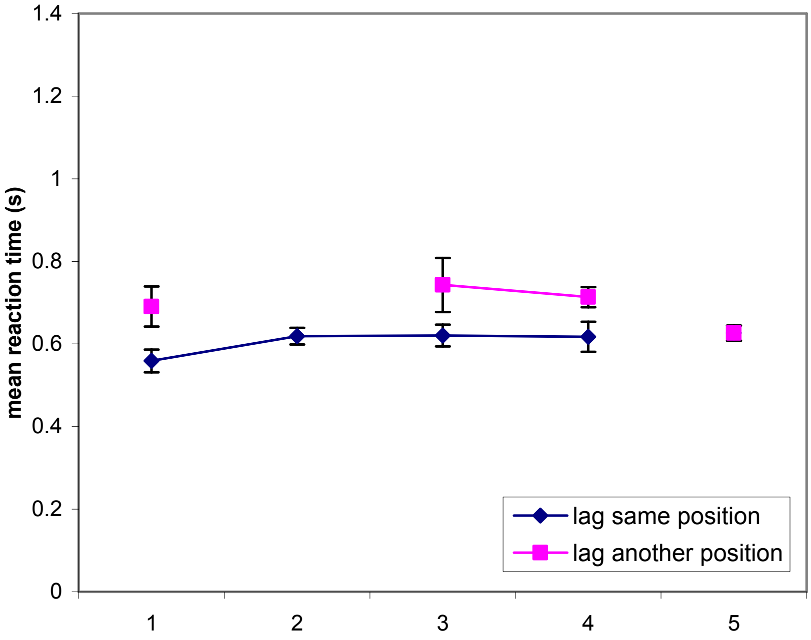


Figure 14. Effects of lag to the same position on the screen and lag to another position on the screen, cases with verbal material/ set size 2/ no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

The results for the conditions with verbal material/ set size 2/ object switch are illustrated in Figure 15. Reaction times for lag 3 to another position were reliably longer than reaction times for lag 3 to the same position, $t(10) = 3.57$, $p < .01$, partial $\eta^2 = .56$. The difference between reaction times for lag 4 to another position and reaction times for lag 4 to the same position was not significant, $t(10) = -1.65$, $p = .13$, partial $\eta^2 = .21$.

Reaction times for lag 5 to the same position were not significantly different from reaction times for lag 3 to lag 4 to the same position, $F(1, 10) = 4.04$, $p = .07$, partial $\eta^2 = .29$. Reaction times for lag 5 to another position were reliably shorter than reaction times for lag 2 to lag 4 to another position, $F(1, 10) = 26.23$, $p < .01$, partial $\eta^2 = .72$.

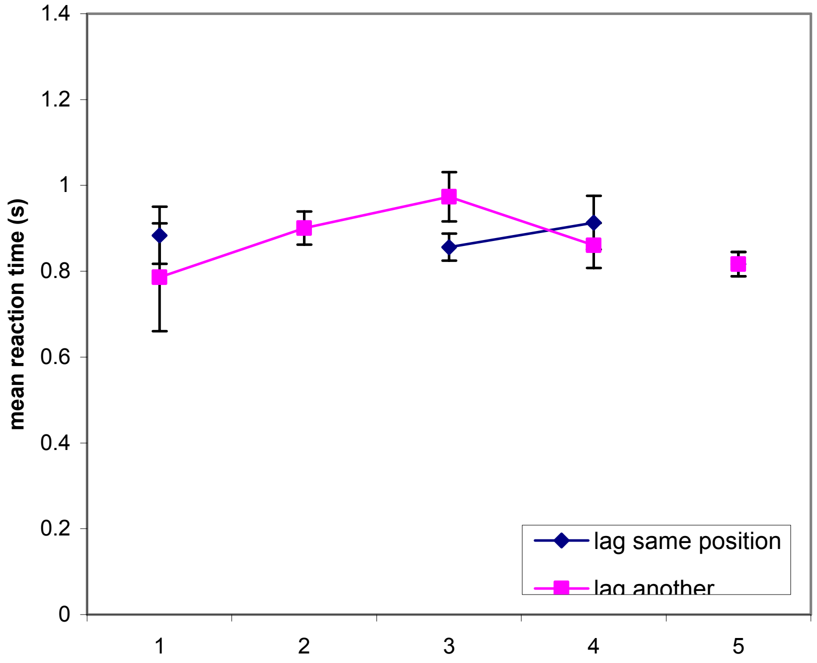


Figure 15. Effects of lag to the same position on the screen and lag to another position on the screen, cases with verbal material/ set size 2/ object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

Figure 16 shows the results for the cases with verbal material/ set size 5/ no object switch. Reaction time for lag 3 to another position were reliably longer than reaction times for lag 3 to the same position, $t(9) = 3.77$, $p < .01$, partial $\eta^2 = .61$. The difference between reaction times for lag 4 to another position and reaction times for lag 4 to the same position was not significant, $t(9) = 1.81$, $p = .10$, partial $\eta^2 = .27$.

Reaction times for lag 5 to the same position were reliably longer than reaction times for lag 2 to lag 4 to the same position, $F(1, 9) = 13.62$, $p < .01$, partial $\eta^2 = .60$. The difference between reaction times for lag 5 to another position and reaction times for lag 3 to lag 4 to another position was not significant, $F(1, 9) = .03$, $p = .87$, partial $\eta^2 = .00$.

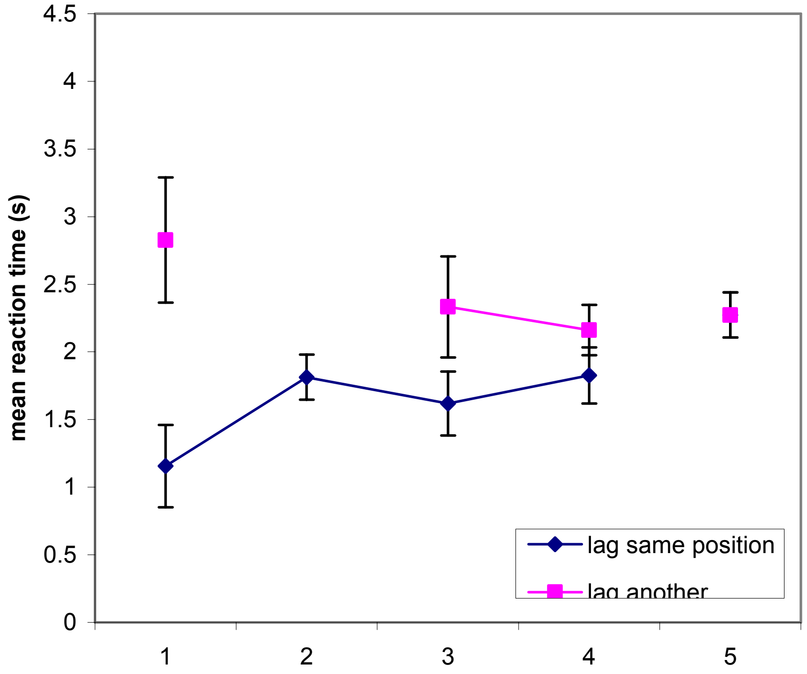


Figure 16. Effects of lag to the same position on the screen and lag to another position on the screen, cases with verbal material/ set size 5/ no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

Results for the conditions with spatial material/ set size 2/ no object switch are illustrated in Figure 17. Reaction times for lag 3 to another position were significantly longer than reaction times for lag 3 to the same position, $t(11) = 4.66$, $p < .01$, partial $\eta^2 = .66$. Reaction times for lag 4 to another position were significantly longer than reaction times for lag 4 to the same position, $t(11) = 4.01$, $p < .01$, partial $\eta^2 = .59$.

Reaction times for lag 5 to the same position were significantly longer than reaction times for lag 2 to lag 4 to the same position, $F(1, 11) = 40.53$, $p < .01$, partial $\eta^2 = .79$. The difference between reaction times for lag 5 to another position and reaction times for lag 3 to lag 4 to another position was not significant, $F(1, 11) = 1.96$, $p = .19$, partial $\eta^2 = .15$.

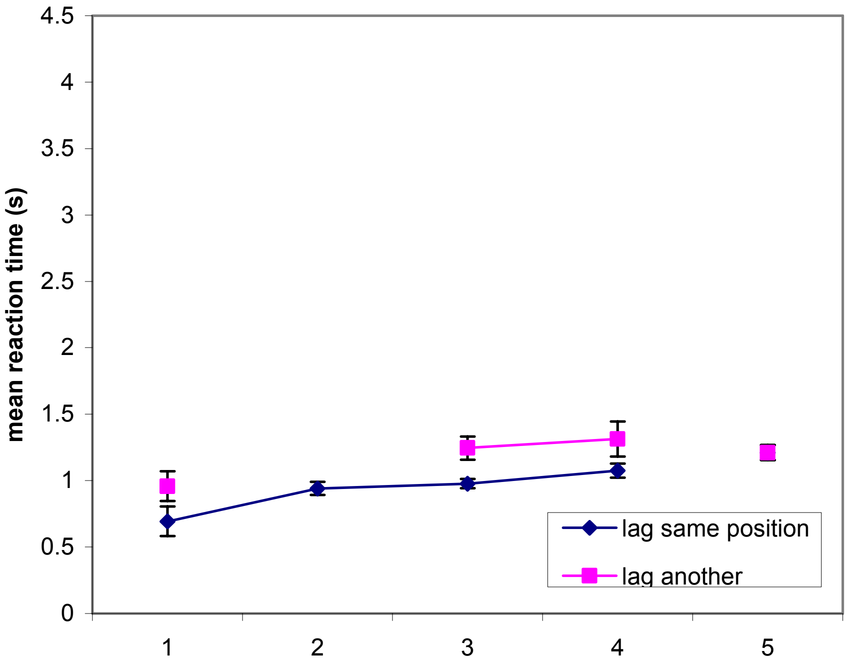


Figure 17. Effects of lag to the same position on the screen and lag to another position on the screen, cases with spatial material/ set size 2/ no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

Figure 18 shows the results for the cases with spatial material/ set size 2/ object switch. Reaction times for lag 3 to another position were not reliably longer than reaction times for lag 3 to the same position, $t(9) = .71$, p = .50, partial $\eta^2 = .05$. The difference between reaction times for lag 4 to another position and reaction times for lag 4 to the same position was not significant either, $t(9) = 1.75$, p = .11, partial $\eta^2 = .25$.

Reaction times for lag 5 to the same position were not reliably different from reaction times for lag 3 to lag 4 to the same position, $F(1, 9) = 2.11$, p = .18, partial $\eta^2 = .19$. The difference between reaction times for lag 5 to another position and reaction times for lag 2 to lag 4 to another position was not significant either, $F(1, 9) = 4.09$, p = .07, partial $\eta^2 = .31$.

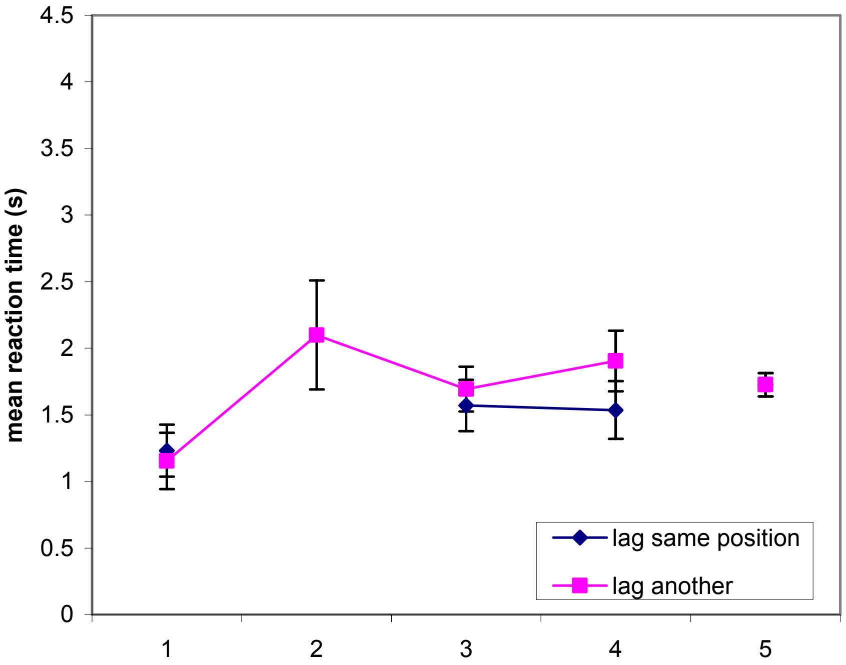


Figure 18. Effects of lag to the same position on the screen and lag to another position on the screen, cases with spatial material/ set size 2/ object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

In the analyses of all trials, latencies for lag 5 to another position were significantly shorter than latencies for lag 2 to 4 to another position, *F*(1, 9) = 5.45, p < .05, partial η^2 = .38.

Results for the conditions with spatial material/ set size 3/ no object switch are illustrated in Figure 19. Reaction times for lag 3 to another position were not significantly longer than reaction times for lag 3 to the same position, *t*(11) = .61, p = .55, partial η^2 = .03. In contrast, reaction times for lag 4 to another position were significantly longer than reaction times for lag 4 to the same position, *t*(11) =2.98, p < .05, partial η^2 = .45.

Reaction times for lag 5 to the same position were not reliably different from reaction times for lag 2 to lag 4 to the same position, *F*(1, 11) = 4.23, p = .06, partial η^2 = .28. The difference between reaction times for lag 5 to another position and reaction times for lag 3 to lag 4 to another position was not significant, either, *F*(1, 11) =.10, p = .76, partial η^2 = .01. The lack of a reliable difference between the 2 kinds of lag 3 may be due to the high standard deviation in the lag 3 to another position condition.

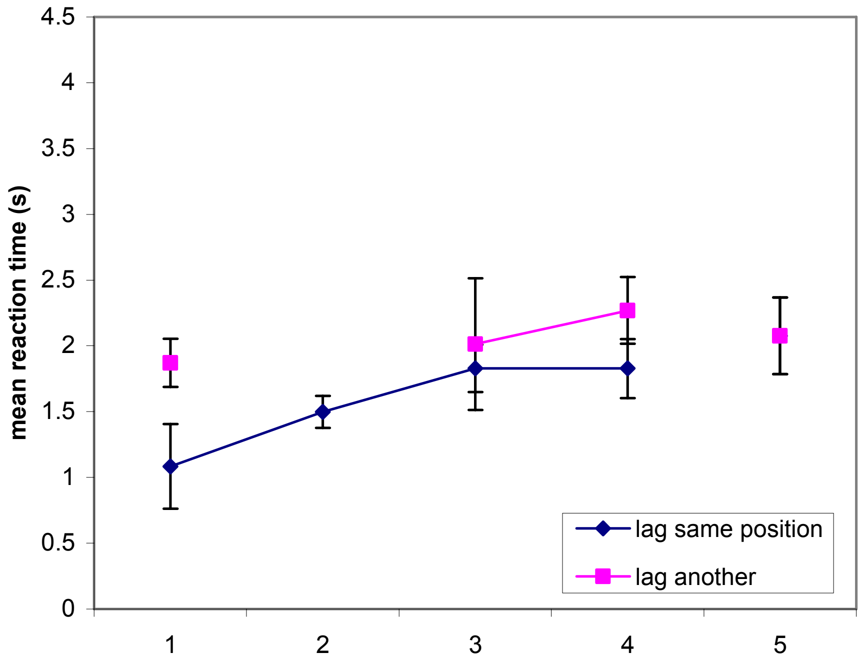


Figure 19. Effects of lag to the same position on the screen and lag to another position on the screen, cases with spatial material/ set size 3/ no object switch. Only that part of the data is included for which the lag to the position not of interest is 5 (a new item for that position). Error bars represent 95 % confidence intervals.

In the analyses of all trials, reaction times for lag 3 to another position were reliably longer than reaction times for lag 3 to the same position, $t(11) = 2.40$, $p < .05$, partial $\eta^2 = .34$. Furthermore, reaction times for lag 5 to the same position were reliably longer than reaction times for lag 2 to 4 to the same position, $F(1, 11) = 8.09$, $p < .05$, partial $\eta^2 = .42$.

7.3 Discussion

Clear evidence for the existence of temporary bindings which are not relevant anymore could be found in all conditions with verbal material, for set size 2/ no object switch, for set size 2/ object switch, and for set size 5/ no object switch. The significant difference between latency for lag 3 to another position and latency for lag 3 to the same position always occurred and is consistent with the result from Experiment 4. A reliable difference in the same direction between latency for lag 4 to another position and latency for lag 4 to the same position was only found for verbal material/ set size 2/ no object switch.

Significant differences between latencies for the two kinds of lag 3 and for the two kinds of lag 4 indicate that the bindings between a consonant and a position representation stay for a longer time than indicated by the fourth experiment, but it must be noted that reaction times in this experiment were generally shorter than in the fourth (due to more sessions and thus more practice). That means, on average, less time passed during four updating cycles.

Additionally, in all conditions with verbal material of the sixth experiment, a reliable difference between reaction times for a new stimulus and a stimulus already presented occurred, always only for lag to the same position on the screen or only for lag to another position on the screen. Such pattern of results can only be explained by the influence of bindings. Residual activation of stimulus representations independently from bindings instead would produce the same effects for lag to the same position on the screen and lag to another position on the screen.

Altogether, for the conditions with verbal material, Experiment 6 provides clearer evidence for the existence of bindings, which are not relevant anymore, than Experiment 4. This is probably the result of greater power obtained through several sessions in Experiment 6. The replication of effects across experiments is very encouraging.

Results in the spatial material conditions were similar to those in the verbal material conditions, although the evidence for the existence of temporary bindings for the time after their relevance was not as clear as for the verbal material conditions. For set size 2/ object switch, no effect at all reached significance. However, that may be due to the fact that an object switch is an additional cognitive operation that makes the updating process more complex. Results from the no switch conditions are regarded to be more trustworthy, since they reflect the basic process of updating a binding between a stimulus and a position representation.

Results from Experiment 5, which correspond to the conditions with set size 2 in this experiment, could be replicated. Here, there was a reliable difference between the two kinds of lag 4 additionally to a reliable difference between the two kinds of lag 3, an effect which did not appear in Experiment 5. The same combination of results occurred with verbal material. It can be argued like before, that shorter reaction times overall were responsible for the ostensible longer lasting effect of irrelevant bindings.

For the higher set size of three spatial positions, only the difference between latencies for the two kinds of lag 4 was reliable. For lag to the same position on the screen, the difference between latencies for lag 5 and previous lags just failed to reach significance.

The sixth experiment differed from the fourth and fifth experiment in the number of different stimuli in the pool from which the presented stimuli were selected and in some parameters of the algorithm equating the frequencies of the lag categories. Furthermore, altogether more no switches than switches occurred in the sixth experiment, but not in the Experiments 4 and 5. These differences between the experiments were assumed to have no influence on the effects of interest. Anyway, the conditions of the Experiments 4 and 5 were repeated in Experiment 6, alongside with the new conditions.

The main purpose of Experiment 6 was to examine the proactive facilitation/ interference effect under working memory conditions and under conditions exceeding the capacity of working memory. Evidence for proactive facilitation/ interference was found for both cases, though evidence was stronger for working memory conditions. This pattern of results is probably due to greater power in the low set size conditions, which was obtained because more trials resulted in completely correct answers and were analyzed there.

With the results from the high set size conditions, it can be shown that the maintenance of bindings, which are not relevant anymore, in the low set size conditions is not the result of the low memory load not exhausting working memory capacity, like it was speculated before. The opposite prediction, corresponding to the results of Cowan et al. (2005), was not confirmed either within this new paradigm. The results of the experiment presented here do not support the hypothesis that temporary bindings in working memory are protected against interference from older contents.

The results for the whole data sets, presented in the Appendix, are sometimes consistent with the results obtained for the partial data sets, sometimes not. Some aspects of these data can not be interpreted easily, for example shorter reaction times for lag to another position on the screen than for lag to the same position on the screen in some cases. However, the results discussed before for the partial data sets should be regarded with much more confidence. Results for the conditions with high set size, object switch for both kinds of material are only available for the whole data sets and thus provide useful additional information. These results are very similar to those in the no switch conditions in the analyses of correct trials supporting the conclusions drawn before.

In the analyses of all trials, including error trials, even more effects indicating proactive facilitation/ interference reached significance, probably due to greater power. Although these analyses have to be regarded with caution, they further support the results obtained in the analyses of correct trials.

8 General Discussion Experiments 4, 5, and 6

The present series of experiments concerned the question if working memory contents are protected from proactive interference. This question was still open since the results of previous studies were not consistent with each other. The present experimental series did not aim to explain this inconsistency, but to investigate a new aspect of this question within a new paradigm, offering several advantages over previously used paradigms. It was examined for two kinds of material, verbal and spatial, if temporary bindings between representations of a stimulus and a position are directly and completely dissolved during an updating or if they can still be detected at a time when they are not relevant anymore. In Experiment 6, this question was investigated, for both kinds of material, under working memory conditions and under conditions exceeding working memory capacity.

For all combinations of conditions, clear evidence was found that the bindings between a stimulus and a position representation were not directly and completely dissolved during an updating, although the effects could not be detected in some of the tests. When updating involved the creation of a binding which never existed before in that trial (presentation of a new stimulus), latencies were longer than latencies obtained for bindings to be constructed which had been held in working memory before, but were updated later, while there was no effect of a previous stimulus presentation on another position on the screen. Sometimes, this pattern of effects was not found, but the opposite one: There was no effect for the same position on the screen, but shorter latencies occurred for new stimuli presented, compared to the cases in which bindings between the stimulus and another position were in working memory before, but were updated later. Further evidence were longer latencies when bindings between the stimulus and another position were held in working memory before, but were updated later, compared to latencies for the cases in which the stimuli were previously presented on the same position. This effect was found in some conditions for lag 3, in some for lag 4, and in some for both.

A difference between previous experiments of other authors and the paradigm used here is that here, the source of the effect is the presentation of the same stimulus as before, while in previous experiments, a similarity manipulation was used. Consequently, temporary bindings which become irrelevant after an updating have a chance to become relevant again in the paradigm used here. This fact is a potential reason for the occurrence of the proactive facilitation/ proactive interference effect in the present experiments. It is possible that the strength of a temporarily irrelevant binding is not lowered to zero after it has been updated. If this is the case, it should not last longer than until the end of a trial, because otherwise, no difference between a new stimulus and a stimulus already presented would have been detected. Repeated presentation of the same stimuli in the present paradigm extends the concept of proactive interference as a negative effect with proactive facilitation as its positive complement. Proactive facilitation has to a chance to occur with the repeated presentation of stimuli on the same position and proactive interference with the repeated presentation of stimuli on another position.

In future research, it would be interesting to see if proactive facilitation/ interference gradually decline over time, if the effects can be replicated with other experimental designs, and if the inconsistency between the results of different authors can be dissolved, perhaps by a differentiated view of the proactive facilitation/ interference effect.

Results for working memory conditions and conditions exceeding working memory capacity were similar and contradicted the hypothesis that working memory contents are protected from proactive interference, contrary to long-term memory contents. The present results do not support a theoretical view in which working memory and long-term memory are clearly separable from each other, but contradicting results from other studies have to be taken into account when such far reaching implications are discussed. Of course, a potential separation of working memory and long-term memory involves other aspects besides forgetting mechanisms, for example temporal duration and storage capacity (see Eysenck & Keane, 2005).

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Appendix

Results of the analyses of all trials are shown in the following tables in brackets whenever they differed from the results of the analyses of completely correct trials regarding the significance decision.

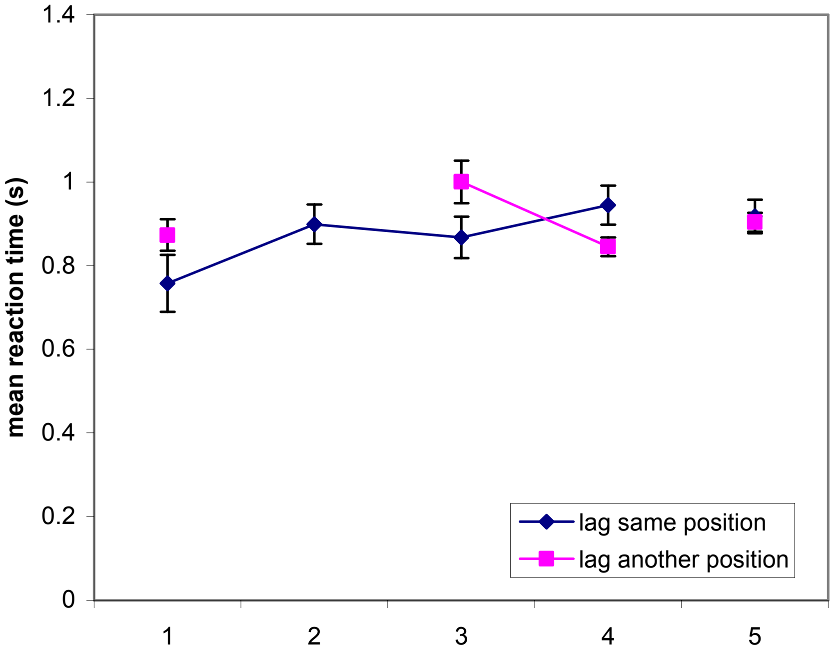

Figure 20. Experiment 4 (verbal material and set size 2). Effects of lag to the same position on the screen and lag to another position on the screen, cases with no object switch. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 1. Test statistics for Experiment 4 (verbal material and set size 2), no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(21) = 3.16	p < .01	partial η^2 = .32
lag 4 to the same position and lag 4 to another position	*t*(21) = -3.64	p < .01	partial η^2 = .39
lag 5 to the same position and lag 2-4 to the same position	*F*(1, 21) = .36	p = .55	partial η^2 = .02
lag 5 to another position and lag 3-4 to another position	*F*(1, 21) = .92	p = .35	partial η^2 = .04

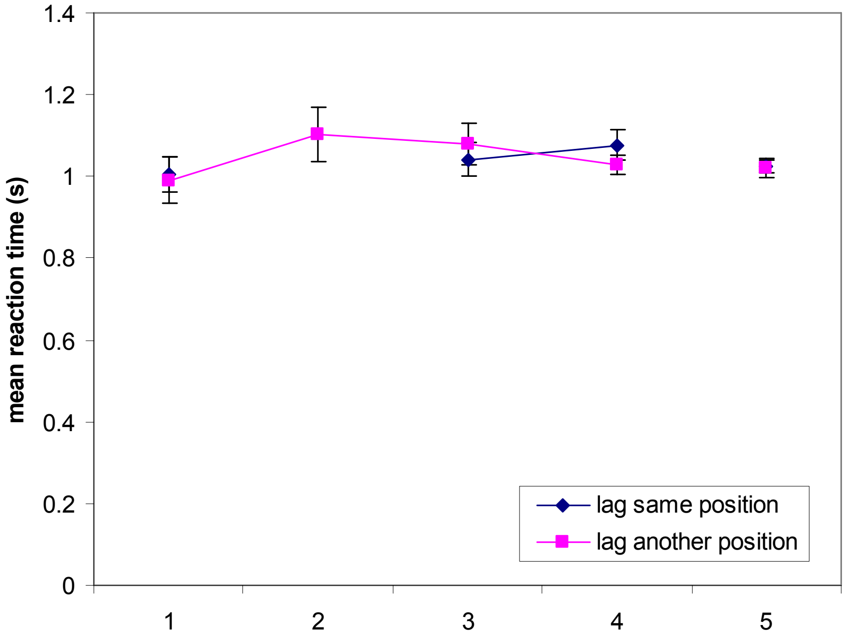

Figure 21. Experiment 4 (verbal material and set size 2). Effects of lag to the same position on the screen and lag to another position on the screen, cases with an object switch. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 2. Test statistics for Experiment 4 (verbal material and set size 2), object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(21) = 1.15$ $(t(21) = 2.21)$	$p = .26$ $(p < .05)$	partial $\eta^2 = .06$ (partial $\eta^2 = .19$)
lag 4 to the same position and lag 4 to another position	$t(21) = -2.33$ $(t(21) = -2.00)$	$p < .05$ $(p = .06)$	partial $\eta^2 = .21$ (partial $\eta^2 = .16$)
lag 5 to the same position and lag 3-4 to the same position	$F(1, 21) = 5.78$	$p < .05$	partial $\eta^2 = .22$
lag 5 to another position and lag 2-4 to another position	$F(1, 21) = 14.00$	$p < .01$	partial $\eta^2 = .40$

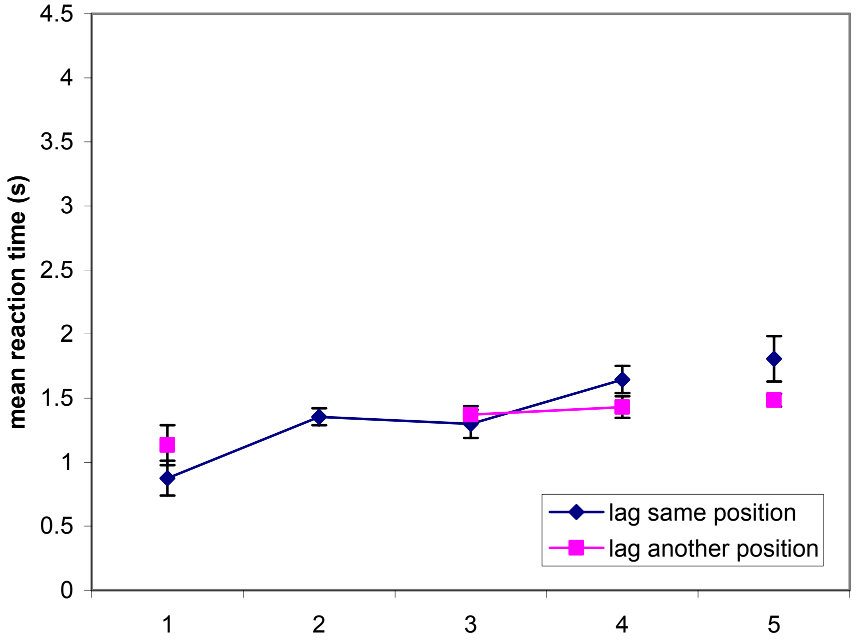

Figure 22. Experiment 5 (spatial material and set size 2). Effects of lag to the same position on the screen and lag to another position on the screen, cases with no object switch. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 3. Test statistics for Experiment 5 (spatial material and set size 2), no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(19) = .96$	p = .35	partial $\eta^2 = .05$
lag 4 to the same position and lag 4 to another position	$t(19) = -3.48$	p < .01	partial $\eta^2 = .39$
lag 5 to the same position and lag 2-4 to the same position	$F(1, 19) = 12.21$	p < .01	partial $\eta^2 = .39$
lag 5 to another position and lag 3-4 to another position	$F(1, 19) = 3.89$ ($F(1, 19) = 8.72$)	p = .06 (p < .01)	partial $\eta^2 = .17$ (partial $\eta^2 = .32$)

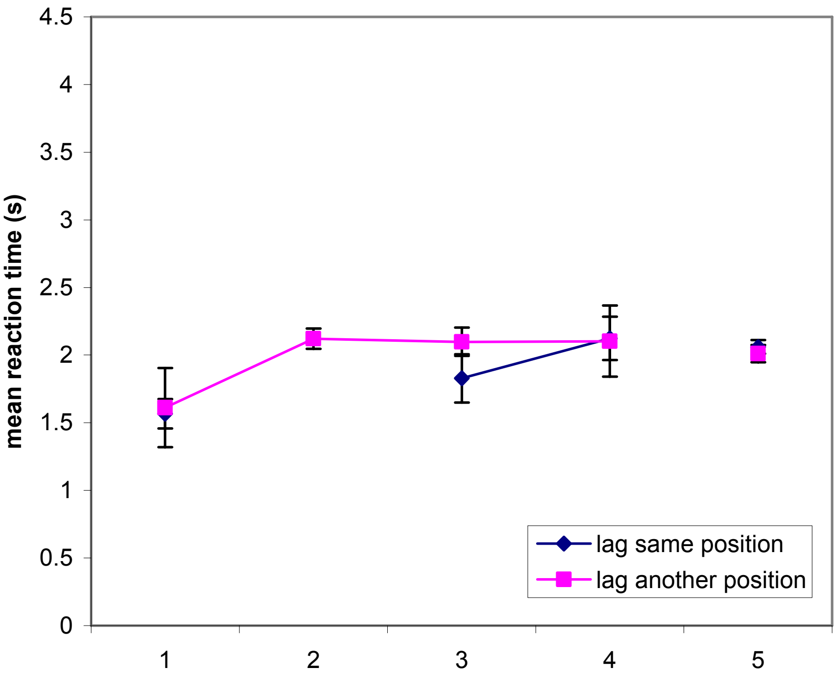

Figure 23. Experiment 5 (spatial material and set size 2). Effects of lag to the same position on the screen and lag to another position on the screen, cases with an object switch. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 4. Test statistics for Experiment 5 (spatial material and set size 2), object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(19) = 2.28	p < .05	partial η^2 = .21
lag 4 to the same position and lag 4 to another position	*t*(19) = -.10	p = .92	partial η^2 = .00
lag 5 to the same position and lag 3-4 to the same position	*F*(1, 19) = 4.89 (*F*(1, 19) = 3.46)	p < .05 (p = .08)	partial η^2 = .21 (partial η^2 = .15)
lag 5 to another position and lag 2-4 to another position	*F*(1, 19) = 5.97	p < .05	partial η^2 = .24

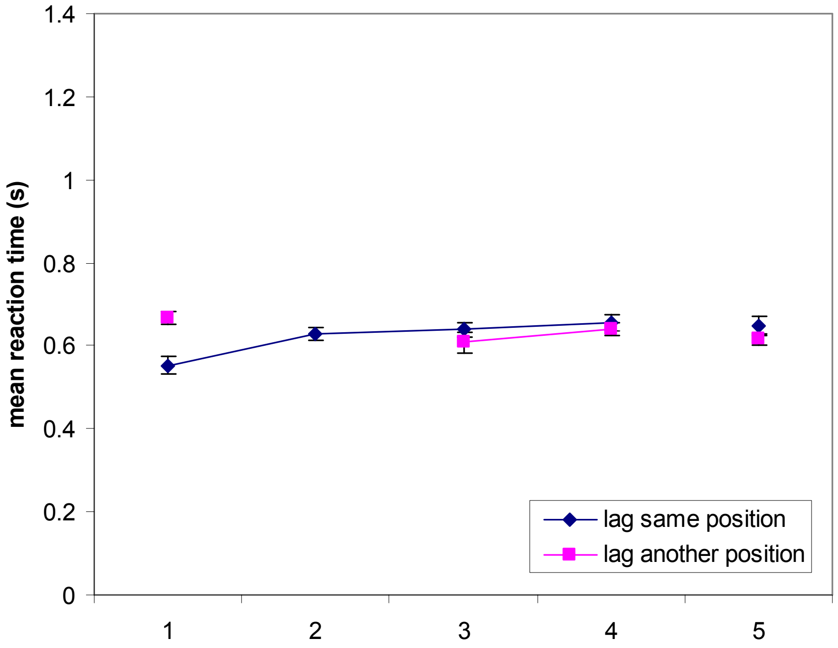

Figure 24. Experiment 6, conditions with verbal material, set size 2 and no object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 5. Test statistics for Experiment 6, verbal material, set size 2, no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(11) = -1.57	p = .14	partial η^2 = .18
lag 4 to the same position and lag 4 to another position	*t*(11) = -1.03	p = .33	partial η^2 = .09
lag 5 to the same position and lag 2-4 to the same position	*F*(1, 11) = .21	p = .66	partial η^2 = .02
lag 5 to another position and lag 3-4 to another position	*F*(1, 11) = .24	p = .64	partial η^2 = .02

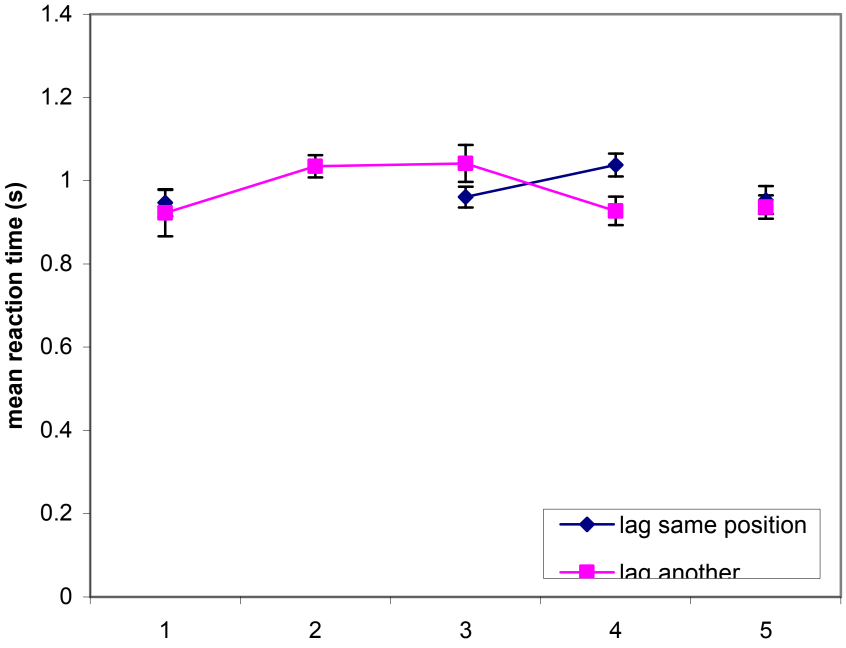

Figure 25. Experiment 6, conditions with verbal material/ set size 2/ object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 6. Test statistics for Experiment 6, verbal material, set size 2, object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(11) = 3.10	p < .05	partial η^2 = .47
lag 4 to the same position and lag 4 to another position	*t*(11) = -5.24	p < .01	partial η^2 = .71
lag 5 to the same position and lag 3-4 to the same position	*F*(1, 11) = 3.39	p = .09	partial η^2 = .24
lag 5 to another position and lag 2-4 to another position	*F*(1, 11) = 7.67	p < .05	partial η^2 = .41

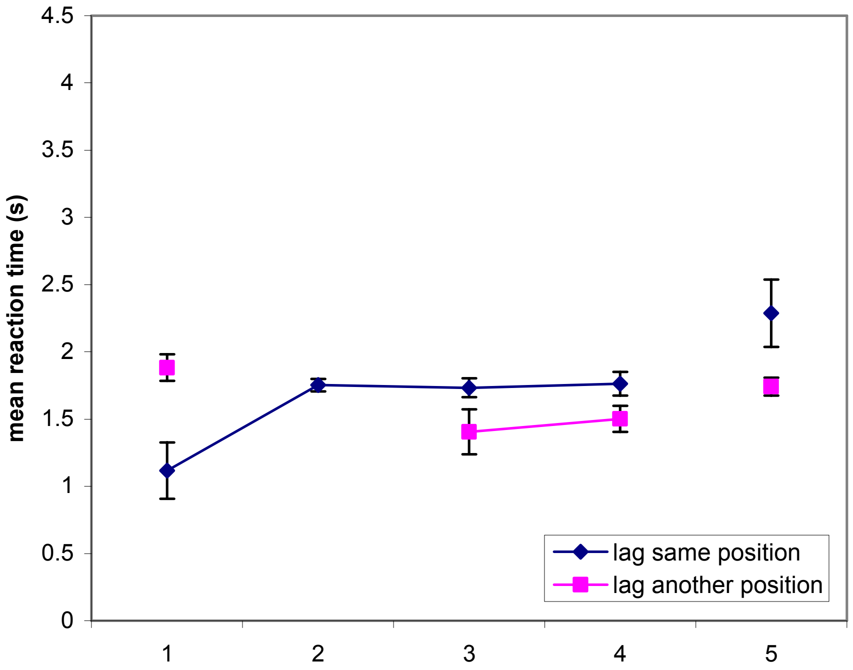

Figure 26. Experiment 6, conditions with verbal material/ set size 5/ no object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 7. Test statistics for Experiment 6, verbal material, set size 5, no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(11) = -3.69	p < .01	partial η^2 = .55
lag 4 to the same position and lag 4 to another position	*t*(11) = -3.51	p < .01	partial η^2 = .53
lag 5 to the same position and lag 2-4 to the same position	*F*(1, 11) = 18.40	p < .01	partial η^2 = .63
lag 5 to another position and lag 3-4 to another position	*F*(1, 11) = 11.73	p < .01	partial η^2 = .52

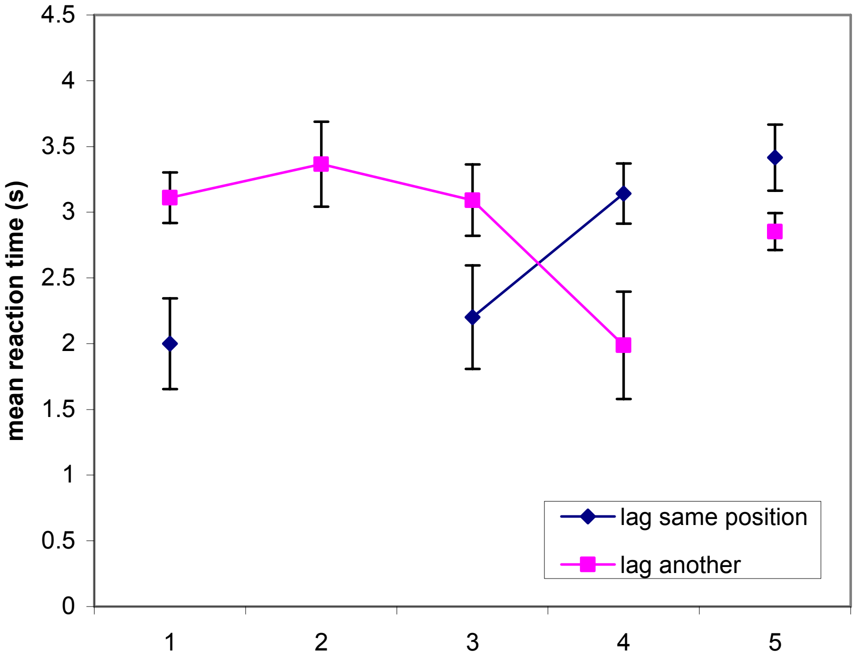

Figure 27. Experiment 6, conditions with verbal material/ set size 5/ object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 8. Test statistics for Experiment 6, verbal material, set size 5, object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(10) = 2.83$	$p < .05$	partial $\eta^2 = .45$
lag 4 to the same position and lag 4 to another position	$t(10) = -3.84$	$p < .01$	partial $\eta^2 = .60$
lag 5 to the same position and lag 3-4 to the same position	$F(1, 10) = 18.35$	$p < .01$	partial $\eta^2 = .65$
lag 5 to another position and lag 2-4 to another position	$F(1, 10) = .27$	$p = .62$	partial $\eta^2 = .03$

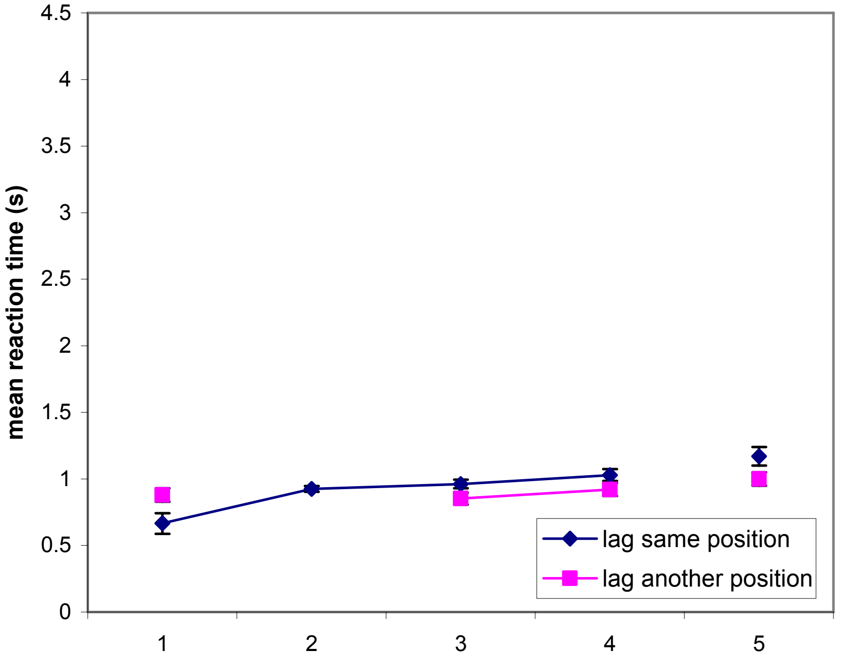

Figure 28. Experiment 6, conditions with spatial material/ set size 2/ no object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 9. Test statistics for Experiment 6, spatial material, set size 2, no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(11) = -2.88$	$p < .05$	partial $\eta^2 = .43$
lag 4 to the same position and lag 4 to another position	$t(11) = -2.57$	$p < .05$	partial $\eta^2 = .38$
lag 5 to the same position and lag 2-4 to the same position	$F(1, 11) = 38.31$	$p < .01$	partial $\eta^2 = .78$
lag 5 to another position and lag 3-4 to another position	$F(1, 11) = 7.14$	$p < .05$	partial $\eta^2 = .39$

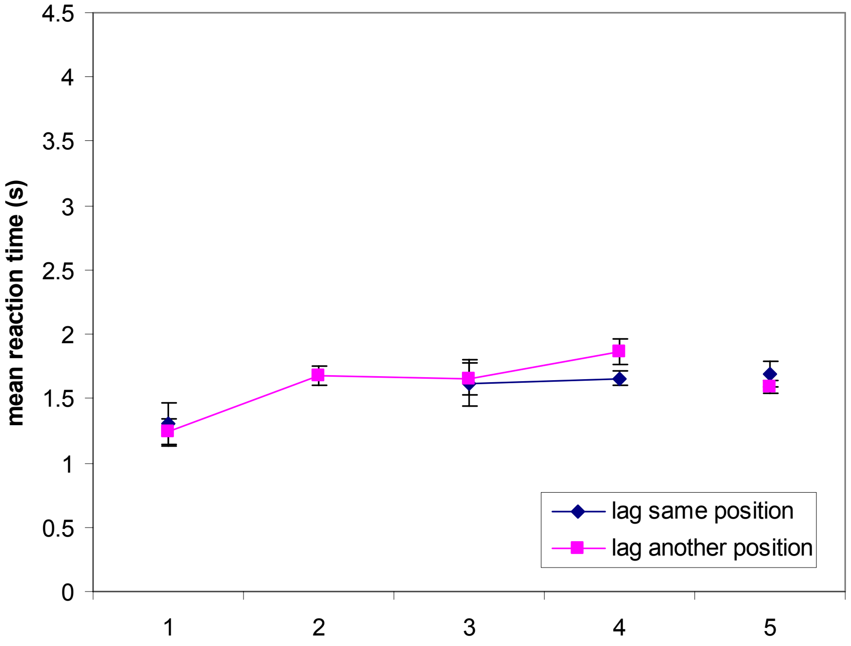

Figure 29. Experiment 6, conditions with spatial material/ set size 2/ object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 10. Test statistics for Experiment 6, spatial material, set size 2, object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(10) = .21$	p = .84	partial $\eta^2 = .01$
lag 4 to the same position and lag 4 to another position	$t(10) = 3.10$	p < .05	partial $\eta^2 = .49$
lag 5 to the same position and lag 3-4 to the same position	$F(1, 10) = .42$	p = .53	partial $\eta^2 = .04$
lag 5 to another position and lag 2-4 to another position	$F(1, 10) = 10.84$	p < .01	partial $\eta^2 = .52$

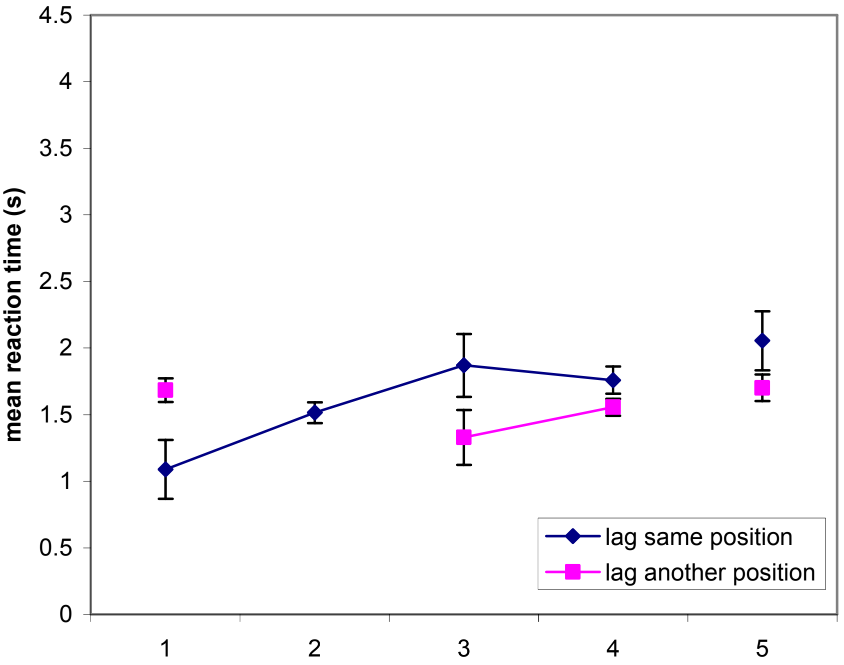

Figure 30. Experiment 6, conditions with spatial material/ set size 3/ no object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 11. Test statistics for Experiment 6, spatial material, set size 3, no object switch

Difference between			
lag 3 to the same position and lag 3 to another position	*t*(11) = -2.59	p < .05	partial η^2 = .38
lag 4 to the same position and lag 4 to another position	*t*(11) = -5.05	p < .01	partial η^2 = .70
lag 5 to the same position and lag 2-4 to the same position	*F*(1, 11) = 11.85	p < .01	partial η^2 = .52
lag 5 to another position and lag 3-4 to another position	*F*(1, 11) = 6.05	p < .05	partial η^2 = .36

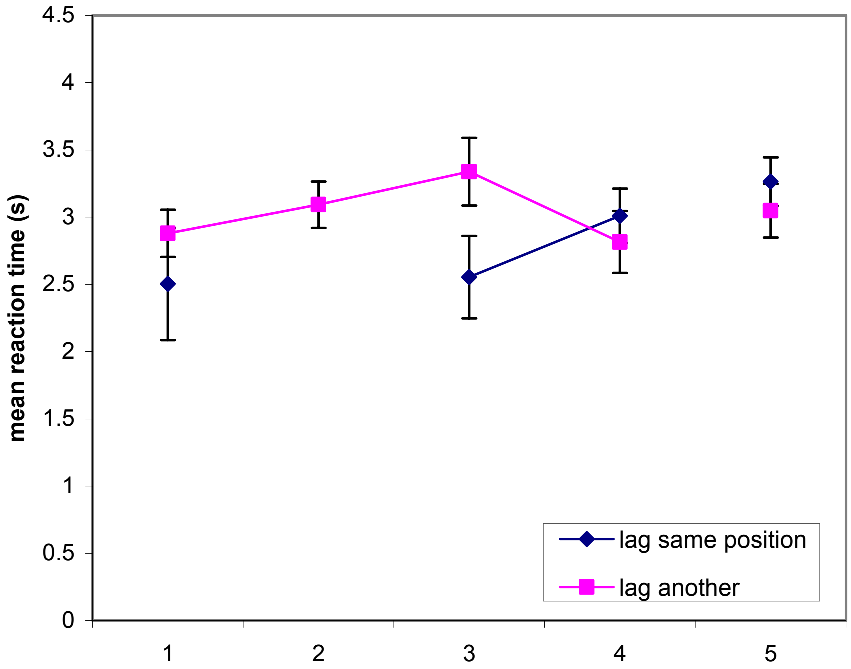

Figure 31. Experiment 6, conditions with spatial material/ set size 3/ object switch. Effects of lag to the same position on the screen and lag to another position on the screen. The whole data set is included. Error bars represent 95 % confidence intervals.

Table 12. Test statistics for Experiment 6, spatial material, set size 3, object switch

Difference between			
lag 3 to the same position and lag 3 to another position	$t(11) = 3.10$	$p < .05$	partial $\eta^2 = .47$
lag 4 to the same position and lag 4 to another position	$t(11) = -1.11$	$p = .29$	partial $\eta^2 = .10$
lag 5 to the same position and lag 3-4 to the same position	$F(1, 11) = 12.31$	$p < .01$	partial $\eta^2 = .53$
lag 5 to another position and lag 2-4 to another position	$F(1, 11) = .06$	$p = .81$	partial $\eta^2 = .01$