
Limitations of Human Visual Working Memory

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Chapter 1

GENERAL INTRODUCTION

A SHORT HISTORICAL SURVEY OF INVESTIGATIONS ON TEMPORARY STORAGE AND RELATED RESEARCH

Overview

In the present dissertation characteristics of visual short-term memory are investigated in a series of experiments. The following chapter is intended to give the reader an impression on the milestones of research on short-term memory in cognitive psychology. There has always been an interest in the functioning of human memory since there has been experimental research in psychology. Going back to the 19th century there was the famous work of Herrmann Ebbinghaus who in 1885 published his book *Über das Gedächtnis*. He investigated memory under carefully controlled conditions with objective and quantifiable observations, constructing lists with nonsense syllables. Ebbinghaus himself, being his only subject, learned thousands of such lists. From carefully recorded learning results he gave a systematic description of the scope of human memory for verbal material.

Very early in memory research a distinction was made between two types of memory systems. This goes back at least as far as to William James who, in his famous work *The Principles of Psychology* (1890), distinguished a primary and a

secondary memory. James associated primary memory with conscious awareness. According to James it contained information of the “just past” and lasted for several seconds. Secondary memory in contrast was seen as a more permanent store. Here properly recollected objects were stored. It contained knowledge of events or facts which we have experienced.

After these very early conceptions of memory there was not much interest for the next 50 years in further developing the idea of distinguishing different memory systems. Not earlier than in the context of approaches of information processing structures that correspond to James’ primary and secondary memory reappeared. A prominent example is Broadbent’s (1958) description of the information-processing system. According to this model information is perceived by the senses and then maintained briefly in a short-term store. From the short-term store information will be selected for further processing by passing a selective filter into a limited capacity channel. Here information is fully perceived and available for further processing including long-term storage of past events.

A detailed account of human memory was given by Atkinson and Shiffrin (1968). They developed a multi-component model of human memory – later termed the “modal model” of human memory – which had an enormous impact on memory research. Their model consisted of three distinct memory stores: The sensory registers, a short-term store and a long-term store. The short-term store was proposed to generally correspond to consciousness, which makes it a parallel to James’ concept of primary memory. Information is held in short-term memory for about 15 to 30 seconds after which it is lost due to decay or interference. The short-term store is of fundamental importance in the memory model. It has the central function of ruling the flow of information by certain control processes like rehearsal and coding of the stored information. Also, control processes of short-term memory decide which information is transferred into long-term memory.

Since then research on short-term memory has further developed, more elaborate concepts have been proposed and also the body of empirical data has grown. A very influential model of the temporary store has been the working-memory model of Baddeley and Hitch (1974) which has found broad acknowledgement and initiated a

whole tradition of research activity. The model now appears in standard textbooks on human memory and is considered to be part of general knowledge of every cognitive psychologist. Most relevant to the research on visual short-term memory is that in this model working-memory is not assumed to be a unitary system within memory. Instead it is constructed as a tripart system that distinguishes a store for visuo-spatial information and a store for verbal material from a control system, the central executive.

Around the same time W. A. Phillips conducted his classical studies on visual short-term memory (Phillips, 1974). He investigated its fundamental features and pioneered the methodology for the investigation of change detection and visual short-term memory. Although Phillips did not develop an elaborate model or theoretical framework of visual short-term memory, his empirical work was considered exhaustive to an extent that the main questions on characteristics of visual short-term memory seemed to be settled. As a result, there were only occasional studies that addressed some specific questions, but only until recently there was no considerable research activity that dealt with issues of visual short-term memory.

With the development of the new scientific paradigm of cognitive neuroscience, with advances in neurobiology, neurophysiology and brain research, major issues of cognitive psychology were taken up again and investigated under new perspectives. Also new questions arose and were addressed in the context of newly developed research areas. One such comparably new field in the area of research on human vision are studies on the phenomenon called “change blindness”. It refers to the observation that subjects fail to see large changes in visual scenes when they occur during disruptions such as eye movements, blank intervals, blinks, or movie cuts. It was concluded that we consciously perceive only very limited parts from our visual environment and store them in visual short-term memory (O’Regan, 1992; Rensink, 2000a, 2000b). From investigations on “change blindness” new insights into how we represent our visual environment were gained, in which short-term memory has a central role.

Also relatively new is the concept of transsaccadic memory. It has been developed in a line of research which investigates, how we build up a representation

of our visual world from one saccadic eye movement to the next. Transsaccadic memory is postulated to maintain visual information that has to be preserved across saccades. As some parallel features of transsaccadic memory and visual short-term memory have been found, the two systems have been claimed to be grounded on the same underlying structure (Irwin, 1991).

Much attention was received by the recent and very influential study on visuo-spatial working-memory by Luck and Vogel, published in *Nature*, 1997. They wanted to know how much information can be maintained in the store and determine the capacity of the store. In order to do this the unit of the store has to be known, so that the amount of stored information can be measured. Luck and Vogel approached this important issue, namely in what format information is stored in visuo-spatial working-memory. Is it stored in terms of whole and integrated visual objects? Or is information maintained in the form of single features? In other words, the authors addressed the problem of “binding”, which is a major subject in research on attention, and asked how this problem is related to visual short-term memory capacity.

An example of a theoretical framework that tries to encompass research in cognitive psychology and in neurophysiology is the neurocognitive theory on visuo-spatial working-memory, attention, and scene representation by Schneider (1999). It describes a two-stage conception of visuo-spatial processing that is based on the two-stage framework developed by Neisser (1967). Schneider (1999) developed a modified and extended version of this account in relating findings from behavioural experimental research to neurocognitive data.

The more recent concepts and empirical evidence are closely linked to the present work and will be taken up in the course of the present dissertation. Therefore, beginning with the working-memory model of Baddeley and Hitch (1974), the current concepts together with the experimental paradigms that were used to investigate them, will be outlined in more detail in the following section.

RECENT DEVELOPMENTS

The multi-component model of human working-memory by Baddeley and Hitch, 1974

Working-memory is a theoretical construct that was first introduced by Baddeley and Hitch (1974) in their model of human working-memory (see also Baddeley, 1986). The model represents a development of earlier models of short-term memory, such as those of Broadbent (1958) and Atkinson and Shiffrin (1968)(see above). As opposed to these older models the function of working-memory in complex cognition has been stressed, rather than memory itself. Also, in his model Baddeley focuses on the short-term store as the centre of cognition. Most importantly, the older models were assumed to comprise a unitary temporary storage system. But they met some problems such as accounting for the relationship between type of encoding and long-term memory, in explaining why patients with grossly defective short-term memory had apparently normal long-term memory and in accounting for the effects of a range of concurrent tasks on learning, comprehending and reasoning (Baddeley, 2000). To overcome these weaknesses the concept of a unitary short- term store has been abandoned by Baddeley and Hitch (1974) in favour of a multicomponent system (see

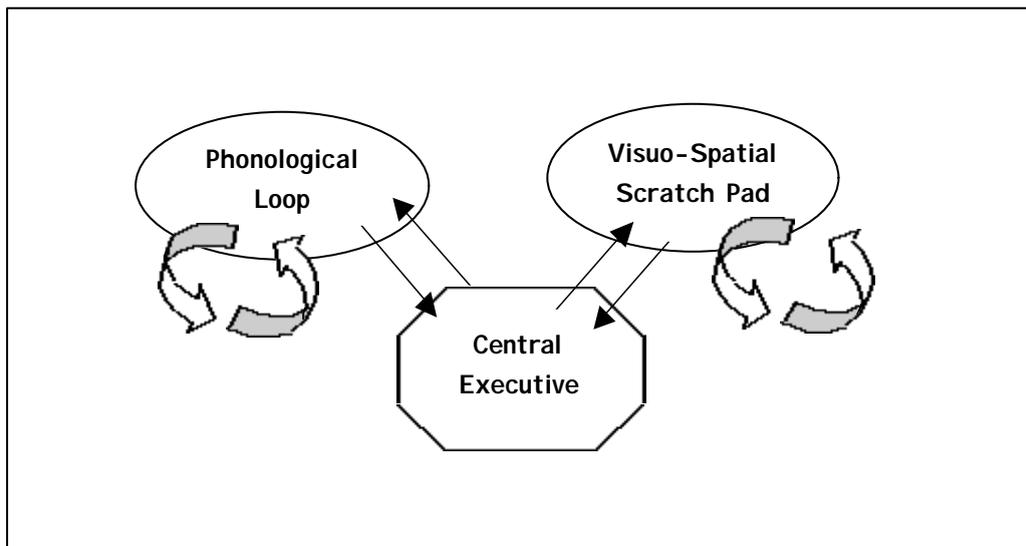


Figure 1.1 The working-memory model after Baddeley and Hitch, 1974.

figure 1.1). In the new model working-memory consists of three components – the central executive for reasoning, complex decision making and controlling some subsidiary slave systems for stimulus specific processing. Two such independent stores have been outlined in the original formulation of the theory, namely the articulatory loop and the visuo-spatial scratch pad (VSSP). The articulatory loop is needed for temporary storage and processing of verbal material, the visuo-spatial scratch pad processes visual information.

Features of the articulatory loop have been extensively investigated and are well established by empirical data. It has been found that the articulatory loop is time-based and therefore stores verbal material that can be uttered within a limited time. Evidence for a word-length effect in measuring the memory span supports this finding (Baddeley, Thomson, & Buchanan, 1975): The number of words that can be memorized depends on their length. If the words are long, only few can be maintained. If words are shorter, memory span for words increases. It appeared that the store can hold as much spoken material as can be uttered within approximately 2 seconds. The articulatory loop is also characterized by phonemic coding. This has been inferred from evidence that short-term memory for verbal material that is phonemically similar is worse than memory for sequences of words that are phonemically easier to distinguish (Baddeley, 1966).

The visuo-spatial scratchpad is a rehearsal system for visual material. It is defined by its main function to temporarily store visual information and to serve as an on-line "cache" for visual and/or spatial information (Logie, Zucco, & Baddeley, 1990; Logie, 1995). Its second function refers to the ability to manipulate the contents of short-term storage. A typical example is a mental imagery task that requires the active construction of a visual image (e.g. Brandimonte et al., 1992). Most of the empirical studies in the working-memory framework concentrated on distinguishing the VSSP from the articulatory loop. Evidence for distinct subsystems has mainly been taken from dual-task experiments. Still missing, until today, is the attempt to detail the characteristics of the visual store, paralleling the work on the articulatory loop.

Focus of the empirical work on Baddeley's working-memory model has been to show the non-unitary nature of working-memory and the separability of its subcomponents. This feature is strongly supported by the finding of selective interference effects from dual-task paradigms with normal adults (Baddeley, 1986; Logie, 1995), but also from studies with brain-damaged patients (Della Sala & Logie, 1993) or from developmental studies (Hitch, 1990). In the dual-task experiments frequently a memory task which has been developed by Brooks (1967) has been applied. In order to show the existence of two separable subcomponents of working-memory, Baddeley, Grant, et al. (1975) conducted a dual-task experiment with Brooks' visual imagery task as a spatial primary task and either a spatial or a verbal secondary task. The results showed that two spatial tasks cannot be accomplished simultaneously. Baddeley, Grant et al. (1975) inferred from this result that both tasks need processing resources from the same capacity-limited subsystem of VSSP. The verbal and the spatial task, on the other hand, could be conducted at the same time. This was suggested to be the case, because the two tasks use resources from two different subsystems. A further example of this experimental approach and support for the separability of subcomponents in working-memory is a study by Logie and Marchetti (1991). They demonstrated the double dissociation that retention of spatial patterns, but not retention of non-spatial visual information was disrupted by arm movements. On the other hand, retention of non-spatial visual information, but not retention of spatial patterns, was disrupted by a visual interference task. From this finding it was inferred, that memory for non-spatial and memory for spatial visual information is not stored within the same memory structure.

Dual-task experiments were also used to increase task difficulty and to find the limit of the processors. In the original studies (Baddeley & Hitch, 1974), subjects had to remember sequences of up to six digits in a primary task while performing simultaneously varying secondary tasks such as verbal reasoning, comprehension, and learning of verbal material. The results showed that performance in the tasks was not affected by a concurrent digit load of up to three. However, with sequences of six digits, performance on all tasks was significantly poorer. This was attributed to the functioning of the central executive that is responsible for attending to and coordinating the processing of all incoming information. The articulatory loop was

able to maintain up to three digits without overloading the central control system. However, a digit load of greater than three exceeded the capacity of the articulatory loop and placed additional demands on the central processor. Because a division of the central processor capacity was now allocated to maintain the longer digit sequence, performance on the other tasks got worse.

Baddeley's working-memory model can help to summarize current insights on short term retention and initiate further research. It has proven to be very useful and meanwhile underwent modifications and further development (Baddeley, 1986; Logie, 1995; Smyth, Pearson, & Pendleton, 1988). In a recent suggestion a fourth component is added to the original model, namely an episodic buffer, which is proposed to provide temporary storage of information held in a multimodal code. It is supposed to be capable of binding information from the subsidiary systems, and from long-term memory, into a unitary episodic representation (Baddeley, 2000). The working-memory model has been successful in giving an integrated account not only of data from normal adults, but also neuropsychological, developmental and neuroimaging data (Becker, 1994; Gathercole, 1999; Smith & Jonides, 1997). The main contribution of working-memory was to outline separate subsystems of short-term memory, distinguishing storage functions for verbal and for visual material. It has initiated a great extent of research; numerous studies directly investigated questions related to the working-memory model. Especially popular is the model in research on language processing. Open questions remain mainly concerning the central executive. But also a detailed description of the characteristics of the visuo-spatial subcomponent remains subject to further research.

The classical studies by W. A. Phillips

Classical studies on short-term retention of visual stimuli were carried out by Phillips in the 1970s. The experimental methodology he used is now widely applied in studying change detection and hence, visual short-term memory. Phillips used abstract visual material in the form of random patterns of black and white square matrices which were of varying complexity, e.g. 4×4, 6×6 or 8×8 squares. In his experiments he showed on different trials one such matrix and after a varying

retention interval between 0 and 9 seconds he showed a second matrix. The two matrices either were identical or differed in one square – either a black square disappeared and became white or a black square appeared at the place of a white square. Subjects were asked to indicate whether the two patterns were identical or different. Accuracy of report was measured. The results for patterns of three levels of complexity are shown in figure 1.2 in which percent correct responses are shown as a function of the delay between the first and second display. It can be seen that memory for successively presented patterns is close to perfect, and that performance declines dramatically after an interval of only 1 second. This decline is stronger for the more complex patterns of 6×6 or 8×8 squares than for the simpler one of 4×4 squares. So, memory performance declines with the duration of the retention interval. However, the decline between 2 and 9 seconds of retention is comparably flat. In a series of this type of experiments Phillips could show that visual short-term memory is different from a sensory store in that it has a limited capacity, it is not tied to

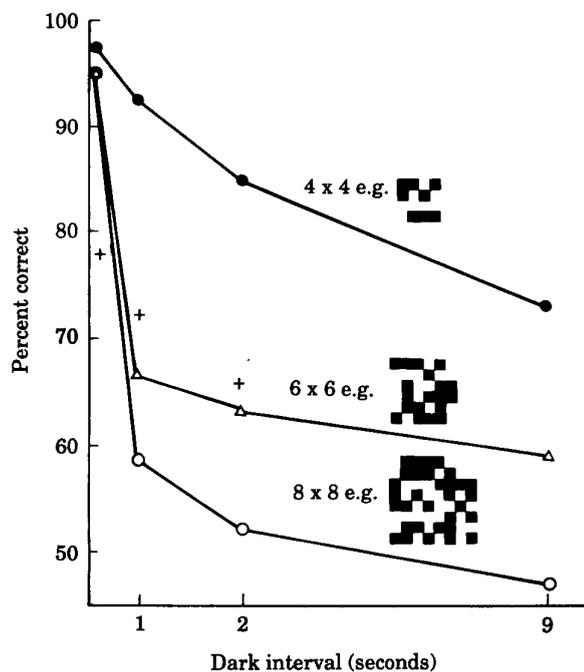


Figure 1.2 Accuracy of report in a same/different task with random square matrices of different complexity that had to be retained for a duration between 0.5 and 9 seconds (from Phillips, 1974).

spatial position, it is not maskable, it does not show loss of efficiency over the first 600 ms and slow loss over at least the first 9 seconds, and finally, it is dependent on pattern complexity (Phillips, 1974). Also, the distinction between the visual short-term store and visual long-term memory has been shown by using this kind of visual material in a recognition task (Phillips & Christie, 1977). Phillips and Christie (1977) conducted a recognition task with the pattern matrices in which they presented a number of patterns one after the other. Task of the subjects was to remember as much patterns as possible. In the recognition phase pattern matrices were again shown to the subjects. They had to tell whether they had seen a matrix before or whether it was a new one. It appeared that the subjects could only remember the very last pattern of the series that had been shown to them. This suggests that with sequential presentation visual short-term memory has a capacity of only one visual display and that each time a new display is presented, it overwrites the previous one.

With these results the fundamental questions on the characteristics of visual short-term memory seemed to be generally answered so that for the time being there was no further extended research activity on this subject. Only recently, the issue was taken up again (by Luck and Vogel, 1997, see below) and short-term memory functions were investigated from new perspectives such as change detection (e.g. Pashler, 1988), attention (e.g. Rensink 2000b), or scene representation (e.g. Henderson & Hollingworth, 1999).

Change blindness experiments

The subject of the limitations of short-term visual representations received much attention in connection with the phenomenon of “change blindness”. In a change-blindness experiment abstract visual objects or natural scenes are shown to the subjects e.g. in a “flicker paradigm” (see figure 1.3): Alternately two pictures are presented which differ from each other in an object or a feature that changes. The task of the subjects is to find the change. If the two pictures are presented subsequently without interruption then the change is detected very easily. However, when the two pictures are separated by brief visual disruptions or distraction, which in the experiments could occur as e.g. eye movements, blank intervals, blinks, movie

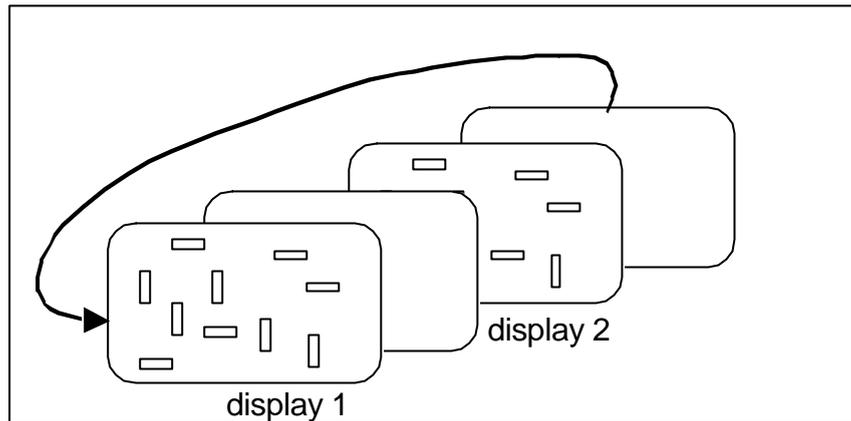


Figure 1.3 The flicker paradigm: Two displays alternate disrupted by a blank interval.

cuts etc. (O'Regan, Rensink, & Clark, 1999; O'Regan, Deubel, Clark, & Rensink, 2000; reviews: Rensink 2000c; Simons & Levin, 1997), then it becomes extremely difficult to find the change. All the different disruptions mask the transient caused by the local change that would otherwise attract attention, so that the change is easily detected. The results of the various experiments are all similar: In all of them it was shown that normal human subjects do not immediately notice the large and often dramatic changes in visual stimuli. From this evidence for “change blindness” it has been inferred that only little information from our visual environment is consciously perceived and stored in visual short-term memory (O'Regan, 1992; Rensink, 2000a, 2000b). This finding, that the visual representation we preserve from one view to the next is very limited, has challenged the traditional view in perception research that the normal observer of the visual world stores a detailed visual representation, which is long-lasting and spatiotopic, forming a coherent and richly detailed internal picture of the visual environment. Instead it appears that people can monitor just between one and four items for a change (Rensink, 2000c). This number corresponds to estimates of the attentional capacity (Pylyshyn & Storm, 1988), the capacity of transsaccadic memory (Irwin, 1991, 1996), and also of visual working-memory (Cowan, 2001; Luck & Vogel, 1997; Schneider, 1999; Shibuya & Bundesen, 1988). If only so little of our visual environment is stored, how can it be explained that we have the impression to perceive a detailed, stable and coherent visual world around us? In the framework of the coherence theory by R. Rensink (2000a) the function of providing spatio-temporal coherence is attributed to focused attention. It is focused

attention that is needed to see the changes in change blindness experiments.

Coherence theory also implies that there is little visual short-term memory apart from what is being attended.

Not only at the conceptual level, but also regarding the methodology there are close relations between the study of the phenomenon of change blindness and the investigation of the visual short-term store. The flicker paradigm resembles standard short-term memory paradigms as for instance that used by W. A. Phillips (as described above) to an extent that often allows direct comparison of results. As can be taken from figure 1.4, in a flicker experiment the first picture and the image with the change are continually alternating with a brief blank interval between them. The blank interval causes transients that cover the local motion signals caused by the change which usually would draw attention to the location of the change, so that it would easily be detected. The alternation continues until the observer sees the change and responds to it (Rensink et al, 1995, 1997). Performance is measured by response times. In a short-term memory paradigm (e.g. the Phillips paradigm) subjects have to respond to a change between the first and the second display that are both shown only once. This corresponds to a single alternation of displays in a flicker experiment. The short-term memory paradigm has therefore sometimes been termed a “one-shot” change detection paradigm (e.g. Rensink, 2002).

Transsaccadic memory

When a scene in a natural environment is perceived the eyes move approximately three times per second with saccadic eye movements. Each time a different area, an object or part of a scene is fixated for about 300 ms and projected onto the fovea of the retina. During saccades, which last about 30 ms, visual encoding is suppressed (Matin, 1974), so that a representation of our visual environment has to be built up by a series of snapshots of the fixations that are interrupted by blind intervals during the saccades. This means that information from separate fixations must be retained and integrated as the eyes move from one local region to the next. A frequent proposal is that information such as target locations and identity of objects is accumulated and temporarily stored across saccadic eye movements in a

transsaccadic memory store. This memory store has often been identified with visual short-term memory.

A typical question in research on transsaccadic memory is what kind of information is preserved from one fixation to the next across a single saccadic eye movement. How is this information represented in the store? What is its capacity and how is the transsaccadic integration of successively obtained information accomplished so that we get the impression of a stable and continuous world across eye movements around us? In a series of studies Irwin (e.g. 1992, 1996) explored the properties of transsaccadic memory. A first major finding in these studies was that visual information is *not* accumulated and integrated in a very detailed, high-capacity and spatiotopically organized visual buffer. This was evidence against the traditional view widely held in perception (e.g. McConkie & Rayner, 1976; Wolf et al., 1980; Jonides et al., 1982) which proposed that when the eyes move, the contents of new eye fixations was spatiotopically superimposed on the contents of previous eye fixations and integrated in such a way that a detailed composite representation of the visual environment would emerge. Instead, several investigators found that pre- and postsaccadic information is not fused in successive fixations in that way to obtain an integrated composite pattern (e.g. Irwin et al., 1983; O'Regan & Levy-Schoen, 1983; Rayner & Pollatsek, 1983). Nevertheless, transsaccadic storage of information does occur, but instead being of high detail it is more limited and abstract. So, changes of visual objects across saccades in properties such as letter case and object size and spatial positions are often not detected (Irwin et al., 1983). In experiments carried out by Irwin and colleagues subjects were required to compare two random-dot patterns or letter displays which were separated by a saccade. The second display was either identical or different to the first. Task of the subjects was to report whether they could identify a change in the second pattern. Irwin found a capacity limitation of transsaccadic memory that could be estimated to be in the order of 3 – 4 items: Accuracy was higher for simple patterns than for complex patterns. It was also higher when only 6-dot patterns were presented compared with 8- or 10-dot patterns. In arrays of letters only 3 – 5 letters could be retained across saccades independent of the total number of letters presented (see also Irwin, 1992). By varying the interval between the first and second pattern between 1 to 5000 ms it could be demonstrated

that there was only a little effect on performance, suggesting that information can be held in transsaccadic memory for a relatively long time without substantial loss (Irwin, 1991). In addition, displacement of patterns had no effect on performance, indicating location-independent representation of information. More recently it has been found that transsaccadic memory for absolute spatial locations is poor, while relational information is well retained from one fixation to the next (Carlson-Radvansky, 1999; Verfaillie & De Graef, 2000).

To summarize, some parallel characteristics between short-term memory and transsaccadic memory can be determined. These are similar to an extent that transsaccadic memory and visual short-term memory are claimed to rely on the same underlying structure. In research on transsaccadic memory theoretical concepts are discussed that are clearly related to questions on visual short-term memory. Also, the methodology is in part comparable to paradigms used in research on short-term memory, which enables us to directly compare and relate data from both areas of research.

The study by Luck and Vogel, 1997

A very influential publication on visual short-term memory was the study of Steven Luck and Edward Vogel, published in *Nature*, 1997 (extended version: Vogel, Woodman, & Luck, 2001). The authors reverted to the subject of characterizing visual short-term memory when there was only little interest in the subject after the initial studies of W. A. Phillips (see above). In the meantime neurobiological accounts on visual working-memory had been developed, and research had begun to delineate the neural substrate of working-memory systems and to search for physiological explanations for memory functions (e.g. Goldman-Rakic, 1987, 1996; Jonides et al., 1993; Petrides, 1996; Smith et al., 1995; Smith & Jonides, 1997). The influence of the broader approach of cognitive neuroscience was certainly one motivation to take up behavioural studies on working-memory, especially as new questions resulted from the new lines of research.

Most of the experiments of the present dissertation are closely related to the work of Luck and Vogel (1997). In fact, one chapter (chapter 3) directly deals with the

question that Luck and Vogel (1997) were investigating in their series of experiments. It is the question on the relation between the capacity of visual short-term memory (VSTM) and the format in which the information is stored in VSTM. In a series of experiments they used an experimental paradigm that was similar to the change detection paradigm formerly used by W. A. Phillips: Subjects first saw a display that contained a number of visual objects that had to be remembered. After a viewing time of 100 ms the display disappeared, then a defined blank interval (900 ms) followed until a second display was shown. This second display was either identical to the first display or one of the objects differed in one of its features. Task of the subjects was to indicate whether they could identify a difference between the two displays. Performance was assessed as a function of the number of items in the stimulus display. The visual items were geometrical objects in form of squares or bars that could vary in visual properties such as size, colour, or orientation.

In a first set of experiments Luck and Vogel determined working-memory capacity for simple colours. The results show nearly perfect performance for display sizes of 1 – 3 items and a systematic decline with increasing number of items from 4 to 12. A capacity estimation indicated that roughly four items could be held in visual working-memory. In a second set of experiments Luck and Vogel addressed the issue of the unit of visual working-memory. Is information stored in terms of single features or of integrated visual objects? This question was investigated by varying the number of features that could change in an experiment. In one condition, e.g., objects of different colours and orientations could only change their colour on a given trial, orientation never changed. In a second condition only the orientation could change. In order to solve the task it was sufficient to retain only the relevant, possibly changing feature. In a third and critical condition the change could occur in one of both features. Which feature would change was not known to the subjects, so that it was necessary to retain both, colour and orientation of the items. The experimental results showed that visual objects could be memorized equally well no matter whether only one of the features was relevant for the task, so that only one feature had to be retained, or whether up to four features had to be stored in order to be able to solve the task. From the experimental results Luck and Vogel drew the conclusion that information is stored in terms of integrated objects. At the same time

they rejected an alternative view that information is stored in terms of the features of objects. In their view, storage is object-specific and refers to whole internal objects as a configuration of conjoined features, which is independent of the number of its dimensions, hence of the complexity of the objects. They stated that the capacity of the visual short-term store comprises about four such items.

As will be shown in the course of the present dissertation these results can basically be confirmed – with a crucial difference, however. It will be shown that the processing of objects actually is dependent on the complexity of the objects: Objects that are defined by a conjunction of features are not retained as accurately as objects that are defined by one feature only.

The neurocognitive theory of visuo-spatial working memory by Schneider, 1999

An important contribution to research on human short-term memory is the theoretical framework by Schneider (1999) in which he suggests how visuo-spatial working memory, attention and scene representation are related. In his neurocognitive approach Schneider (1999) takes into account not only behavioural data, but also concepts that are based on neurobiological research such as single unit recordings in monkeys, lesion data in humans and monkeys, and neuroimaging studies. He provides theoretical concepts for a fuller understanding of how the visual world is represented “inside the head”. The theory of Schneider (1999) is an exemplary approach in the interdisciplinary field of the cognitive neurosciences which has been established in the recent years.

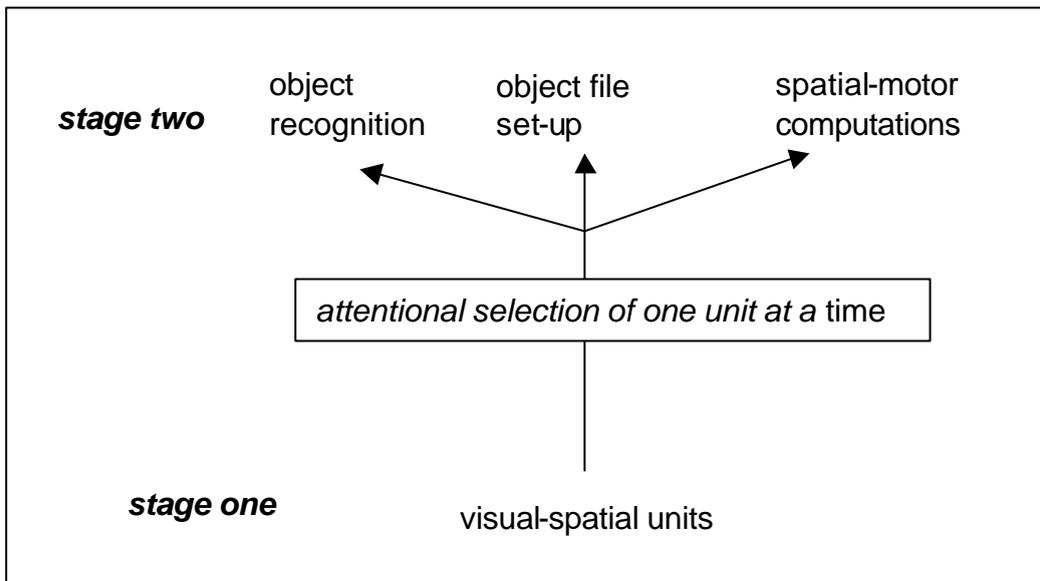


Figure 1.4 The two stages in the modified two-stage theory of visuo-spatial processing by Schneider, 1999.

Schneider (1999) developed a modified and extended version of the two-stage conception of visuo-spatial processing by Neisser (1967) by taking into account current relevant neurocognitive data. The two stages (refer to figure 1.4) shall briefly be described with an emphasis on stage two, a part of which is visuo-spatial working memory (VSWM). In stage one elementary low-level information of the currently available retinal input, such as colour, texture or oriented contours, is computed in parallel. In addition the information is divided into segments called *visual-spatial units*. Stage two contains high-level visuo-spatial information which is selected by an attentional process from the visual-spatial units provided by stage one. It delivers the visuo-spatial information for goal-directed actions and comprises three processing streams which operate in parallel: object recognition, the computation of a spatial-motor program for the selected unit, and the setting-up of an object file. An object file contains high-level visuo-spatial attributes, such as complex shape parts or colour, and an index that allows access to the visuo-spatial attributes of an object file. It guarantees the spatio-temporal continuity of an individual object. On the basis of neurophysiological data (as described e.g. in Zeki, 1993; Milner & Goodale, 1995) Schneider (1999) proposes that the high-level visual attributes are located within the inferior-temporal and posterior parietal areas in the primate brain. The indices are

proposed to be located within the posterior parietal cortex, based on the specific neuropsychological symptoms that are observed in patients that suffer from the so-called *Balint* syndrome (Rafal, 1997). One part of the second stage of the model by Schneider (1999) is VSWM. It is postulated that it has a capacity of up to four object files. Always only one of the four objects is activated at a time, the other selected objects are off-line. Access to the temporary store of stage two is controlled by activation-based competition between the objects. This means that an object gets into the store when it has a sufficient level of activation, that has to be higher than the activation of at least one of the stored objects. A refreshment process is responsible for increasing the activation level of the stored objects in order to prevent them from getting lost from VSWM, in other words, to prevent forgetting.

According to Schneider (1999) VSWM has two functions. Firstly, the function to actively organize and modify information such as mental imagery operations. And secondly the short-term retention of relevant information. In his view the short-term function is not only required, when visual objects are not longer visible, but also when they are still present at the sensory surface. He postulates that one object in VSWM is active at a time and gets bottom-up support of activation flow from the retinal input, the remaining up to three objects do not get this constant activation flow. The short-term function of VSWM is used to maintain these objects without direct activation in the store and to prevent them from getting lost. Frontal areas, and in particular areas of the prefrontal cortex (PFC), are involved in the short-term function of VSWM (e.g. Courtney et al., 1997; Miller, Erikson, & Desimone, 1996; Rao, Rainer, & Miller, 1997). It is suggested that the PFC contains indices which control the object file indices which are located in parietal areas. By this a loop between indices in PFC and indices in parietal areas is established. It is assumed that this loop is responsible for a refreshment process that increases the activation of an index. Thus the index is prevented from being forgotten.

In the course of his theory Schneider (1999) further specified how the particular functions of visuo-spatial processing can be conceptualised. He suggested, e.g., that the objects in VSWM could be distinguished and segregated by a mechanism of temporally-based neural coding (following, e.g., von der Malsburg, 1981; Singer, 1989; Singer et al., 1997). He also has described on a mechanistic level the

functioning of short-term maintenance, refreshment and forgetting. His new theoretical concepts are illustrated by a number of experimental data which include, among others, evidence from research on transsaccadic memory and on change blindness. In being very explicit about specific mechanisms that are involved in visuo-spatial processing Schneider (1999) provided theoretical concepts that can be tested experimentally. The concept of VSWM as defined in the neurocognitive theory of Schneider (1999) forms the theoretical basis for the present dissertation. It inspired most of the experiments introduced here and was essential for the theoretical assessment of the results.

THE SCOPE OF THE PRESENT DISSERTATION

Limitations of human visual working memory

Following on from the above mentioned studies the present dissertation contributes to an understanding of the nature of temporary storage of visual representations, which is accomplished by visuo-spatial working memory (VSWM). An important achievement of the empirical work in the framework of Baddeley's concept of working memory was the finding that there is a separate store for temporary retention of visual information as opposed to verbal material. However, while there has been extensive research on characteristics of the subcomponent of working memory for verbal material, the articulatory loop, such as its capacity or the duration of the store, the same is not true for the visuo-spatial scratch pad, the subcomponent of VSWM for visual information: The knowledge about properties of the visual store has been only very rudimentary to date. The current series of experiments contributes to exploring the characteristics of the visual short-term store and will add to our knowledge on the conditions of temporary storage of visual representations.

In most theories of working memory postulated functions include the short-term retention of visual information, and also active organization and modification (Miyake & Shaw, 1999). In the present dissertation aspects of the short-term

retention function of visuo-spatial working memory as defined by Schneider (1999) (see above) are investigated. Throughout the study, therefore, reference will be made to visual short-term memory (VSTM) as a subcomponent of VSWM.

It is a defining characteristic of VSTM to be limited in several aspects. The general aim of the present dissertation is to delineate these limitations in more detail. The limitations of three aspects of VSTM will be addressed:

- ✓ Firstly, limitations in the duration of the store are explored for a new type of visual stimulus material used throughout the present study. What is the time-course of VSTM? When does retention for very short intervals rely on VSTM alone, after the decay of iconic representations? How long can the information be represented in the store before it is forgotten?
- ✓ The second aspect refers to limitations of the capacity of VSTM. How much information can be maintained in VSTM? This question of the amount of information stored in VSTM cannot adequately be answered without specifying the format in which the information is stored in VSTM. Is information stored in terms of the number of whole objects, or does the number of features of the objects determine the capacity? The present dissertation investigates whether the binding of object features has costs for storage in VSTM. This issue has also been addressed by Luck and Vogel (1997). However, somewhat different results were obtained. The results of the current work, together with a modified view on the issue are presented.
- ✓ Thirdly, limitations in VSTM that occur due to conditions of retrieval are studied. Overall performance limitations cannot be attributed to a limitation in the capacity of the store alone, but also to other components of VSTM. In the present dissertation the process of VSTM retrieval is studied in a series of experiments. Severe limitations of this process are described. In research on VSTM the aspect of retrieval so far has received only little attention. Up till now there are no systematic investigations and no exact theoretical ideas on how the retrieval of information from VSTM could be conceptualised. Here, together with empirical results a description of retrieval limitations in VSTM on a more theoretical level is provided.

Common of all the experiments of the present dissertation is the stimulus material and also the experimental procedure. Therefore, both will be described in the following section.

Approach of the present study

Stimulus material

It has been mentioned before that the choice of visual stimuli has implications for the kind of questions that can be addressed and for the theoretical inferences from the experimental results. In the various studies that deal more or less directly with short-term memory functions different types of stimuli have been used. They vary in their degree of abstractness and range from very simple, abstract and static visual objects (e.g. Phillips, 1974; Luck & Vogel, 1997) to complex and dynamic natural scenes, such as film clips (e.g. Levin & Simons, 1997), and even real-life interactions (Simons & Levin, 1998). Obviously the advantage of using realistic stimuli is that they can more directly be related to everyday life. However, it is difficult to control for all the processing factors that are involved. Abstract visual material, occurring under artificial laboratory conditions, can be well controlled and more concisely be analysed.

Throughout the present study visual material of a very high degree of abstractness and simplicity is used, namely individual objects of the simple geometrical form of a rectangle (see figure 1.5). These rectangles are defined by simple visual features such as colour, orientation, and length. They are well suited for the purpose of

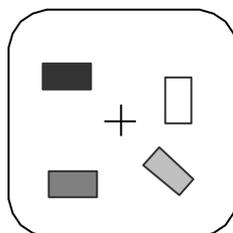


Figure 1.5 An example of the stimulus material used in the experiments of the present study: multidimensional abstract objects of different colour (represented by different shades) and form.

investigating the issues of visual working memory that are subject of the present study. A very important feature of the stimuli is that they encourage encoding and storage within the visuo-spatial format. When meaningful pictures such as a flower or a house are shown they are immediately categorized and access to name and associated semantic information is provided. More importantly, an alternative verbal code is generated. Thus information that is not strictly visual – like digits and letters which are often used in visuo-spatial tasks (e.g. Pashler, 1988) – is very likely to be processed with the contribution of verbal memory resource.

Furthermore, it can be expected that in a memory task usually the most efficient and economic memory strategy is applied. Therefore, objects that are visually simple, but complicated to name will preferably rely on a visual code rather than a verbal code. In the case of the multidimensional geometrical objects it is reasonable to presuppose that they are stored primarily visually and not verbally. If a verbal encoding strategy would be used for each of the objects a unique combination of colour, location, orientation, and size (e.g. “the horizontal, green, small rectangle on the top left side”) had to be encoded and stored within a very limited time. Luck and Vogel (1997) provided evidence that for such multi-dimensional geometrical objects subjects use a visual rather than a verbal code in a short-term memory task: In experiment 2 of their study they introduced a verbal memory load while arrays of coloured squares had to be memorized. Memory performance was not poorer than in the same experiment without verbal load. Their results support earlier findings on the role of verbal codeability in the storage of visual information using random shapes (Clark, 1965; Kelly & Martin, 1974). No effect of verbal codeability on performance was found for simple figures which means that subjects did not rely on a verbal code in retention, but on a visual code. Further evidence for the present assumption is provided by Posner and Konick (1966) who found that with simple stimuli recognition performance was not influenced by verbal cues. For complex visual material (pictures), on the contrary, it has been found that the degree to which the stimulus can be described verbally is directly related to recognition accuracy (Wyant, Banks, Berger, & Wright, 1972).

As has been mentioned already, an important reason to choose geometrical objects and not, e.g., random shapes (as in Clark 1965, or Kelly & Martin, 1974) or

random square matrices (as in Phillips, 1974) is that our stimulus material, which consists of single, well defined objects of variable and controllable complexity, are readily perceived as independent units. This is important in order to determine the unit of the store. When the retention of defined objects is required it is possible to refer to the capacity in terms of the number of objects or to the number of their features.

Experimental Paradigm

The standard experimental paradigm in the present study was a change-detection task that is similar in its procedure to the paradigms used by Phillips (1974) or Luck and Vogel (1997)(see figure 1.6): On different trials first a sample array is presented that contained the stimuli which were required to be remembered by the subjects. After a defined retention interval a test array was shown. The standard task of the subjects was to decide whether the test array was the same as the sample or whether the test array contained an object that differed in one of its features from the respective object in the sample array. In half of the trials the test array was identical with the sample array. In the other half of the trials one of the test stimuli differed in one feature value of one object (e.g. the colour of a particular object was red in the test array, whereas the colour of the respective object in the sample array appeared to

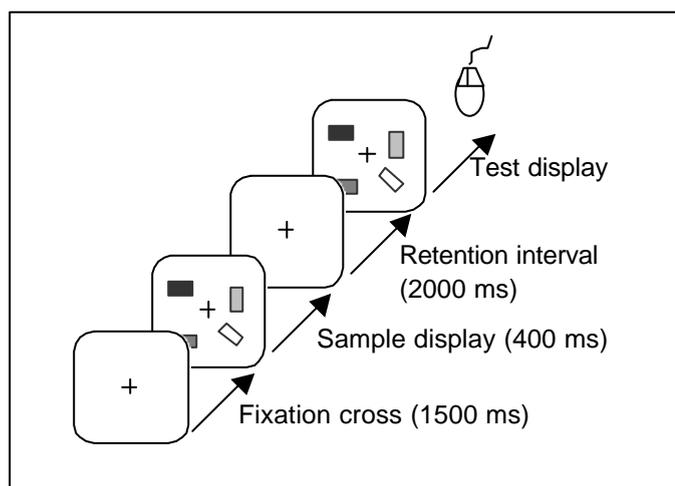


Figure 1.6 Example of the change detection paradigm that has been used in different variations in the experiments of the present study.

be green). This kind of test display is labelled “whole test array” to discriminate it from other modified test displays. Another kind of test display, called the “single test item” display, consisted of just one object that occurred at the same location as it has been presented in the sample display before. Subjects responded by a mouse click: the right button when the objects of sample and test array were the same, the left button to indicate a difference. Response was measured by accuracy (% correct).

An important characteristic of the paradigm used is that the information that has to be retained is presented simultaneously in one display and not sequentially as in some other studies visual short-term memory (e.g. by Postman & Philips, 1965; Philips & Christie, 1977). There are findings in favour of the technique of simultaneous presentation. Frick (1985) has shown that short-term retention of information that is presented simultaneously (all stimuli at once) is significantly better than retention of the same information presented sequentially (one stimulus at a time). This result is interpreted such, that visual short-term memory operates on only one picture at a time and contains spatial, but not temporal information. Frick (1985) concludes that information that is presented sequentially is not as a whole retained reliably in visual short-term memory. The suggestions of Frick (1985) correspond to the conclusion of Phillips and Christie (1977) who claim that visual working-memory has the capacity of only one visual display. In their experiments they used a visual recognition memory task with meaningless black and white random square matrices. They investigated the serial position curve, which represents the probability of correctly recalling a matrix as a function of its serial position in the course of presentation. After showing a number of the matrices to the subjects they tested recognition for matrices that either had been shown before or that were new. A new matrix differed in one square from a previously shown matrix. The results show a recency effect for only the last item of the list, i.e. recognition accuracy was approximately the same for all objects apart from the one that was shown last. It appears that whenever a new display occurs it presumably overwrites the preceding one. Hence, visual memory seems to refer to one given picture, display, or scene. The amount of information contained in this single picture can be retained to a certain extend, i.e. within the capacity limits of the store, but from sequentially presented information only the last sequence is retained. A further

reason to use a paradigm with simultaneous presentation of information is that it can be related to major work on visual short-term memory that has been described above. In particular Philips (1974) and Luck and Vogel (1997) also used this experimental procedure. Furthermore, also in empirical work from the above mentioned related fields such as visual search, change blindness, or transsaccadic memory information is retrieved from one single display. Therefore, a more direct comparison of results is feasible.

The structure of the present study

Together the three aspects of VSTM limitations as mentioned above comprise a large and diverse field of experimental evidence and theoretical issues on VSTM. Therefore, in the present dissertation the three aspects of retention, format and retrieval of VSTM, are treated in rather independent chapters. Chapter 2 (including experiments 1 and 2) is dedicated to the issue of limitations in maintaining information in VSTM. Chapter 3 (including experiments 3a, 3b, 4) is concerned with the capacity of VSTM, more specifically with the relation between the format of VSTM and storage limitations. Chapter 4 (including experiments 5 – 7, 8a, 8b) investigates limitations of retrieving information from VSTM. Each of the three chapters begins with a separate introduction, which will inform the reader specifically about the state of the present research on the relevant issue and on the respective questions and hypotheses that will be investigated. At the end of each chapter the findings and theoretical implications concerning the particular aspect are discussed. In the final summarizing chapter 5 more general issues are discussed and more speculative and theoretical ideas on VSTM processing are presented.

Chapter 2

LIMITATIONS IN MAINTAINING INFORMATION

Introduction

The first empirical question of the present dissertation addresses the temporal limitations of visual short-term memory (VSTM). For how long can information be retained in VSTM? What is the time-course of VSTM decay? This is an important aspect in the context of the present investigations, since the novel type of stimulus material used here, allows to study effective memory capacity as a function of retention time. To delineate the duration of VSTM it is interesting to define, when VSTM begins and when it ends. With the present approach the contributions of iconic memory can be separated from VSTM. Also, it will be investigated for how long the new type of information can be retained in VSTM before it is forgotten.

For very short-term retention of visual material it is important to consider that at least two memory systems are involved. In addition to VSTM, there is also storage by the high-capacity sensory store for visual material. The foundation for this assumption has been laid by the study of Phillips (1974, refer to chapter 1 for details). He derived from his experiments on retention of matrix patterns that performance was made up of two components, namely of sensory memory, that could be observed at ISIs of about 100 ms or less and which is of high accuracy, and of the visual short-term store, that is capacity limited and with longer ISIs will show a slow loss over at least the first 9 seconds. Sensory memory for visual material has

first been termed *iconic memory* (by Neisser, 1967). It was initially regarded as a unitary system within the visual modality (Sperling, 1960; Averbach & Coriell, 1961). The current view, however, is that it can be subdivided into several components (e.g., Coltheart, 1980; Di Lollo & Dixon, 1988; Irwin & Yeomans, 1986). Besides *neural persistence* which refers to the immediate neural activity induced by the stimulus, a *visible persistence* and an *informational persistence* of the stimulus are distinguished (Coltheart, 1980). Visible persistence is a phenomenological vestige of the removed stimulus and relates to the fact that the stimulus can actually be *seen*. It is negatively related to the duration of the stimulus (known as the inverse duration effect) which is negligible for stimulus exposures exceeding 100 ms (Di Lollo & Dixon, 1988, 1992; Dixon & Di Lollo, 1994). The decay of visible persistence, therefore, depends on the duration of the stimulus, i.e. it is time-locked to its onset. *Informational persistence*, on the other hand, occurs at a higher level of processing. It is also referred to as the *visual analog representation* of the stimulus (Di Lollo & Dixon, 1988). It is non-visible, maskable, and contains precategorical information about form and spatial locations of the initial stimuli. It is not affected by the duration of the inducing stimulus and decays rapidly within 150 – 300 ms after the offset of the stimulus (Irwin & Yeomans, 1986), i.e. it is time-locked to the termination of the stimulus. In the present experiments on the duration of VSTM a beneficial influence of the visual analog representation on performance

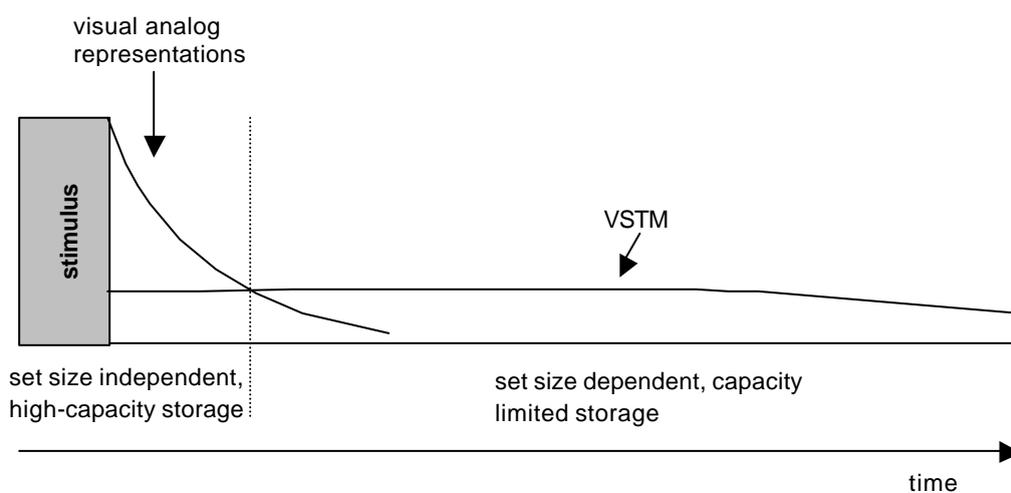


Figure 2.1 Temporal relation between storage by visual analog representation and by VSTM.

can be expected at very short retention times, such as below 300 ms. At longer retention times the visual analog representation is no longer available, therefore, the task must be solved by relying on VSTM alone. Hence, performance will decline in this case. (Refer to figure 2.1 for an illustration of the hypothesized temporal relation between the two visual stores.)

The difference in duration is not the only factor by which visual analog representations can be separated from VSTM. The two memory systems also differ in their capacity. As opposed to the unlimited storage of visual analog representations, storage capacity of VSTM is limited. This feature has been described by Phillips (1974). In his experiments he observed an effect of pattern complexity in VSTM storage (see figure 1.2). However, the study of Phillips (1974) has the disadvantage that the amount of stored information, contained in the black-and-white matrices, cannot be described in a simple way. As a consequence, the temporal course of VSTM storage cannot be related to a straightforward quantitative capacity measure. This deficiency will be diminished by the new type of stimulus material that was used in the present experiments. It consisted of separable objects with well defined perceptual attributes. Hence, in order to segregate storage that relies on visual analog representations from storage in VSTM, in the present study the effective memory capacity will be assessed as a function of retention time.

In two experiments memory performance for 2, 4 or 6 visual objects was assessed as a function of retention time by varying the interval between the sample display and the test stimulus. Experiment 1 tested shorter retention durations between 100 and 800 ms, addressing the transition from storage by visual analog representations to VSTM. Experiment 2 tested memory performance also for longer retention durations up to 8000 ms. A control condition was added in experiment 1, in which sample and test display were presented without interruption, immediately after each other. In this condition no memory is necessary. The change in one object will directly be visible. Performance in this control condition will reflect the maximum performance that could be reached in the memory conditions with a contribution of the visual analog representation. It is hypothesized that as long as visual analog representations are available for the short-term storage, no performance differences according to the number of stored objects should occur. However, when visual

analog representations decay and storage has to rely on VSTM, set size effects on memory performance should become evident in the experiment. Because the visual analog representations have an approximate duration up to 300 ms (Di Lollo & Dixon, 1988), the transition from storage by visual analog representations to VSTM storage is hypothesized to occur between 100 and 300 ms after stimulus offset. When memory has to rely on VSTM alone, performance is expected to remain stable on a level depending on set size.

Experiment 1

Method

Subjects 6 subjects (4 females, 2 males), aged between 20 and 38 years (mean age: 25) participated in the experiment. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment. They were paid for their participation.

Apparatus The experiment was run on a IBM compatible PC with a Sony 21" colour display (resolution: 1024 x 768 pixels; refresh rate 74 Hz.).

Stimuli On each trial two displays with visual stimuli appeared that were separated by an empty screen: first, a sample display, and second, a test display (see below for the exact procedure). The sample display contained an array of 2, 4 or 6 multidimensional stimuli. All stimuli had the geometrical form of a rectangle and differed with respect to the visual dimensions size (long – $1.34^\circ \times 0.36^\circ$ or short – $0.67^\circ \times 0.36^\circ$), colour (red or green) and orientation (horizontal and vertical). Objects on average had a luminous directional energy of approximately 12 cd/m^2 , the luminance of the grey background was about 5 cd/m^2 . Objects occurred at eight possible locations forming a square ($6.36^\circ \times 6.36^\circ$) around a white fixation cross in the centre of the screen. Stimuli were randomly generated, no object was repeated in a display. However, single feature values could occur in more than one object, but

not more often than twice. The test display consisted of a the same number of objects at the same locations as in the sample array at that trial (“whole test display”, see figure 2.2). In 50% of the cases all objects were identical to the objects in the sample array (“*same*”-trial) and in the other 50% of the cases one of the objects differed from the respective sample stimulus in one of its features (“*different*”-trial).

Procedure Participants were seated in front of the computer display at a viewing distance of 1m in a room with dim illumination. During the experiments the subject’s head was fixated on a chin rest. Prior to each block oral instructions were given followed by up to 25 practice trials to ensure that the procedure, which is sketched in figure 2.2, was understood. Subjects initiated the start of a trial by mouse-click. In each trial first a fixation cross appeared for 1500 ms followed by the presentation of the sample array. The exposure duration of the sample array was 200 ms. It was followed by a variable retention time, during which just the grey background and the fixation cross were visible. Possible blank intervals were 0, 100, 200, 300, 400, 600 and 800 ms. Then the test display was presented and remained visible until subjects pressed a mouse button according to the instruction. The general instruction was to press the right mouse button when the test display was the same as the sample array (“*same*”-trial). When one of the objects in the test display differed from the respective object in the sample array subjects were instructed to press the left mouse button (“*different*”-trial). Subjects were asked to respond as

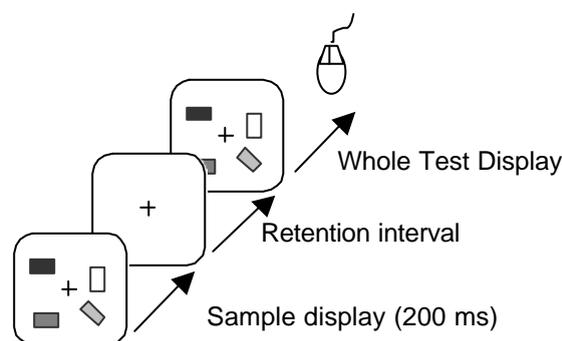


Figure 2.2 Experimental procedure and stimuli in experiment 1 with a whole test display and with variation of retention time (0, 100, 200, 300, 400, 500, 600, 700, 800 ms).

correctly and as quickly as possible. In case they were not sure about the right response they were instructed to guess. In case of an error they received a feedback tone. Session duration was approximately 1 hour.

Design All combinations of the 3 set sizes, the 7 different retention intervals and the 2 same-different conditions required 42 trials for complete replication. A block consisted of 126 trials, which were generated at random. Each subject performed 8 blocks during two sessions, i.e. 24 complete replications of each condition.

Results

Results of this experiment 1 are depicted in figure 2.3. Performance is shown for the three tested set sizes as a function of retention time. In the control condition, in which there was no blank interval between sample and test display, a performance level of around 95% for all set sizes was reached (set size 2: 96.5%, MSE 1.0; set

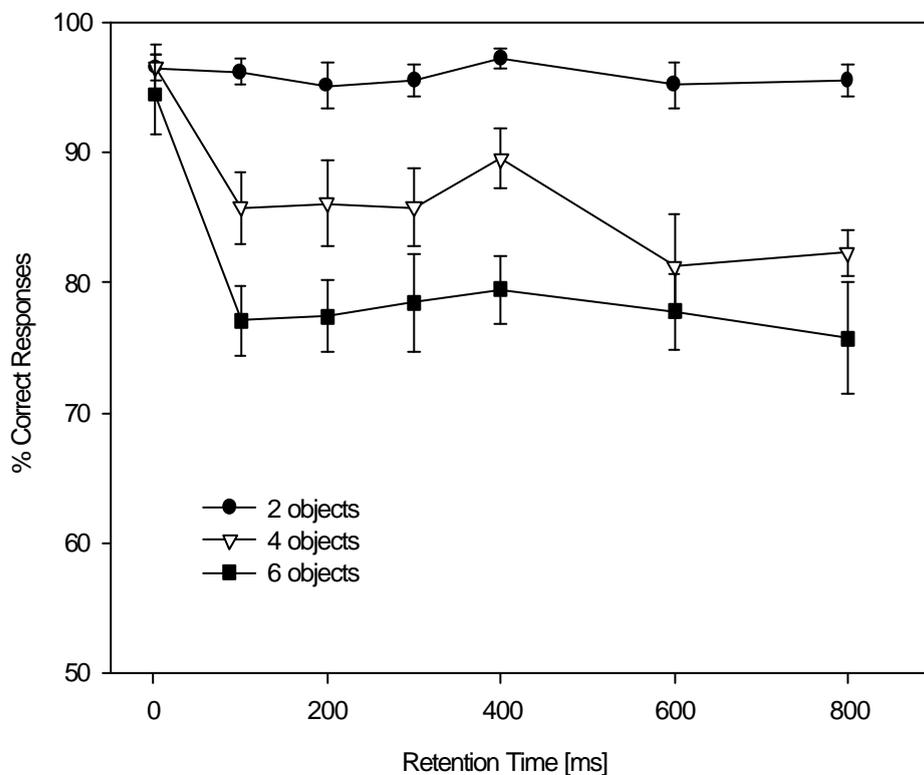


Figure 2.3 Results of experiment 1: Mean accuracy as a function of retention time for the set sizes of 2, 4, and 6 objects.

size 4: 96.5% correct, MSE 1.7; set size 6: 94.5, MSE 3.0). At longer retention times (100 – 800 ms) a distinct set size effect can be observed. The performance level of each of the three tested set sizes is stable for all these tested retention times. Throughout the experiment performance is best when only two objects have to be retained; a very high accuracy of above 95% is then achieved in the task. Clearly poorer performance can be observed at the larger set sizes of 4 objects (about 85% correct). An even lower level of performance is reached for the set size of 6 objects (approximately 78% correct). The performance levels according to the set sizes suggest that VSTM capacity comprises at least two objects, because for set size 2 memory performance is nearly perfect. On the other hand, VSTM memory capacity is smaller than 4 objects, because a performance level of 85% correct suggests already a certain loss of information. We conclude that VSTM has a capacity of roughly three items.

The results of the present experiment are confirmed by a two-way (retention time \times set size) repeated measures ANOVA on performance data (% correct). It revealed significant effects of retention time, $F(6,30) = 11.89$; $p < 0.01$, and a significant effect of set size, $F(2,10) = 56.14$; $p < 0.01$. When retention time = 0 ms is not included in the calculation, the differences of performance with respect to the retention time is not significant, $F(5, 25) = 1.92$; $p > 0.05$. Also, there is no interaction of retention time with set size, $F(10, 50) = 0.42$, $p = 0.93$.

The pattern of results, that shows a stable level of performance which is dependent on set size for all data points except the control condition, is consistent with what was expected, when retention has to rely on VSTM alone. Nevertheless, it is surprising that a set size effect can be observed at a retention time as short as 100 ms! Here, the visual analog representation should still contribute to the storage and no dependence of set size should occur. It seems that the visual analog representation is wiped out, yet leaving the contents of short-term memory unimpaired.

What factor could be responsible for the present result? It may be important for the present study to consider the possibility of multiple visual transients (Phillips & Singer, 1974; Stelmach et al., 1984; Becker et al. 2000). It could be that the onset of the objects in the test display after the blank interval causes visual transients for all

objects across the entire visual field, so that the location of the critical item cannot easily be detected within the visual analog representation. The role of visual transients for detecting – or rather for being blind for – a change in visual scenes or displays has recently been stressed in studies on change blindness (e.g. Rensink et al., 1997; O'Regan et al., 1999). When transients are introduced in two successive pictures that contain a local change that normally is detected very reliably, subjects are no longer able to perceive that change. In a study of O'Regan et al. (1999), these transients are generated by 'mud splashes' – black-and-white textured rectangles or ovals – spread out on the picture. It is also possible to generate transients which induce change blindness by introducing e.g. saccadic eye movements, blinks, movie cuts, etc. (Rensink, O'Regan, & Clark, 1995; O'Regan et al., 2000; Levin & Simons, 1997). Multiple transients can also be generated by a blank interval (Rensink et al., 1997; Rensink et al. 2000) in change blindness experiments. So, possibly also in the present experiments multiple transients caused by the onsets of the objects in the second display after the blank interval may be responsible for the fact that the visual analog representation cannot be used effectively for the memory task.

Experiment 2

In order to eliminate the multiple sources for transients in the test display, in this second experiment the experimental paradigm was slightly modified. Instead of presenting all objects again in the test display, only the critical item was presented and irrelevant items were not shown again ("single test item" display, see figure 2.4). Thus, transients are now elicited solely by the critical item. Furthermore, to make sure, that the relatively low memory performance at a retention time of 100 ms in the previous experiment 1 was not caused by a possibly too short encoding time, in this experiment 2 encoding time was increased to 400 ms. In addition to the shorter retention times up to 800 ms a data point with a retention time of just 14 ms was introduced in the present experiment to test the capacity of the visual analog representation. Moreover, longer durations up to 8000 ms were tested, in order to observe a possible decay of VSTM. Taking into account also earlier studies that

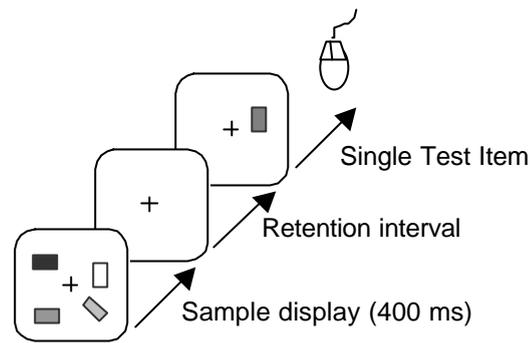


Figure 2.4 Experimental procedure and stimuli in experiment 2 with a test display containing a single object and with variation of retention time (14, 125, 250, 500, 1000, 2000, 4000, 8000 ms).

investigated short-term retention of visual material (Kikuchi, 1987; Parr, 1992; Phillips, 1974) the following rough assumptions on the expected memory performance of the present experiment were made:

1. Performance with short retention times (14 – 250 ms) is expected to be of very high accuracy for all set sizes and therefore different from the performance at the longer retention intervals (500 ms or longer).
2. At retention times, that are longer than the duration of visual analog representations, which is approx. 300 ms, level of performance will be considerably lower. In addition set size differences in the level of memory performance will be evident.
3. From a retention time in the range of several seconds not much further decline will be observed.

Method

Subjects 7 male and 3 female subjects, aged between 20 and 43 years (mean age: 27.5) participated in the experiments. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment.

Stimuli Except for the fact that the rectangles all had the same size ($0.36^\circ \times 1.34^\circ$), the visual objects were the same as in Experiment 1. Instead of a “whole test” display a “single item test” was used (see figure 2.4).

Procedure Except as noted here, the procedure was the same as in Experiment 1. The display time of the sample array was 400 ms. Eight different retention intervals (14, 125, 250, 500, 1000, 2000, 4000, 8000 ms) were tested in two separate blocks. The first block consisted of the 5 shorter retention times, the second block consisted of the 3 longer retention times. The intervals in each block were selected at random in every trial. The durations of both blocks were approximately the same, the second type of block being slightly longer. Session duration was approximately 1 hour.

Design The experimental design was a 8×3 within-subject factorial, with eight levels of intervals between sample and test array and three set sizes. In the first block (shorter retention times: 14, 125, 250, 500, 1000 ms) all combinations of the 5 retention times, 3 set sizes and the 2 same-different conditions required 30 trials for complete replication. Each of this type of block consisted of 180 trials, which were generated at random. In the second type of block (longer retention times: 2000, 4000, 8000 ms) all combinations of the 3 retention times, 3 set sizes and the 2 same-different conditions required 18 trials for complete replication. Each block of this type consisted of 108 trials. The order of blocks was balanced among subjects. The subjects performed 12 (6×2) blocks altogether during three sessions, i.e. 36 complete replications of each condition.

Results

Figure 2.5 shows average performance in retaining the multidimensional objects as a function of retention time and number of objects. It can immediately be seen that there is a clear set size effect for all retention intervals. Furthermore, memory performance declines continually from the shortest up to the longest tested interval. This general result is confirmed by a two-way (retention time \times set size) repeated measures ANOVA on performance data (% correct responses). It reveals significant

main effects of set size, $F(2, 16) = 182.0$, $p < 0.001$, and of retention time, $F(7, 56) = 11.25$; $p < 0.001$. There was no significant interaction between the factors of set size and retention time, $F(14,112) = 1.08$; $p = 0.38$.

Data are again not in agreement with the first assumption formulated above. Also in this experiment no contribution of the visual analog representation was observed at very short retention intervals (14, 125, and 250 ms) as can be inferred from the clear set size effect at these intervals. It is now possible to exclude, firstly, that insufficient encoding time is responsible for this result. Further support is given by a study by Schneider and colleagues (1999), in which the encoding time was carefully controlled in experiments that were similar in the procedure to the experiments of the present dissertation. When the sample display was presented for 200 ms, followed by a mask, asymptotic level of memory performance was observed. Therefore, the duration of 200 ms of the sample display, which is not followed by a mask, was certainly sufficient for encoding the stimuli in experiment 1, much more so the encoding time of 400 ms in the present experiment (also refer to Kyllingsbaek,

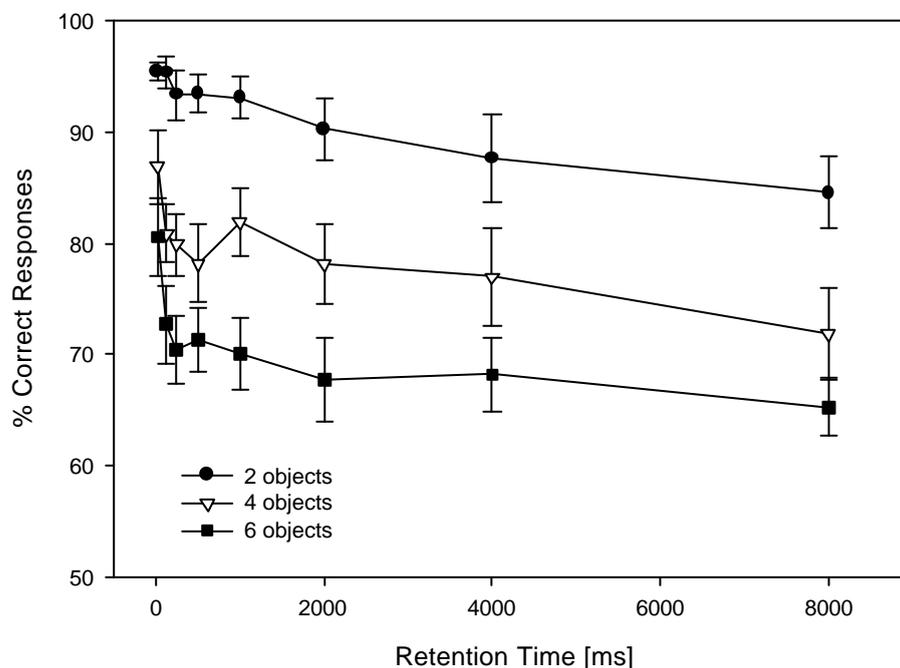


Figure 2.5 Results of experiment 2: Mean accuracy as a function of retention time for the set sizes of 2, 4, and 6 objects.

2003). Secondly, the factor of multiple transients that are caused by the onset of irrelevant objects in the test display can be excluded as a cause of the observed set size effect at 14 ms. However, the observed data are in agreement with the second assumption: results show a very flat but continuous decay with larger ISIs depending on set size. Consistent with the third assumption, results show only a very flat drop of performance between the two longest retention intervals of 4 and 8 seconds.

Two separate t-tests were conducted in order to test the more specific hypotheses: Firstly, the null hypothesis that performance at a retention interval of 14 ms is not different from the performance at all other retention intervals was tested. This was done by calculating the contrast between the performance at 14 ms and all other retention intervals. The analysis yields that, although performance at an ISI of 14 ms is not near perfect and in addition depends on set size, it is nevertheless significantly better as the performance across all other, longer retention times ($F(1,8) = 17.17, p < 0.01$). Secondly, the null hypothesis was tested that beyond 4000 ms there is no decrease in performance. This hypothesis cannot be rejected: The contrast of the performance at a retention time of 4000 ms is not significantly different from the performance at a retention interval of 8000 ms ($F(1,8) = 3.224, p > 0.1$). This means that the function of memory decay levels off at a retention interval larger than 4000 ms and does not further decay significantly, although between the last two data points (4000 and 8000 ms) there is a difference of as much as four seconds.

In summary, contrary to initial expectations performance even at the shortest possible ISI of 14 ms is not near perfect and is dependent on set size. Evidently there is no contribution of visual analog representations in this task. The decay as a function of retention time can, nevertheless, roughly be divided into two parts: At shorter retention intervals (up to 2000 ms) a moderate memory decline can be observed. At longer retention intervals a level of performance is reached that is maintained without significant loss up to the longest tested interval of 8 seconds. This finding on the general course of memory loss over time is in agreement with results found in the literature (e.g. Kikuchi, 1987; Parr 1992; Phillips, 1974).

Discussion of experiments 1 and 2

In the change-detection experiments of the current chapter the maintenance of distinct multidimensional figures in the visual short-term store has been investigated. What is the effect of varying the duration for which visual information can be retained? Two predictions on the outcome of the experiments have been made beforehand: Firstly, the visual short-term store is known to be of limited capacity. Thus, a set size effect for all tested ISIs which exceed the duration of the high-capacity visual analog representation was expected. An amount of information that is within the capacity of the store should be retained at a very high performance level, i.e. near 100% accuracy. For amounts of information that exceed the capacity of the store performance should be worse. Secondly, at shorter ISIs, when the visual analog representation is still available (in the range from 14 – 300 ms), a very high memory performance for all set sizes was expected. At longer retention intervals, when memory performance has to rely on VSTM alone, lower performance would be observed for set sizes exceeding the capacity of VSTM. The results of the experiments 1 and 2 can be summarized as follows:

1. A set size effect is observed for all tested retention intervals (> 0 ms):
Memory performance was near perfect for two objects (~95%), somewhat lower for four objects (~85%) and clearly reduced for six objects (~78%). We conclude that VSTM has a capacity of less than four and more than two items. Within the first few seconds a flat and continuous decay of VSTM can be observed for all set sizes that exceed its capacity (4 and 6 objects). From roughly 4 seconds of retention up to the longest tested ISI (8 seconds) there is no more significant loss of information. Memory performance for all set sizes remains at a constant level.
2. There is no reflection of visual analog representations of the stimuli at ISIs shorter than 300 ms. Even at the shortest possible blank interval of 1 frame (14 ms) memory performance is not near perfect and a set size effect is observed at all intervals.

1. Set size dependent flat decay of information in visual short-term memory

The observed time course of memory loss reflects a decay function which apparently is exponential with significant decay in the beginning and a flattening of the curve at longer ISIs. Significant forgetting does not occur after 4 seconds of retention. Absence of further decay has been reported for even longer retention up to 9 s (Phillips, 1974), up to 12 s (Kikuchi, 1987) and up to 15 s Parr (1992). The level of memory performance is clearly set size dependent. Two objects can be kept in short-term memory without considerable loss. Four objects can be stored only with an accuracy of at least 80%. Short-term memory obviously cannot completely store this amount of information. This means, that short-term memory has a capacity of at least two, but fewer than four visual items.

There have been earlier studies on retention of visual information that used a different kind of visual material. Kikuchi (1987) reports results from a Phillips' type of delayed matching experiment using random dot patterns as stimulus material. In the first experiment of this study ISI and number of dots was varied. For all amounts of dots performance was best when the comparison pattern appeared immediately after the target pattern, namely at an ISI of 5 ms. At greater ISIs performance dropped to between 65% and 80% at 4 s and in addition an effect of display size was observable. At ISIs greater than 4 s no more drop of performance was observed. Pashler (1988) conducted a comparable change detection experiment (experiment 3 of the study) using letter strings as stimulus material. He found very good performance (86% correct) at the shortest ISI of 34 ms, performance strongly decreased at an ISIs of 67 ms (68% correct) and did not much deteriorate further at 217 ms (65% correct) In a study of Parr (1992) performance in a change detection task with simple squares of varying size was best when there was no delay between sample and test stimulus (90% correct), performance decreases considerably at an ISI of 5 seconds (74% correct) and does not decrease further up to an ISI of 15 seconds (70% correct). The findings of all three studies are in agreement with the findings of the present study.

How can it be explained that memory performance can be kept relatively constant at a certain level? Why is there no further loss of information with increasing

retention time? Should the stored information not be forgotten after a certain time? A reasonable explanation is that the stored information is held in short-term memory until it is requested using active mechanisms to prevent loss of information by passive decay or interference. Such an active mechanism might be a rehearsal processes that regularly refreshes the memory contents (e.g. Atkinson & Shiffrin, 1968, see chapter 1). In his framework of working-memory Baddeley (e.g. Baddeley, 1986) suggested that the slave systems, the articulatory loop and the visual scratch pad, serve as rehearsal systems for verbal and visuo-spatial information, respectively. Also Schneider (1999) in his neurocognitive theory (see chapter 1) describes a refreshment process of visuo-spatial working memory (VSWM). It is needed to keep a certain level of activation for each object, so that it can remain in VSWM. Thus the refreshment is responsible to prevent forgetting of the stored objects. Accordingly, what is observed in the present retention tasks is in fact the capability of visual short-term memory to preserve via rehearsal or refreshment a limited amount of information for a certain duration. In the present experiments the longest tested duration was 8 seconds, in related studies it was 15 seconds (Parr, 1992). It is supposed that this interval can be prolonged for a much longer time, given the subjects are completely occupied in the retention task and do not lose attention by distraction or sleepiness.

2. No contribution of visual analog representations at retention times up to 300 ms

In the present experiments no set size independent level of performance close to 100% was observed for retention intervals shorter than 300 ms, which was expected as a reflection of visual analog representations. Possibly multiple transients could be responsible for this result (Phillips & Singer, 1974; Stelmach et al., 1984; Becker et al. 2000). In order to solve the present change detection task and to find the location of the critical item, subjects might rely on the transients that are elicited by the local change of the critical item. In experiment 1 a “whole test display” was used, that consisted of all the objects that have been presented also in the sample display, with a possible change in one critical object. By the onset of the test display after the blank interval, multiple visual transients would occur in the entire display, including

the irrelevant, unchanged objects besides the target object. A consequence could be that the location of the critical item cannot unambiguously be determined, because it is not possible to distinguish between relevant and irrelevant signals. To exclude this possibility, in experiment 2 a “single item test” was used, which contained only the critical item. Transients are now confined to the location of this item, so that it can be found without problems. In addition, in experiment 2 an extremely short interval between sample and test display was added, to make sure that a time interval is tested, at which the visual analog representation should be present. However, also in the second experiment, no contribution of the visual analog representation to memory performance was observed. It seems that it is generally not available in the present task.

It should nevertheless be noted, that performance at an interval of 14 ms in experiment 2 is clearly better than performance at the longer tested retention intervals. This could mean that a destruction of the visual analog representation gradually becomes stronger, reaching its maximum at 100 ms at the latest. At retention intervals shorter than 100 ms short living information can be used for the task. This could be visual analog representations or signals like a strong, low level motion cue. Another explanation could be, that general experimental conditions for change detection are particularly good, when changes can be detected at a relatively high rate at very short blank intervals. For example, higher ambient luminance increases change-detection rates (Hecht & Schlaer, 1936, cited after Stelmach et al., 1984). Evidence for a very steep decline of accuracy within the first 80 ms in a change detection task has also been reported in a study by Stelmach, Bourassa, and Di Lollo (1984). The stimulus material they used was a square display of 41 randomly distributed elements, which were composed of five closely packed dots (like the number five of a dice). Sample and test display were shown on an oscilloscope for 500 ms each, separated by a blank interval, that varied according to the block between 0, 10, 20, 40, 80, 160 or 320 ms. In a two-alternative temporal forced-choice procedure subjects had to detect changes between the two displays. Their results show very high accuracy of 100 % for an ISI of zero and slightly less for an ISIs of 10 ms, which is clearly in agreement with the present data. Further, performance rapidly declines reaching a level just below 70 % at an ISIs of 80 ms.

Performance up to 320 ms remains constant: Also these data are conform with the present evidence that was obtained at ISIs of 14 ms, 100 ms and longer. Taken together, the results of this study confirm that a very rapid loss of information within the first 100 ms or earlier is possible in a change detection task. However, the exact beginning of decay as a function of ISI may depend on additional factors like luminance conditions (Stelmach et al., 1984).

A further explanation for the fact that the information provided by visual analog representations cannot be used for detecting changes has to be considered: Perhaps the representation of the first display is overwritten by the second display. So first, the information of what is contained in the first display is encoded into memory. A visual analog representation of high detail exists for a duration of approximately 100 – 300 ms. When after a certain duration the test display comes up this information is masked by the onset of the second-frame stimulus (Gegenfurtner & Sperling, 1993; Loftus et al.; 1992, Becker et al., 2000). The visual analog representation of the first display is overwritten and cannot be used for the task any more. In order to test, whether a representation of the first image is preserved and to which extent, a cueing technique can be applied. In a change detection paradigm, similar to the one used in the present study, a cue was presented between the sample and the test display (Wesenick, 2000). Significantly higher memory performance was observed when a cue was presented compared with the condition without cue. This was especially evident for retention times up to 500 ms in which with a cue a performance level of approx. 90% was reached for four objects. Performance without cue was only below 80%. Comparable evidence was reported in a current study by Germeys, de Graef, Panis, van Eccelpoel, and Verfaillie, (2004). In a change detection task with a circular array of 5 letters subjects had to decide whether one object had changed across a blank interval. In experiment 3 of the study a cue was inserted at variable times (0, 50, 100, 150, 200, 250, 300, 400 ms) within a retention time of 700 ms. Performance was near perfect at the shortest cue delay (97% at 0 ms) and gradually declined with increasing delays (82% at 400 ms). Change detection performance was well above performance in a no-cue control condition (71%). The two studies show, that a visual analog representation does indeed exist, which starts to decay following stimulus offset. The results are in accordance with the view that the second display

overwrites the contents of the first display, so that its contents cannot be accessed afterwards.

In the present study on short-term memory this line of argumentation was pursued in a number of additional experiments, which also include studies in which a visual cue is used. These are presented in chapter 4 which is dedicated to the issue of retrieval. At the present point of investigation it becomes apparent that the way in which memory is tested is an important factor. Experimental manipulations like a blank interval and a second display have certainly a critical influence on memory performance. Therefore, in order to learn more about features of short-term memory and about the nature of visual representations it is necessary to learn more about conditions of retrieval of information from short-term memory.

The next two chapters investigate issues that originated from experimental results and their discussion of this first chapter on short-term retention of visual information. The following chapter 3 deals with the question on the storage capacity of visual short-term memory. From observing a clear set size effect in all three experiments of the present chapter, the question on the storage capacity arose and how it can be defined in terms of the unit of the store. In chapter 4 in a series of experiments the issue of retrieval is investigated in more detail.

Chapter 3

THE STORAGE FORMAT AND ITS RELATION TO CAPACITY LIMITATIONS

Introduction

One of the major issues in cognitive science is to investigate the limitations of human abilities to solve cognitive tasks and to determine the processing restrictions in the performance of a variety of such tasks. Especially the limitation to immediately retain new information has been examined in a large number of studies. With Millers (1956) classic work on the capacity of short-term memory and his finding of what he called an *immediate-memory span* for the recall of digits of 7, plus or minus 2, the issue of cognitive capacity became very popular. One of the most intensely studied human cognitive limitations certainly is the highly limited capacity of working memory to temporarily hold information in an accessible state so that it is available for current cognitive operations. There is an extensive discussion on the issue with a great deal of controversy (see e.g. the BBS target article by N. Cowan, 2001 and commentaries). This controversy, however, concerns not so much empirical results per se, but rather how the results can be interpreted and how they relate to theoretical constructs.

Very early in psychological research on what was called the “span of attention, apprehension or immediate-memory” (Sperling, 1960, p. 1), it was found, that from briefly presented visual displays of letter arrays only four or five items could be reported correctly (e.g. Catell, 1881; Jacobs, 1885). In his well known article, which contains experiments using the newly developed partial report technique, Sperling (1960) included also whole report experiments to test immediate memory. In experiment 1 an array of a varying number of up to 12 letters and/or digits in different arrangements was shown for 50 ms on a tachistoscope. It was followed by a blank screen. Subjects were asked to recall as many letters as possible after presentation. The results showed that no more than an average of about 4.5 items could be reported from a single array. The same results were obtained in experiment 2, in which exposure duration was varied between 50 ms and 500 ms. In the partial report procedure a cue indicated which row of the presented stimulus array had to be reported. When the cue appeared before or very shortly after the array (–100, 0, 150, 300 and 500 ms), most of the letters in that row could be reported. However, when the cue was delayed for 1 second the number of correctly reported items corresponded closely to the number of letters that subjects give in whole reports. Over the years many more studies on the capacity issue followed. In most studies verbal material was used in these studies, one of the best known studies being Miller (1956), in which the recall of digits was tested. Also, as has been mentioned in chapter one, within the framework of working-memory the capacity of the verbal rehearsal system, the articulatory loop, has been thoroughly investigated. It was found that immediate memory span for spoken words represents the number of items that can be uttered in about two seconds (Baddeley, Thomson, & Buchanan, 1975). In contrast, there are much less studies which investigated the capacity of visual short-term memory. This can partly be attributed to the problem of choosing the appropriate stimulus material. It is difficult, even for visually presented stimuli, to exclude extensive use of verbal coding. For example, also the visually presented letters and digits in the study of Sperling (1960) rely to a large extent on speech-based codes.

Different measures and tasks have been applied to determine the capacity of the visual short-term store such as recognition memory (Clark, 1965; Kelly & Martin,

1974; Hines, 1975), performance in delayed matching to sample tasks (Reicher, 1969; Cermak, 1971; Philips, 1974; Parr, 1992; Luck & Vogel 1997; Vogel, Woodman, & Luck, 2001; Wheeler & Treisman, 2002), performance in tasks that require whole report (Henderson, 1972; Oyama, Kikuchi, & Ichihara, 1981), partial report of matrix patterns (Wilson, Scott, & Power, 1987), and memory span in imagery tasks where subjects were required to follow a mental pathway through imagined square matrices or cubes of an increasing number of units (Kerr, 1987; Cornoldi, 1991). In those different tasks and procedures a variety of stimulus material was used such as number-matrix patterns (Brooks, 1967; Baddeley, Grant, Wight, & Thomson, 1975; Baddeley & Lieberman, 1980), textures and faces (Harvey, 1986), random square matrices (Philips, 1974; Philips & Christie, 1977), pictures (Wyant, Banks, Berger, & Wight, 1972; Shaffer & Shiffrin, 1972; Potter, 1976), random shapes (Kelly & Martin, 1974; Hines & Smith, 1977) and multidimensional geometrical forms (Luck & Vogel, 1997).

It is difficult to make clear suggestions about a capacity limitation of the visual short-term store. It has been proposed that it is limited to only one single pattern or picture (Phillips & Christie, 1974; Frick, 1985) and that it depends on pattern complexity (Shaffer & Shiffrin, 1972; Philips, 1974). More recently Luck and Vogel (1997) came up with the suggestion of a capacity limit for nonverbal material of about four items. This is consistent with estimates from “whole report” studies on iconic memory and with estimates on the capacity of transsaccadic memory (Bundesen, 1990; Irwin, 1992; Irwin & Andrews, 1996; Schneider, 1999). However, the general question is how we can define the capacity using a quantitative measure and what is its relevant relation, i.e. what is the unit of the store? Is the measure related to the complexity of the displayed visual material, is it related to its informational contents or to the number of presented items/objects?

Luck and Vogel (1997; Vogel et al., 2001) claim that information is stored in visual short-term memory in terms of integrated objects. At the same time they reject the alternative view that information is stored in terms of the features of objects. In their view, storage is object-specific and refers to whole internal objects as a configuration of conjoined features, which are independent of the number of their visual dimensions, hence of the complexity of the objects. They state that the

capacity of the visual short-term store comprises about four such items. The hypothesis of object-based working-memory was developed on theories of attention that claim that attention processes integrated objects, rather than individual features. There is rich evidence for the fact that always all features of an object are accessed by attentional processes, even if in a given task only one feature has to be attended (Duncan, 1984; Egly, Driver, & Rafal, 1994; Kahnemann, Treisman, & Gibbs, 1992; Vecera & Farah, 1994 – cited after Vogel, Woodman, & Luck, 2001). For items, that are selected by attentional processing, are stored in working-memory, the format of working memory could be the same as the format of attention (Vogel, Woodman, & Luck, 2001).

To test this hypothesis Luck and Vogel (1997) carried out a series of experiments with delayed matching tasks (see also chapter 1). In a first set of experiments they assessed the capacity for simple objects that differed in just one feature dimension. From the results it was estimated that visual working-memory can hold roughly four items. In a second set of experiments multifeature objects were used to address the issue of the storage unit of visual working-memory. Is information stored in terms of single features or in terms of integrated visual objects? In experiment 6 of the study (Luck & Vogel, 1997, which is the same as experiment 11 in Vogel et al., 2001) a sample display with 2, 4, or 6 objects was shown to the subjects for 100 ms. The objects differed in colour (red, blue, green or black) and in orientation (horizontal, vertical, left and right oblique: $\pm 45^\circ$). The presented objects had to be memorized across a retention interval of 900 ms. Then a test array appeared for 2000 ms. It contained the same number of objects as had been shown in the sample display. Furthermore, the objects appeared at the same locations as before. In half of the trials one of the objects differed in one of its features. General task of the subjects was to indicate by mouse-click an observed change of an object in the test display compared with the respective object in the sample display. In addition to the visual task a verbal load procedure was used to rule out contributions from verbal working memory: In every trial a new combination of two digits had to be remembered and to be rehearsed subvocally until they had to be reported at the end of each trial. In this particular experiment three specific memory tasks were compared: In the *colour* condition only the colour of an object could change, so the observers needed to

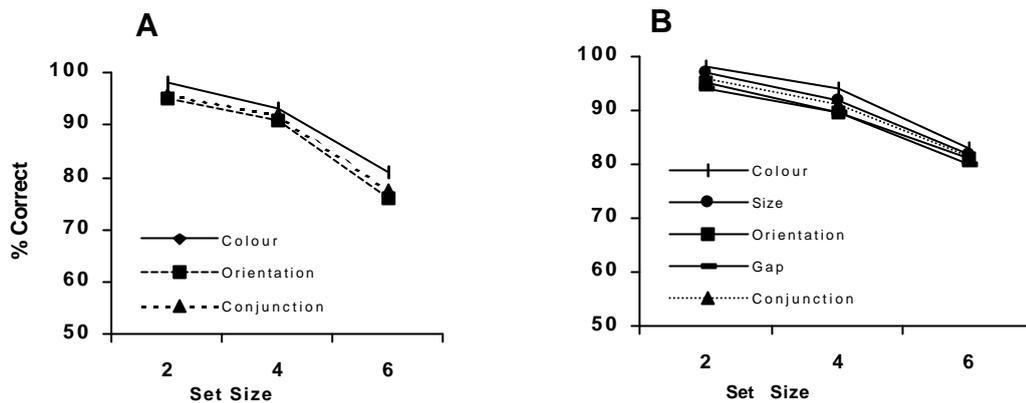


Figure 3.1 Results of experiments 6 and 7 from the study by Luck and Vogel, 1997. Memory performance is depicted as a function of set size.

remember only the colour of the objects. In the *orientation* condition only the orientation could vary, therefore it was sufficient to retain only orientation values of the objects. In the third and critical *conjunction* condition either colour or orientation could change in an object. In order to solve the task, both features had to be remembered, which means that twice as many feature values had to be remembered at a given set size. This manipulation makes it possible to distinguish between object-based and feature-based storage in visual working memory: From Luck and Vogel (1997) follows, if the hypothesis was true that each feature takes separate storage space, then performance in the conjunction condition at a given set size should be the same as the performance in the single feature condition at twice that set size. On the other hand, if visual working-memory contained integrated object representations, and storage thus being independent of object complexity, then the performance in the three tasks should be the same. As turned out the latter case was true: accuracy in all conditions was essentially the same. The same result was obtained even when the number of features in the object was increased to four: colour, size, orientation, and gap (Luck and Vogel, 1997; or experiment 14 in Vogel et al., 2001) (see figure 3.1). Based on these data Luck and Vogel (1997) concluded that just the number of objects determines the capacity limit of the visual short-term store and not the number of dimensions, which means that binding the features to

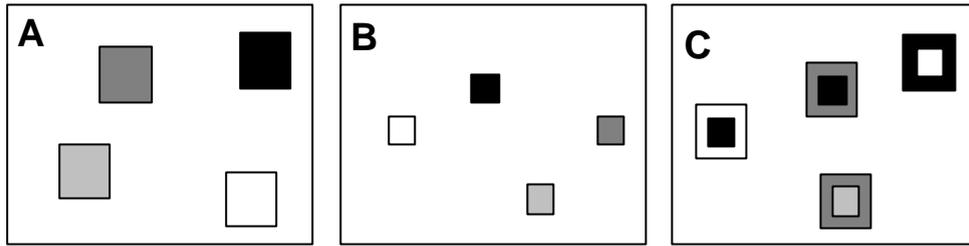


Figure 3.2 Stimulus material used by Luck and Vogel, 1997. A and B: objects having a single feature: large and small coloured squares; C: objects with a conjunction of two colours.

whole objects has no costs. This is a remarkable result. Even in the case of object-specific storage one would expect at least some costs for confining the features to integrated objects in the conjunction condition. A further notable result was that colour and orientation were both retained equally well. Without further assumptions, generally a difference in processing the different features should be expected, equal performance being the special case, for it is known from visual perception that object attributes such as colour and form are processed separately (e.g. Livingston & Hubel, 1988; Zeki, 1993; Moutoussis & Zeki, 1997).

A further experiment (experiment 8 of Luck and Vogel, 1997 or experiment 15 of Vogel et al., 2001) was conducted to rule out a possible explanation for the surprisingly good performance in the conjunction condition, that does not assume storage of integrated features: for each feature dimension an independent memory

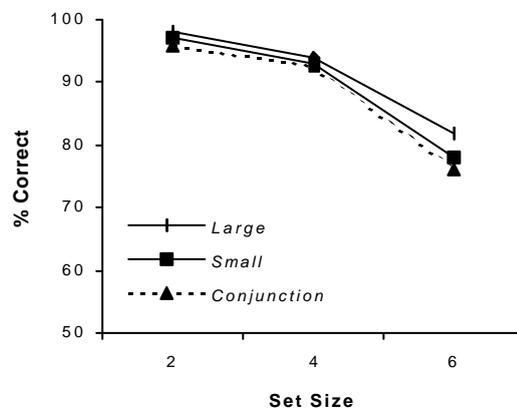


Figure 3.3 Results of experiment 8 from the study by Luck and Vogel, 1997. Mean accuracy is depicted as a function of set size.

system might exist. In order to distinguish between independent storage and integrated object representation a conjunction condition of features of the same dimension, namely colour, was created: subjects had to retain squares that were composed of a small coloured square inside a larger square of a different colour. In the single feature conditions either the inner, small squares or the outer larger squares had to be remembered. (See figure 3.2 for an example of the stimuli used.) If there are independent memory systems for each feature dimension, then in this colour-colour conjunction condition performance should decline compared with the single feature condition. However, in support of the ‘integrated objects’ hypothesis would be a performance level, that is equally high in the conjunction condition as in the single feature condition. The results of the experiment, which was basically the same as Luck and Vogel’s experiment 6 (or 11, respectively) apart from stimulus type, show no difference in performance in the different conditions (see figure 3.3). Objects, composed of two colours could be retained just as well as objects of only a single colour. This means that twice as many colours could be retained in the conjunction condition compared with the single feature condition. With these results Luck and Vogel (1997) rejected the parallel-storage account in favour of their original proposal that objects are stored as integrated wholes: they claim that integrated objects, and not the number of features are the unit of visual working-memory. The results of Luck and Vogel (1997) are very important and have far-reaching implications for theories not only on working-memory, but also on perception and attention. The assumption of Luck and Vogel leads to questions like, what underlying mechanism keeps the features of an object bound together in short-term memory? The importance of the issue requires a verification of the empirical results. Therefore, the goal of the present study was to replicate and extend the findings of Luck and Vogel (1997) on this issue.

Experiment 3a

The following experiment of the present study was conducted to verify, whether the conjunction of features can be retained really just as well as only a single feature

of the presented objects. It parallels experiment 6 of Luck and Vogel (1997), with the difference that instead of two features, objects were characterized by three features. Subjects were required to retain 2, 4 or 6 rectangles that were defined by colour, orientation and length. The experiment, like Luck and Vogel's (1997), contained two types of blocks, namely single feature and conjunction blocks. In a single feature block only one prespecified feature dimension of multidimensional objects changed and subjects had to memorize just the feature values of one dimension, namely colour in the *colour* condition, orientation in the *orientation* condition and length in the *length* condition. In *conjunction* trials any feature dimension of the object could change and therefore all three features had to be retained.

Method

Subjects 4 male and 6 female subjects, aged between 22 and 38 years participated in the experiment. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment.

Stimuli The sample display contained an array of 2, 4 or 6 multidimensional stimuli, which were similar in size, colour and orientation to those used by Luck and Vogel (1997). All stimuli had the geometrical form of a rectangle and differed with respect to the visual dimensions size (long: $0.18^\circ \times 1.8^\circ$ or short: $0.18^\circ \times 0.9^\circ$), colour (red or green) and orientation (horizontal and vertical). Objects on average had a luminous directional energy of approximately 12 cd/m^2 , the luminance of the grey background was about 5 cd/m^2 . Objects occurred at eight possible locations forming a square ($6.36^\circ \times 6.36^\circ$) around a white fixation cross in the centre of the screen. Stimuli were randomly generated, no object was repeated in a display. Single feature values could occur in not more than two objects. The test display consisted of a single object at a location that had been occupied in the sample array at that trial. In 50% of the cases the test stimulus was identical to the stimulus presented in the sample array at the same location ("*same*"-trial) and in the other 50% of the cases it differed from the respective sample stimulus in one of its features ("*different*"-trial).

Procedure Participants were seated in front of the computer display at a viewing distance of 1m in a room with dim illumination. During the experiments the subject's head was fixated on a chin rest. Prior to each different block oral instructions were given followed by up to 25 practice trials to ensure that the procedure was understood. Subjects initiated the start of a block by mouse-click. A fixation cross appeared for 500 ms followed by the presentation of the sample array. The exposure duration of the sample array was 100 ms. The retention time was 900 ms, during which just the fixation cross on the grey background was visible. Then the test display was presented and remained on the screen until subjects pressed a mouse button according to the instruction. The general instruction was to press the right mouse button when the test object had been the same as the object at the respective location in the sample array ("*same*"-trial). When the test object differed from the respective object in the sample array subjects were instructed to press the left mouse button ("*different*"-trial). The experiment consisted of 4 different blocks with slightly different tasks. In one type of block the value of any dimension could change, in the other three types of blocks the value of only one dimension could change. Specifically, the four task conditions were:

- 1) Memorize the values of all dimensions as the value of any dimension can change.
- 2) Memorize colour only as only the colour of a rectangle can change.
- 3) Memorize orientation only as only the orientation of a rectangle can change.
- 4) Memorize length only as only the length of a rectangle can change.

In the first condition the changing dimension (colour, size or orientation) was determined at random. Subjects were asked to respond as correctly and as quickly as possible. In case they were not sure about the correct response they were instructed to guess. After an interval of 1500 ms the next trial started. Session duration was approximately 1 hour.

Design All combinations of the 3 set sizes and the 2 same-different conditions require 6 trials for complete replication. Each block consisted of 120 trials, which were generated at random. There were 4 different task-conditions dependent on the block (see above). The order of blocks was balanced among

subjects. The subjects performed 12 (3 x 4) blocks altogether during three sessions, i.e. 60 complete replications of each condition. “*Same*”- and “*different*”-conditions occurred equally often.

Results

Our analysis differs slightly from the way Luck and Vogel (1997) presented their results. Performance to retain a given feature was assessed, depending on whether it was tested in the single feature condition, when it was the only feature to be retained, or in the conjunction condition, when it was one of several features to be retained. For example, it was compared how well the colour of an object could be retained in the single feature condition in which only colour could change with the memory performance in such trials of the conjunction condition, in which colour changed. Therefore, performance in the conjunction condition was not assessed as a whole, but the trials were divided according to the changing dimension (colour, length and orientation). As a matter of course only the *different*-trials could be analysed, because the *same*-cases could not be associated with non-change of a particular dimension. This seemed to be a more appropriate way to find out, whether the conjunction of features can be retained just as well as only a single feature.

In the analysis of the present experiment, that concerned the specific memory performance according to the changing feature, d' measures were used to measure memory performance instead of % correct responses (Macmillan & Creelman, 1990). The reason for this is, that subjects may have different response biases with respect to changes of the particular features. For example, it could be the case, that subjects feel more confident in deciding that a change in colour occurred compared with a change in length. Therefore, in cases of uncertainty there might be a stronger bias to choose the *different*-response in conditions with potential length changes as with potential colour changes. By using the measure of d' the response bias is taken into account, so that performance data with respect to specific feature changes can better be compared. Sensitivity (d') was estimated for different set sizes and tasks, using hit rates (H) and false alarm rates (FA). In the single-feature conditions a hit was defined as a correct response on a *different*-trial in which subjects correctly identified a

different item. A false alarm was defined as a wrong response on a *same*-trial, when subjects responded mistakenly "different" to an unaltered object. d' was estimated for the performance in the single feature conditions by subtracting the z -score of the hit rate from the z -score of the false alarm rate:

$$d'_{single} = z_{FA} - z_H$$

D' is undefined for hit rates of 1.0 or false alarm rates of 0, because respective z -scores are infinite. Accordingly, hit rates and false alarm rates were corrected in these cases. Proportions of 0 and 1 were converted to $1/(2N)$ and $1-1/(2N)$, respectively (Macmillan & Creelman, 1990).

In the conjunction condition d' was estimated for changes in the three feature dimensions separately: a hit was defined as a correct response on a *different*-trial of one dimension in which subjects responded correctly to a change in this dimension. As the *same*-cases could not be associated with a particular dimension, the false alarm rate was calculated for the performance in the conjunction condition as a whole. Respectively, a false alarm was defined as a wrong response on any *same*-trial, when subjects responded wrongly *different* to an unaltered object. d' was estimated for the performance in the conjunction condition by subtracting the z -score of the hit rate for one particular dimension from the z -score of the false alarm rate as a whole:

$$d'_{conjunction} = z_{FA-all} - z_{H-colour/length/orientation}$$

Corrections in the case of $FA=0$, and $H=1.0$ were as described above.

Figure 3.4-a shows memory performance after a sensitivity analysis for changes in the conjunction and single feature conditions averaged across all changes in the three feature dimensions. It can be seen, that contrary to the results of Luck and Vogel (1997), performance in the conjunction condition is lower than in the single feature conditions. This is confirmed by a three-way (condition \times changing dimension \times set size) repeated measures ANOVA on d' estimates: there is a highly significant main effect of condition (single feature condition vs. conjunction condition), $F(1,9) = 26.17$, $p < 0.01$. However, the degree of difference varies according to the feature dimension (see figures 3.4b – d): It is very distinct for colour, less so for length and orientation. The general level of performance, also in

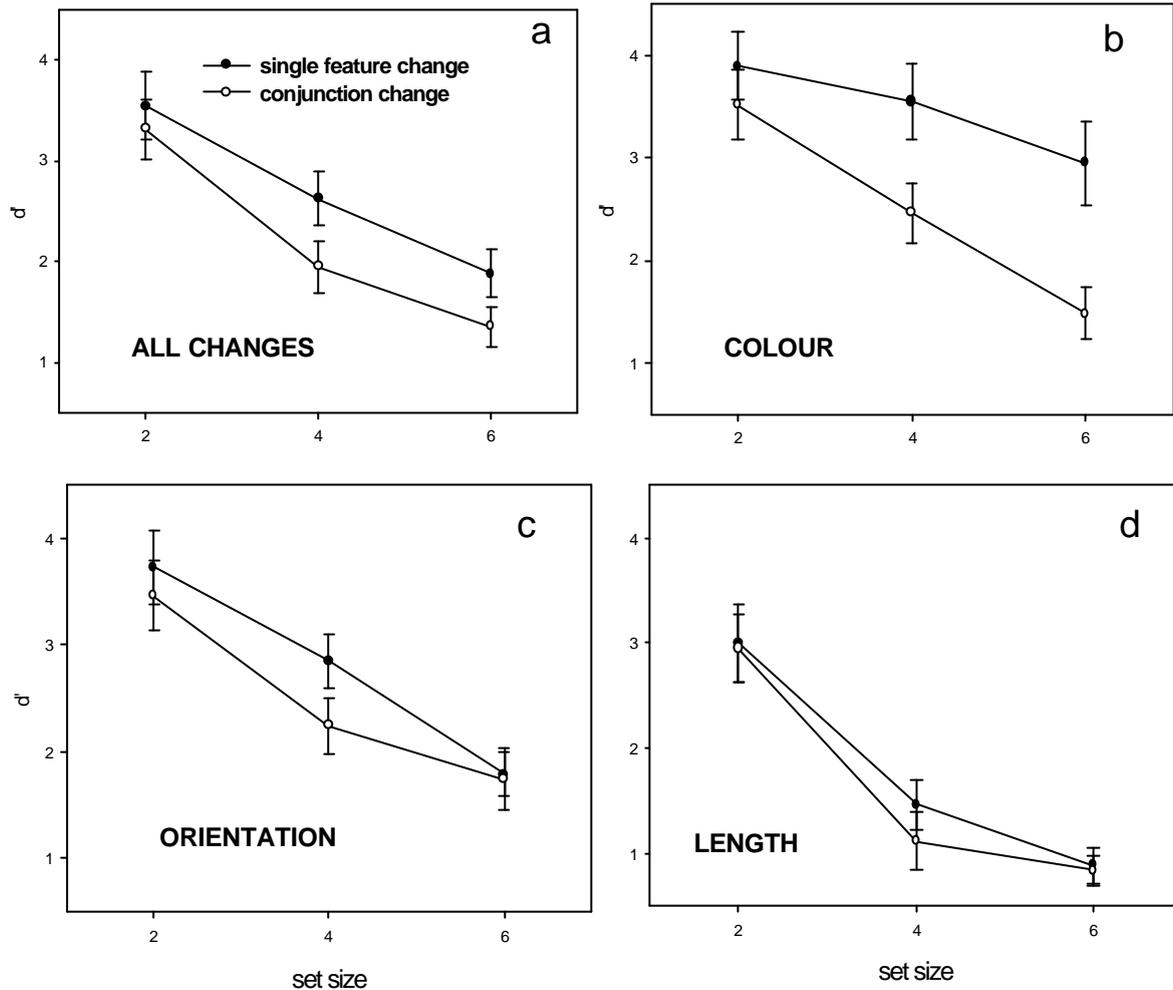


Figure 3.4 Mean accuracy in experiment 3a, measured by d' as a function of set size. a: Performance in all conjunction changes and all single feature changes. b – c: Performance in conjunction and single feature conditions according to the specific changes in the three features of colour, orientation and length.

contrast to the results of Luck and Vogel, is dependent on the feature dimension, too: Colour was retained best with only a modest decrease of performance with set size and a sensitivity as large as $d' = 2.96$ at set size six, which roughly corresponds to about 90% correct responses. Memory performance for length was comparably low, while working memory for orientation being between colour and length.

Accordingly, the statistical analysis reveals a highly significant effect of the changing dimension (colour, length, orientation), $F(2,18) = 66.62$, $p < 0.001$, and a significant interaction for *task* and *feature*, $F(2,18) = 11.36$, $p = 0.001$ and for *feature* and *set size*, $F(4,36) = 5.6$, $p = 0.001$. However, in agreement with Luck and Vogel, is the clear and statistically significant set size effect that was observed for all

conditions: memory performance declines with increasing set size ($F(2,18) = 83.90$, $p < 0.001$).

Experiment 3b

The observed difference between the outcome of experiment 3a and Luck and Vogel's (1997) experiment 6 concerning the performance in conjunction vs. single feature conditions might be due to the fact that in the current study a conjunction of three features was tested, but Luck and Vogel (1997) assessed the conjunction of only two features. This could mean that binding two features in an object is possible within the storage limit, but that with three features storage capacity is exceeded and performance declines. This possibility is excluded by considering the results of a further experiment by Luck and Vogel (1997). They tested whether the increase of the number of features that are confined in a single objects has an influence on memory performance. For they did not find costs for binding two features they addressed the question, whether there is a limit of the number of features that can be bound together without cost. They report an experiment (Luck & Vogel, 1997; experiment 14 in Vogel et al., 2001, respectively) in which the number of features was increased to four: Objects were varied according to colour, length, orientation and gap (continuous vs. broken by a black gap of 0.26° in the middle of the objects). The three single-feature conditions and the condition in which the conjunction of four features had to be retained were tested. Results show no statistically significant main effect of task; memory performance in the conjunction condition was the same as in the single feature conditions. This is again a very important result! It means that at set size four subjects were able to retain sixteen features, that were distributed across four objects in the conjunction condition, just as well as four features across four objects in the single feature condition. These results again strongly suggest the object-based storage in visual working-memory including up to at least four features that determine an object.

However, as the data from experiment 3a differed from the results of Luck and Vogel (1997), the performance in this type of experiment was examined more closely. In the present experiment the previous experiment 3a was extended. It was investigated, whether a gradual decline in memory performance can be observed, dependent on the increasing number of features that have to be retained in an object. In the previous experiment either one or three features had to be retained. In the present experiment the conditions in which the conjunction of two features had to be retained, while the third feature never changed, were added. By doing so, it was possible firstly, to replicate the results of the previous experiment, and secondly to test, whether a simple relationship between memory performance and number of stored features could be observed. In the present experiment the same kind of stimulus material was used as in experiment 3a. This means that the complexity of the objects was not varied. Instead, storage demands were manipulated by task difficulty: in addition to the single feature condition and the triple conjunction condition, two conditions with double conjunctions were introduced. Hence, it was possible to compare memory performance dependent on the number of features that have to be memorized in one object, occurring in single feature conditions, in double, or in triple conjunctions, correspondingly.

Method

Subjects 4 male and 6 female subjects, aged between 22 and 34 years, mean age 24 years, participated in the experiment. All had normal or corrected-to-normal vision.

Stimuli The stimuli were the same as used in experiment 3a, i.e. the sample array consisted of 2, 4, or 6 rectangles that could differ in the three feature dimensions of colour (red, green), size (long, short) and orientation (horizontal, vertical). The test display consisted of a single object at a location that had been occupied in the sample array in the respective trial. 50% of the cases were *same*-trials and the other 50 % were *different*-trials in which the test stimulus differed in one of its features from the respective object in the sample display.

Procedure Except as noted here, the procedure was the same as in experiment 3a. The experiment consisted of 6 different blocks with slightly different tasks. In the first type of blocks (1 – 3) the value of only one prespecified feature dimension out of three could change, in the second type of blocks (4 – 5) the value of two feature dimensions out of three could change and in the third type of blocks (6) the value of one of all three features could change. In particular the six tasks were as follows:

- 1) Memorize colour only as only the colour of a rectangle can change.
- 2) Memorize length only as only the length of a rectangle can change.
- 3) Memorize orientation only as only the orientation of a rectangle can change.
- 4) Memorize the values of the two feature dimensions colour and length as only colour or length can change.
- 5) Memorize the values of the two feature dimensions colour and orientation as only colour or orientation can change.
- 6) Memorize the values of all feature dimensions as the value of any dimension can change.

In the conditions in which more than one feature could change the changes in all feature dimensions occurred equally often. Session duration was approximately 1 hour.

Design The 6 different tasks were performed in separate blocks. Each of the 6 types of block was repeated 3 times. The 18 (6 x 3) blocks were performed during three sessions. The order of blocks was balanced among subjects. In conditions 1 – 3 only one feature could change, in conditions 4 and 5 two of the three features could change and in condition 6 any of the three features could change. In each block the 3 set sizes and the 2 same-different conditions required 6 trials for complete replications. In blocks 1 – 5 there were 20 replications resulting in 120 trials for one block, i.e. 60 replications of each condition in the 3 repeated blocks altogether. In block 6 there were 21 replications resulting in 126 trials in one block, i.e. 63 replications of each conditions in the three repeated blocks altogether. In block 4 the changes of colour and length occurred equally often. The same holds for changes in colour and orientation in block 5 and for the changes in all 3 features in block 6.

Results

For the reasons explained above also in this experiment d' -measures were used to estimate performance. Results are depicted in figures 3.5 a – e. Like in the previous experiment, also in this experiment it is evident, that memory performance in conjunction conditions is not the same as performance in single feature conditions. This is again not in agreement with the results of Luck and Vogel (1997). Figure 3.5 a shows the performance for the single feature conditions, for the double conjunctions features, and for the triple conjunctions averaged across all changes in the specific feature dimensions. In general, performance was better in the single feature conditions compared with the conjunction conditions. However, performance in double and triple conjunctions do not differ very much. This result is confirmed by a three-way (task \times changing feature dimension \times set size) repeated measures ANOVA on d' estimates. It revealed a significant main effect of the task (single feature change, double conjunction change, or triple conjunction change), $F(2, 18) = 6.884, p < 0.01$. A calculation of single contrasts within the condition of different tasks reveals a significant difference between the single feature condition and the condition with double conjunctions, $F(1,9) = 5.96, p < 0.05$. A highly significant difference was found between the single feature condition and the triple conjunction condition with potential changes in any of the three features, $F(1,9) = 59.83, p < 0.001$. There was no significant difference between the two conjunction conditions. A simple relationship between the degree of decline in memory performance and the increase of to be retained features could not be observed. Figure 3.5 b – d shows memory performance according to the changed feature in single feature, double and triple conjunction conditions. For colour the difference between the single feature condition and the two conjunction conditions is very distinct. For orientation it is less pronounced and in case of length changes no difference can be observed. This is basically the same result as has been observed in the previous experiment. Overall performance according to a single feature is shown in Figure 3.5 e. In general, colour is retained best, orientation is retained less accurately and memory for length is worst. This is confirmed by the statistical analysis which reveals a significant main effect of the changing dimension (colour, orientation or length), $F(2, 18) = 38.94, p < 0.001$. Significant interactions were found between the task and the changing

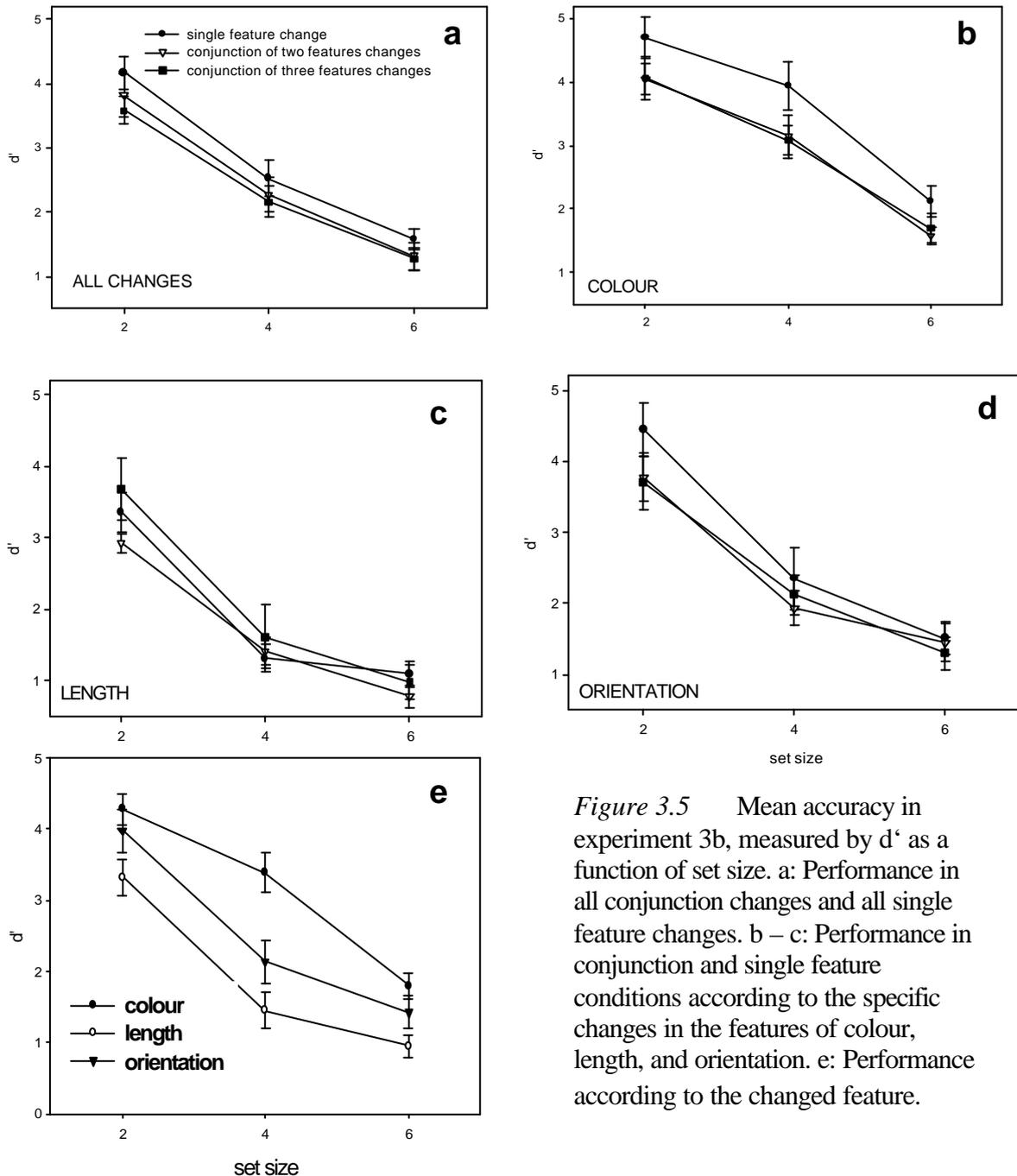


Figure 3.5 Mean accuracy in experiment 3b, measured by d' as a function of set size. a: Performance in all conjunction changes and all single feature changes. b – c: Performance in conjunction and single feature conditions according to the specific changes in the features of colour, length, and orientation. e: Performance according to the changed feature.

dimension ($F(4, 36) = 4.7, p < 0.01$) and between set size and the changing dimension $F(4, 36) = 7.8, p < 0.001$. A highly significant main effect was also found for set size (two, four or six objects), $F(2, 18) = 132.54, p < 0.001$.

Taken together, the empirical data of this experiment confirm the results from experiment 4a: Firstly, in line with the data of Luck and Vogel (1997) is the observation of a consistent set size effect: working-memory performance declines

with the number of to be retained objects. Secondly and not in agreement with Luck and Vogel (1997) is the result that memory performance varies according to the feature dimension that has to be retained. Thirdly, and most importantly, in contrast to Luck and Vogel (1997) memory performance is better when only a single feature of multifeature objects has to be retained compared to memory performance in conditions when conjunctions of features have to be retained. This is clear evidence against a strictly object-based storage account of visual working-memory. There is no difference in performance when conjunctions of two features or of three features have to be retained.

Experiment 4

With the result of very good performance in the conjunction conditions Luck and Vogel (1997) obtained evidence for storage of integrated object representations in visual working memory. An alternative explanation, however, would be the use of completely independent memory systems for each feature type. In order, to find the appropriate explanation, Luck and Vogel (1997) created objects composed of two feature values of the same dimension, namely coloured squares with a small square inside, that had a different colour than the outer square (see figure 3.2). The ability to store these composite objects was compared to the storage of simple large and of simple small squares, having only a single colour. If there are independent memory systems for each dimension, then the storage of colour-colour conjunctions should be much less accurate than the storage of single feature objects. On the other hand, if objects are stored as integrated representations, then conjunctions should be retained as well as single features. Luck and Vogel (1997) obtained the astonishing result of no difference whatsoever in memory performance between single feature objects and colour-colour conjunctions (see figure 3.3).

Since the previous results of Luck and Vogel (1997) could not be confirmed, because the data show costs for binding different features, also differences in memory performance should be observed when feature values of the same dimension

are combined. Therefore, it was considered important to assess memory performance also in the experiment of Luck and Vogel (1997) in which memory for colour-colour conjunctions was tested. Hence, the following experiment 5 was conducted which is a replication of the concerning experiment of Luck and Vogel (1997, or experiment 15 from Vogel et al., 2001). The results of this experiment have been reported earlier in response to Cowan, 2001 (Schneider, Deubel, & Wesenick, 2001).

Method

Subjects 2 male and 8 female subjects, with a mean age of 23.5 years participated in the experiments. All had normal or corrected-to-normal vision.

Stimuli Three sets of stimuli were used according to the task. In the colour-colour conjunction condition squares were presented, that were composed of a coloured larger outer square ($0.7^\circ \times 0.7^\circ$), and a smaller inner square ($0.4^\circ \times 0.4^\circ$) of a different colour. There were two single feature conditions: In the first condition large squares were presented, in the second condition just small squares had to be retained. Eight colours were used for the objects: red, green, blue, yellow, white, purple, brown, grey. In a *different*-trial of the conjunction condition only the colour of the outer or the colour of the inner square changed. The new colour was not present in that object before, so that the resulting square still was composed of two colours. Changes occurred in the inner and outer square equally often. The sample array consisted of 2, 4, or 6 coloured squares that had to be retained. In the test display all the objects were presented again with a possible change of one object. 50% of the cases were *same*-trials and the other 50 % were *different*-trials.

Procedure Except as noted here, the procedure was the same as in experiment 3a. The experiment consisted of 3 different blocks: The first two blocks consisted of the single feature conditions: In the first block only the larger squares were presented. In the second block only the smaller squares were presented. The third block contained the colour-colour conjunctions.

Design Each of the three blocks was repeated 3 times during two sessions. The order of blocks was balanced among subjects. In each block the 3 set sizes and

the 2 same-different conditions required 6 trials for complete replications. There were 144 trials in each block, resulting in 72 replications of each condition in the three repeated blocks altogether.

Results

Accuracy of performance was measured using % correct data. Since only one feature dimension was tested a d' analysis was not necessary in this experiments. Results are depicted in figure 3.6. It is immediately evident, that the performance in the conjunction condition is dramatically worse than performance in the single colour condition. Performance declines with increasing set size from 84.5 % correct at set size 2 to 74.4% at set size 4 and 64.0 % at set size 6. Performance in the single feature conditions, which do not differ from each other, is considerably better: For set size two it is between 93 and 95% correct, for set size four it is between 89 and 90% correct and for set size six it is between 79 and 82% correct. A two-way (condition \times set size) analysis on % correct data showed a significant main effect of condition (large objects, small objects, composite objects), $F(2, 18) = 46.03$, $p <$

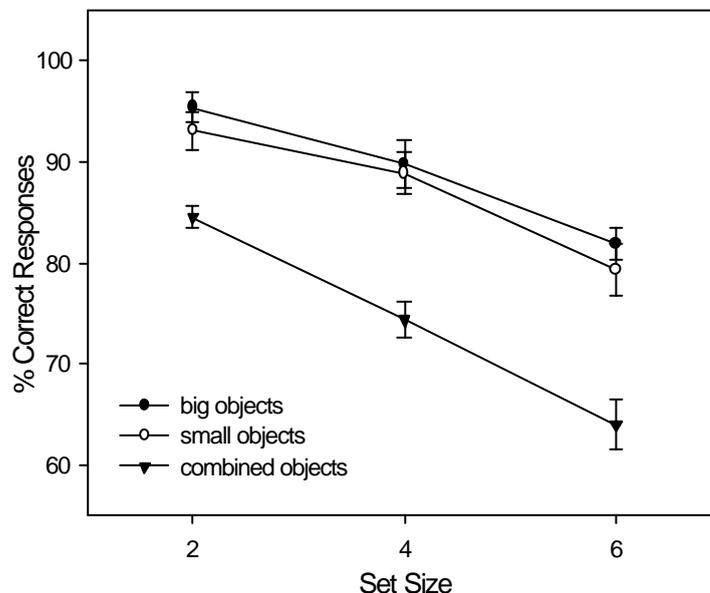


Figure 3.6 Mean accuracy in experiment 4 as a function of set size.

0.001, and of set size (two, four or six), $F(2,18) = 30.73$, $p < 0.001$.

These results are obviously different from the results obtained by Luck and Vogel (1997). The replication of their experiment clearly failed. It could be shown that memory performance for objects composed of a single colour is considerably better than memory performance for objects composed of two colours. In fact, memory for composite objects at set size two – comprising four colours – is close to memory performance for simple objects at set size four – comprising also four colours. This result is strong evidence against integrated object representations. In this special case of combining feature values of the same dimension it seems that working-memory capacity is determined by the number of absolute features and not by the number of objects.

Discussion of Experiments 3a + b, and 4

The issue of the current chapter is the nature of visual representations that are stored in visual short-term memory. By attempting to determine the capacity of the store it was necessary to find out what the unit was, with which the capacity can be measured. In what format is information represented in visual short-term memory? This question touches an issue that is widely discussed as the *binding problem* in vision. In the visual system incoming information is decomposed into separate dimensions which are processed in different areas of the massively parallel brain (e.g. Livingston & Hubel, 1988; DeYoe & Van Essen, 1988; Desimone & Ungerleider, 1989; Zeki, 1993; Ungerleider & Haxby, 1994). The binding problem refers to the question how in visual cognition the distributed information of separately coded features are correctly integrated forming a representation of a common object. The binding problem has primarily been investigated in studies on visual perception, yet the issue is of major relevance also for other levels of cognitive processing, such as in the present study, the short-term retention of visual information: What are the representations in visual short-term memory? Are visual objects stored as integrated wholes, so that objects bound together in the course of perception remain in this bound state when they are stored in short-term memory? Another possibility is that object features might be stored separately, and the unit that

determines the storage capacity being single features. In this case a mechanism is needed that processes these representations and link the features that belong to the same object when the information is needed.

Attentional account of binding: Feature Integration Theory

In perception, attention is proposed to be such a mechanism by which binding is accomplished. A well known psychological theory which gives an attentional account of binding is feature integration theory (FIT) of Anne Treisman and colleagues (e.g. Treisman & Gelade, 1980; Treisman 1988, 1998, 1999). It explains how visual objects are correctly perceived and how miscombining features that belong to different objects is prevented. According to FIT, information that is perceived from our visual environment is initially stored in several independent maps of primitive features. Focussed attention is serially applied to spatial locations and features from different maps that belong to the same object are joined together through their shared spatial location. Without focussed attention there is no connection between features from different maps and it is possible that accidental miscombinations of features that belong to different objects, also called illusory conjunctions, can occur. When the features of one object are bound together by attention they are then entered into updatable *object files* (Kahneman, Treisman, & Gibbs, 1992) which preserve the identity of objects across space and time, i.e. also when the object moves or when its properties change. Whenever attention is allocated to an object always all features of that object are available without additional cost. Thus the experience of stable and unitary objects in our visual environment is guaranteed.

Physiological account of binding in visual perception: Elevated neuronal firing rates and synchronous neural firing

There is physiological evidence that is consistent with FIT. Neuronal responses are modulated by attention: when an object is in the focus of attention. Neurons that belong to features of this object fire at a higher rate than neurons of features that belong to unattended objects. In general, attentional modulation of neural activity can

be observed in most areas of the visual cortex, with increasing attentional influence from primary visual cortex to extrastriate areas. Also, attentional modulation is stronger when besides the attended stimulus an unattended stimulus is present in the receptive field (Treue, 2001). Early studies on the operation of attention in macaque visual cortex (Moran & Desimone, 1985; Luck, Chelazzi, Hillyard, & Desimone, 1997) have shown that information from ignored locations is suppressed in visual areas with large receptive fields (V4 and IT) in which the probability of miscombining features that belong to different objects is high. Suppression is found only when attended and unattended locations are both inside the receptive field of the neurons studied. When only one stimulus was inside the receptive field – a situation in which a wrong combination of features of different object is unlikely – there was no suppression. Elevated firing rate of neurons that code the features of objects have also been observed in single unit recordings of monkeys (Fuster & Jervey, 1981; Miller, Erickson, & Desimone, 1996) and in functional imaging of humans (Cohen et al., 1997; Courtney et al., 1997). However, this account is not sufficient to explain binding when more than one object is attended: When the number of attended objects increases within the receptive field also the number of neurons that fire at an elevated rate increases and miscombinations of features that belong to different objects are likely. An additional binding mechanism has been proposed, namely synchronized neural firing of neurons that represent features of the same object (Gray et al., 1989; Hummel & Biederman, 1992; von der Malsburg, 1981; Niebur, Koch, & Rosin, 1993; Schneider, 1995; Singer, 1989; Singer et al., 1997; Singer & Gray, 1995). The *temporal tagging hypothesis* (Eckhorn et al., 1988; Mozer et al., 1992; Gray et al., 1989) suggests that neurons, that code the features of an object, form a cell assembly (Hebb, 1949) as a processing unit which has two output values: The first is the activation level, which is determined by the firing rate, and indicates whether a specific feature is present in an object. The second value, achieved by synchronization, is a tag, that marks the object to which that feature belongs.

Physiological account of binding in working-memory: Luck and Vogel (2001)

The behavioural data of Luck and Vogel (1997) and Vogel et al. (2001), respectively, as well as the data of the present work, have shown that memory

performance is about the same for objects that consist of a single feature and for multifeature objects, in which the objects can even be composed of feature values of the same dimension, namely two colours. This means that memory performance at a given set size does not depend on the number of features that make up an object. However, a clear effect of memory performance is observed when the number of the objects that have to be remembered is varied: With increasing set size memory performance declines. From the experimental data a working-memory capacity of approximately 3 – 4 objects is calculated. In short, the capacity of working-memory is determined by the number of objects that have to be stored, independent of the number of features that characterize the objects. Vogel et al. (2001) give a physiological explanation of their data and of binding in working-memory. They suggest that synchronized neural firing and elevated neuronal firing rates, that have been proposed for binding in object identification (Gray et al. 1989; Hummel & Biederman, 1992; Niebur, Koch, & Rosin, 1993; von der Malsburg, 1996), make up the two components of a similar mechanism responsible for binding in working-memory. This model, according to Vogel et al. (2001), can provide an explanation for the limited storage capacity: In coding objects by synchronization accidental synchronizations can occur, which means that neurons coding different objects may by coincidence fire at the same time. As a consequence distinct object representations are not as separate any more and the coding can become ambiguous. The probability of accidental synchronization increases with the amount of multiple objects that are coded in parallel. Thus, with the increasing number of objects the quality of representation degrades. This corresponds to the observation that memory performance declines with increasing set size. The suggested mechanism, according to Vogel et al. (2001) also provides an explanation for the fact, that memory performance was not affected by the number of object features: The neurons that code the features of an object all fire in synchrony forming a cell assembly. The number of neurons that constitute a cell assembly has no effect on the probability that this cell assembly would fire at the same time as another cell assembly. Hence, an unlimited number of features could be confined in one object.

Evidence for binding costs in visual short-term memory

The main outcome of the experiments of the present chapter (3a + b and 4) is that it was not possible to exactly replicate the experimental results of Luck and Vogel (1997), which didn't reveal any differences between the single-feature and the conjunction conditions. Neither could their results be confirmed that there are no differences in performance between the feature dimensions. Instead, the present data apparently show processing costs when subjects were required to retain several features of an object and not just one. Experiments 3a and 3b showed that the ability to retain a feature of an object is significantly better when this feature is the only one that has to be remembered in an object compared with the case that the task requires to retain additional features. In addition, the present data suggest differences in the capacity for different features. Colour is retained best in both experiments, length is the most difficult and orientation being in between (see figures 3.4 and 3.5).

By these findings the claim of Luck and Vogel (1997) is clearly falsified that in working memory at least up to four features can be linked together in a single object representation with no costs at all in terms of storage capacity. On the contrary, the data show that besides the severe limit on the number of objects that can be stored (which is in agreement with Luck and Vogel's results) there are also storage limitations with respect to the number of task relevant features that compose each object. Nevertheless, there neither is evidence for the alternative hypothesis devised by Luck and Vogel that implies that the visual working memory capacity is defined by the number of features present in the objects. The results suggest that the capacity is clearly not defined by the number of features, but still might principally be related to whole objects as the relevant unit: For example in experiment 3a at set size two in the conjunction condition four features are distributed across two objects. If features were the unit of working-memory that measure capacity, then performance of two objects in the conjunction condition should be approximately the same as four objects in the single feature condition. This is not the case: it is considerably better. Therefore, it has to be concluded that storage capacity of visual short-term memory is indeed essentially related to the number of objects. However, if the object is composed of more than one feature, then there are processing costs for confining the features that belong to that object. Because of these binding costs memory

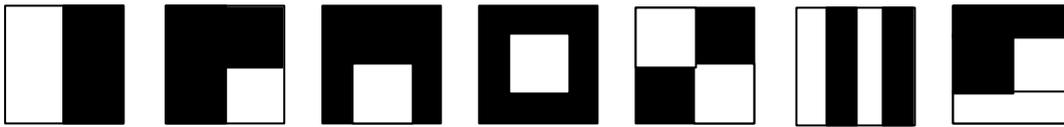


Figure 3.7 Different arrangements of bicoloured squares that have been used in the study by Wheeler and Treisman, 2002.

performance declines when more than one feature has to be retained in one object and binding information is needed to solve the task. However, an important special case is the condition in which an object consists of features of the same dimension. Contrary to the results of Luck and Vogel large differences in memory performance was found when objects of only one colour had to be retained compared with objects that were composed of two colours. In fact, the decline in memory performance by adding a second colour to an object were comparable to the effect of adding a second object in the single colour condition. The present experiments show, that the ability to retain one object of two colours is comparable to the ability to retain two objects that have a single colour. This means that there are moderate costs for binding features of different dimensions in one object. But binding costs for features of the same dimension are considerably larger. Adding a second feature of the same dimension costs as much as adding a new object.

Experimental evidence that support the present view and that are in agreement with the present data have recently been obtained by Wheeler and Treisman (2002) and confirm an earlier report of the present data (Schneider, Deubel, & Wesenick, 2001). In their experiment 3 Wheeler and Treisman (2002) attempted to replicate the concerning experiment of Luck and Vogel (1997), in which objects of two colours had to be retained. They failed to observe equal performance in retaining the different kinds of stimuli. Instead, their results are very similar to the outcome of the present experiment: Retention of large and small squares of a simple colour is about equal. But the retention of bicoloured squares is much worse than the retention of single coloured squares. In their experiment 2 Wheeler and Treisman (2002) even tested different arrangements of bicoloured squares (see figure 3.7). For all different designs they obtained the same result: Three objects, composed of two colours, were

retained as well as six single-coloured squares. It is not clear why there was a different outcome in the experiment of Luck and Vogel (1997). Still, it seems evident that bicoloured squares are not retained as integrated objects, but that within the dimension of colour, capacity is limited by the number of colours that have to be retained.

In their study Wheeler and Treisman (2002) propose two separate mechanisms for the storage of information in visual short-term memory. There is one mechanism that limits short-term visual memory for features on the one hand and a second mechanism for bindings between these features on the other hand. Firstly, it is supposed that feature values from different dimensions are stored in parallel in separate dimension-specific caches. Each feature dimension may have its own capacity limit, independent from other features. Within a dimension the features compete for limited capacity representation, but between dimensions there is little or no competition. The limited capacity is assumed to comprise three or four items. And secondly, binding information can be retained and costs only little in terms of feature capacity. But it depends on other limited attention resources. The authors also give an account for binding on the neural level. Following Singer et al. (1997; Singer & Gray, 1995) they propose that binding is maintained by synchronous neural firing. When binding is required those brain areas were recruited that are involved in focusing attention in visual perception tasks. It is proposed that binding in visual memory requires the maintenance of focussed attention over the delay. Selective spatial attention might thus be the rehearsal mechanism for spatial working memory. Wheeler and Treisman (2002) speculate that in this way some of the same mechanisms that are involved in visual perception are also involved in visual working memory.

In his neuro-cognitive theory on visuo-spatial working memory Schneider (1999) (see chapter 1) designates an object file to be the perceptual unit that is also processed in visual working memory and determines its capacity. According to Schneider (1999) visuo-spatial working memory consists of up to four object files. These object files contain temporary episodic representations of detailed high-level attributes of the regarding object and an index. The index contains temporary information about the attributes of the concerning object and is thus carrying the

binding information. Schneider (1999) suggests that the representation of multiple objects and the correct binding of their attributes on the neural level is achieved by temporal coding (referring to Milner, 1974; von der Malsburg, 1981; Singer, 1989; Goebel, 1991; Schneider, 1995; Singer et al., 1997). The neurons representing the object files that are hold active in working memory fire at different time slices, thus retaining and segregating the objects. The activation of an object file is represented by the activation of its index. From this it follows that similar to the view of Wheeler and Treisman (2002) also Schneider (1999) assumes two components of the units of visual short term memory: the attributes of an object and an index. It is in agreement with his theory that possibly a large number of features can be confined in one object without large storage costs. The separate features each may have different storage capacities. Binding is achieved by the index of the object file. Therefore, the additional processing costs could be attributed to the need of retaining these binding information by the index.

In summary, the present data show that in principle the capacity of visual working-memory relates to objects as the unit of the store. However, there are binding costs when more than one feature in an object has to be stored in visual working memory. The separate features each may have different storage capacity. When two features of the same dimension have to be retained in one object, then memory capacity relates to the number of different features. The data are in agreement with the theoretical view of Wheeler and Treisman (2002) and also of Schneider (1999). Both views imply two storage mechanisms: firstly, the storage of attributes of an object, and secondly the storage of binding information. The storage of an object feature has costs and there are additional costs, when binding is required.

Chapter 4

LIMITATIONS DUE TO RETRIEVAL PROCESSES

Introduction

The present chapter is dedicated to the issue of how information is retrieved from visual short-term memory (VSTM). How are the visual representations that are temporarily stored in VSTM accessed and retrieved for further processing? Memory performance might depend on the precise conditions for retrieval. In certain environments information can be retrieved easily, when sufficient retrieval cues are present and disrupting factors are minimal. In other environments retrieval is largely disturbed. It is an aim of the present research on VSTM to find out about the factors that can disrupt or help retrieval. An example for factors that can disturb the retrieval process are multiple transients that are caused by a blank interval between two displays (Phillips & Singer, 1974; Stelmach et al., 1984; Becker et al., 2000). On the other hand, observers benefit from a postcue in studies with a change detection task in natural scenes (Simons et al., 2002; Hollingworth, 2003). Changes can be detected more reliably when a cue marks the changed item, which is explained by the fact that retrieval and comparison could probably be limited to the target object. However, in other studies no such advantage from a postcue was found (Becker et al., 2000; Landmann et al., 2003).

The question of how information is retrieved from VSTM is not only interesting for its own sake. It is also of relevance for an understanding of other aspects of visual

short-term memory and of the nature of short-term visual representations. For example, in order to estimate VSTM capacity it has to be considered that the observed limitations could partly be attributed to limitations in the retrieval processes and not to actual storage limitations alone. Thus a more accurate estimate of the storage capacity can be obtained if the limitations that are due to retrieval are known. In a related area, in research on visual persistence, different results according to the way memory was tested lead to conclusions on the amount and the nature of the stored information (Sperling, 1960): Memory performance was very limited when the whole report technique was applied. However, testing memory using the partial report technique has led to an estimate of unlimited storage capacity. The discrepant result is due to the nature of very short-term visual representations: Sensory persistence decays very rapidly during the first few hundred milliseconds and is therefore not available long enough for the subject to solve the experimental task in the whole report procedure. This example shows that by applying different methods in memory testing important conclusions on the nature of visual representations can be drawn.

In the context of the present study, in which a change detection task was used, focus was a specific aspect of working memory retrieval: How is the information that is stored in VSTM compared with the online perceptual information? Is there an item-by-item comparison to decide whether the visual objects in memory and the objects currently observed on the computer screen are the same or different? Or is the change detection task solved in a different way? Is the retrieval process limited to a certain number of comparisons or to the amount of to be compared information? This kind of question has also been applied e.g. to visual processing of perceptual information. In research on visual attention extensive considerations have been made on the way objects from multi-element displays are selected. Observations from visual search experiments have led to a major debate on whether information is processed serially, in an item-by-item search, or whether it is processed in parallel. A further aspect that is relevant in this context is the role of spatial locations. Are visual objects accessed for comparison via their locations or is the access object-based? The distinction between objects and locations as preferential unit for further processing is also well known from research on visual attention. There is an extensive debate on

whether objects or spatial locations are selected by attention. Space-based accounts suggest that attention is allocated to spatial regions. Objects, that are located in this attended region are selected for further processing (Eriksen & Yeh, 1985; Posner, 1980). Conversely, object-based accounts claim that attention is directed to integrated objects (Duncan, 1984; Kanwisher & Driver, 1992; Kahneman, Treisman, & Gibbs, 1992).

Experiment 5

In this first experiment on memory retrieval subjects performed a change detection task with four different retrieval conditions. Like in the previous

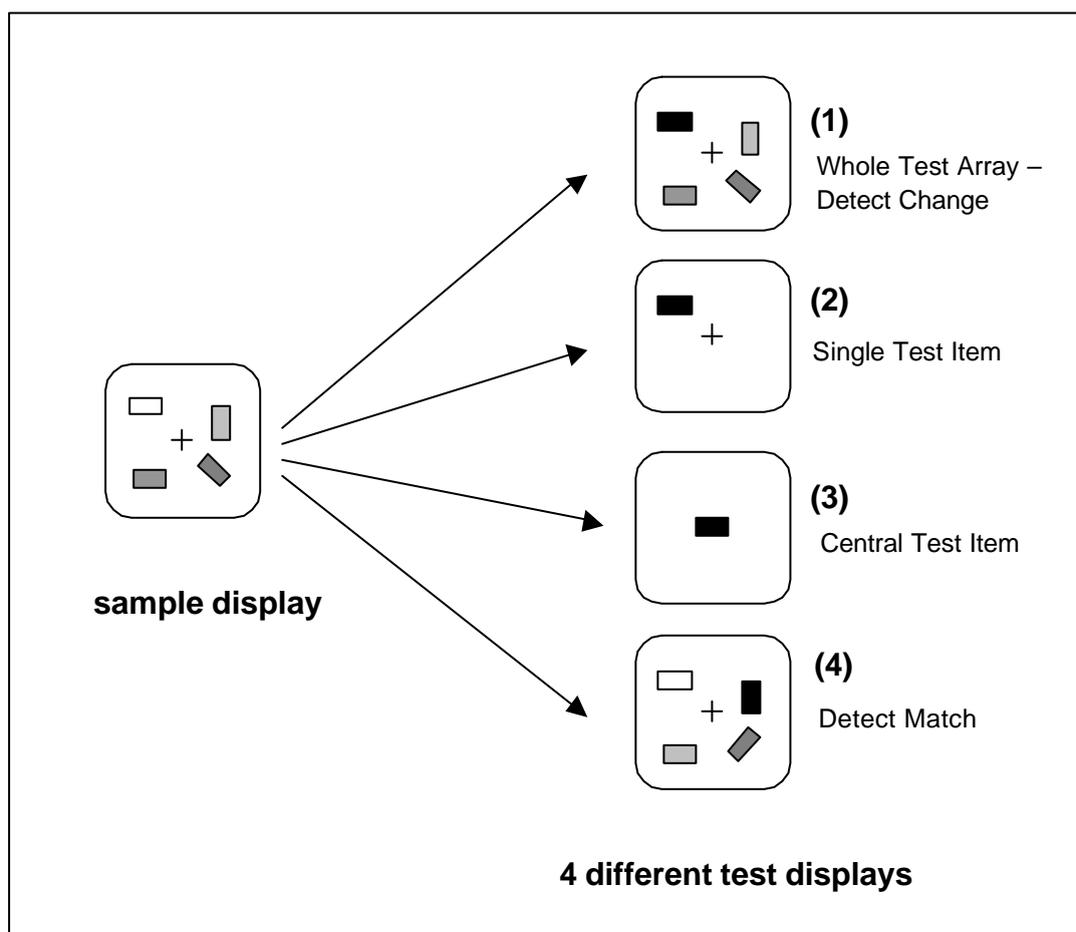


Figure 4.1 Examples of the four different test displays used in experiment 5.

experiments subjects were shown an array of four rectangles which were composed of different colour and orientations. The task was to retain these objects across an interval of 2 seconds. Then a test display appeared and subjects normally had to decide whether there was an item that was different compared to the respective item stored in memory. In order to study retrieval processes the test display was varied in four different blocks (refer to figure 4.1). By the different experimental manipulations it was examined how the comparison between memory content and perceptual information is accomplished. In a first condition in the test display the test objects occurred at the same locations where the respective objects had been shown shortly before in the sample display. One of the objects could change, the other objects remained the same. This condition was labelled the *whole test array – detect change* condition. If there is a serial item-by-item comparison in retrieval, then every object that is stored in VSTM would be compared with the respective item in the test display. When a change is detected the response is given. In a second condition the structure of the test display was varied. Only one item was now presented at a location that was previously occupied in the sample display. This object was either the same as the item shown before at that location or it differed from it in one of its features. This condition was labelled the *single test item* condition. If a serial item-by-item comparison to find the changed item is assumed, then this second condition should be easier than the *whole test array* condition, since in the *single test item* condition the critical item is already provided in the task. It should be sufficient to compare just the critical item with the respective item in memory. In other words, decisions processes are reduced by this technique and therefore better performance has to be expected in the *single test item* condition. (For a discussion on the problem of decision processes refer to, e.g., Palmer, 1990, 1995; Palmer, Ames, & Lindsey, 1993, Shaw, 1980). In a third manipulation again only a single test item was presented. But this time it was shown in the centre of the screen and not at one of the positions of the sample objects. This condition was labelled the *central test item* condition. This manipulation was introduced to learn more about how the critical object is accessed in VSTM for retrieval. It could be accessed by its location, which may be coded in an object file. If it is preferentially accessed by its location, then subjects should be better in the *single test item* condition compared with the *central*

test item condition, because in the *single test item* condition a single comparison of the critical item with the respective item in the sample display is sufficient for the task. In contrast, under this assumption in the *central test item* condition the test item would have to be compared with every item from the sample display until the change is detected. In this case up to four comparisons are necessary to solve the task. Therefore, performance would be worse than in the *single test item* condition. In the fourth manipulation in half of the trials all four rectangles changed in one of their features. In the other half all objects except one changed. The task was to detect an object that matched the object that was located at the respective position in the sample display. This condition was labelled the *detect match* condition. This means that for memory testing the task was not to search for a changed object as before, but for an unchanged object. Under the hypothesis, that sample and test display are compared serially in an item-by-item manner, the result of the comparison should not influence the procedure. It should be just the same to search for a matching item or a changed item. Therefore, performance in the *whole test array – detect change* and the *detect match* conditions is expected to be similar.

Method

Subjects 11 subjects (6 females, 5 males), aged between 22 and 41 years (mean age: 25) participated in the experiment. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment. They were paid for their participation.

Stimuli Except as noted here, the stimuli were the same as in Experiment 1. The sample array consisted of 4 rectangles which all had the same size ($0.34^\circ \times 1.34^\circ$) but differed in colour (red, green, blue, yellow, purple, white) and orientation (horizontal, vertical, left and right oblique). There were 4 types of the test display. For details refer to the subsection *Procedure* below.

Procedure Except as noted here, the procedure was the same as in Experiment 1 (refer to figure 1.7). The display time of the sample array was 400 ms. The interval between the sample array and the test array was 2000 ms. There were 4 blocked conditions in which the test display varied. In conditions 1 – 3 subjects

always had to respond to a difference in the test display with respect to the sample display. In condition 4 subjects had to respond to a match of one object in the test display with the object that had been seen at that location in the sample display.

More specifically:

Condition (1) Whole test array – detect change: The test display was of the same structure as the sample array. The same number of objects as in the sample array occurred at the same locations. In the “same”-condition the test display was exactly the same as the sample display. Subjects were instructed to press the right mouse button in this case. In the “different”-condition the test display differed from the sample display only in one object that changed either in colour or in orientation. Subjects were instructed to press the left mouse button in this case.

Condition (2) Single test item: The test display consisted of one rectangle at a location that had been occupied in the respective sample array. In the “same”-condition this object was exactly the same as the object at that location in the sample display. Subjects were instructed to press the right mouse button in this case. In the “different”-condition the object in the test display differed from the respective object in the sample display in one feature – either in colour or in orientation. Subjects were instructed to press the left mouse button in this case.

Condition (3) Central test item: The test display consisted of a single object that occurred in the centre of the screen. In the “same”-condition this object has been shown before somewhere in the sample display. Subjects were instructed to press the right mouse button in this case. In the “different”-condition the object in the test display was not present in the sample array. Subjects were instructed to press the left mouse button in this case.

Condition (4) Detect match: The test display was of the same structure as the sample array. The same number of objects as in the sample array occurred at the same locations. In the “match”-condition the test display consisted of one object that was exactly the same as the object at that location in the sample display while the other three objects all changed either in colour or in

orientation. Subjects were instructed to press the right mouse button in this case. In the “mismatch”-condition the test display differed from the sample display in all four objects that all changed either in colour or in orientation. Subjects were instructed to press the left mouse button in this case.

Subjects were asked to respond as correctly and as quickly as possible. In case they were not sure about the right response they were instructed to guess. Session duration was approximately 1 hour. In case of a false response subjects received a feedback tone.

Design The four test display conditions were performed in four separate blocks of 80 trials each, which were generated at random. The subjects performed each of the four blocks once during one session. I.e. there were 40 complete replications of the 4 test display conditions and the 2 same-different (or match-mismatch) conditions. The order of blocks was balanced among subjects.

Results

Accuracy of performance was measured using % correct. Results are shown in figure 4.2. There is no difference in memory performance according to the retrieval condition except for the *detect match* condition (56.5% correct, MSE, 2.1), which is considerably worse than the other conditions (75.4 – 78.6 % correct). This result is confirmed by statistical analysis: A one-way repeated measures ANOVA on performance data (% correct) revealed a significant main effect, $F(3, 30) = 23.6, p < 0.001$. A reversed Helmert contrast showed a significant difference when the effect of the *detect match* condition was compared to the mean effect of the three other conditions, $F(1,10) = 103.1, p < 0.001$. Pairwise comparisons (with Bonferroni adjustment for multiple comparisons) among these last three conditions did not show a significant difference.

More specifically the results show, that firstly, there is no difference in performance in detecting a change whether the whole display is presented or only the critical item. This means that, although in the *whole display* condition no information is given on the location of the critical item, performance is just as high as in the

single test item condition when this information is provided by removing the irrelevant objects. This is a result of fundamental importance. Together with further evidence from the current series of experiments it forms the basis of the present view on VSTM retrieval. In anticipation of a more deeper discussion, the view developed here shall briefly be outlined at this point already, because the line of argumentation in the succession of the following experiments will become more lucid for the reader. So, how can the result of similar performance in the *single test display* vs. the *whole test array* conditions be explained? The assumption of an item-by-item comparison does not fit with this result, because in this case lower performance in the *whole test array* condition is expected. It seems that the location of the change can be found very efficiently and without an error-prone and time consuming comparison process. This finding can be explained by assuming that the location of the change is directly indicated, perhaps by a specific signal pointing to the local change. To refer to this signal the concept of a *change signal* was introduced, that indicates the location of the change. The *change signal* is elicited by a mismatch between the information stored in VSTM and the perceptual online information. The *change signal* can be processed by the cognitive system in an efficient way, so that a serial item-by-item comparison for retrieving the memory information is not necessary to solve the task. It is further suggested that the mechanism that is attracted by the *change signal* and

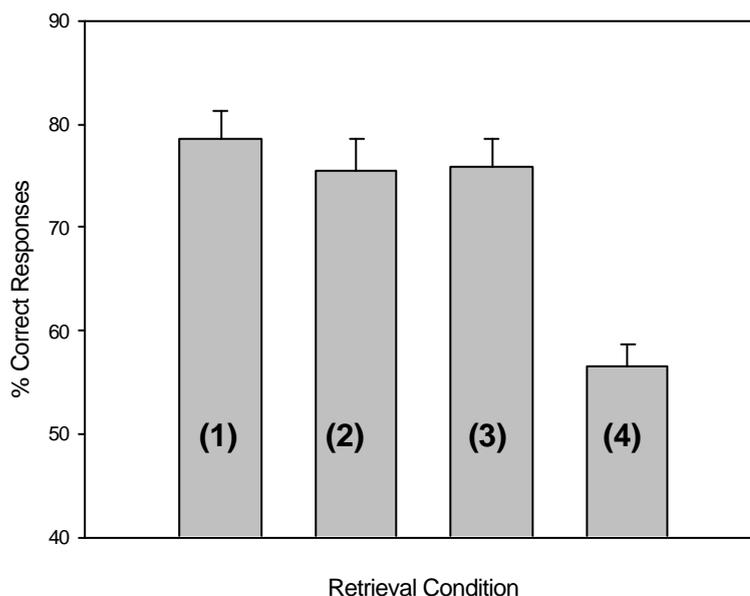


Figure 4.2 Mean accuracy according to the four different retrieval conditions in experiment 6: (1) Whole test array – detect change, (2) Single test item, (3) Central test item, (4) Detect match.

which leads to further processing is an attentional mechanism. So by a mismatch between a memory item and a corresponding item that is currently perceived, visual attention is drawn directly to the critical item so that the change can be detected. In the following the concept of the *change signal* and some of its characteristics will be specified in more detail.

Secondly, the results of the present experiment show, that there is no difference in performance for detecting a change whether the single critical item is presented at its original or at a different location. It was predicted that performance is lower, when the information on the location of the critical item is removed. Obviously the task can be performed equally well without the information where the critical item was located in the memory set. So the hypothesis that information stored in VSTM can effectively be accessed exclusively by the location of the critical object was rejected.

Thirdly, it can be taken from the results that there is a significant decline in performance when the task is to find a matching object in the display among irrelevant objects that all changed. If VSTM retrieval always would be accomplished by a serial item-by-item comparison then performance should be similar to the performance in the detect change task as explained above. So also these results suggests that there is no serial item-by-item comparison in the detect change task. However, the results can be explained by the proposed mechanism in VSTM retrieval that makes use of a *change signal*: On a trial with a matching object there are also three objects that have changed. So in three locations there are mismatches between memory objects and perceived objects which all elicit a change signal. In this case a *change signal* can no longer be used to solve the task efficiently, because it points to three possible targets. Instead, now the matching item has to be searched for by an item-by-item comparison. It may be assumed that this comparison process engages visual attention. Visual attention has been also suggested to be the mechanism that holds the information active in VSTM. So when the comparison process employs visual attention it is disengaged from the rehearsal process. Therefore, by comparing one item from memory the other items in memory are lost from VSTM by overwriting or decay. The observed very low performance of only 56.6% correct responses in the *detect match* condition fits very well with this view.

The performance rate is right above the guessing threshold of 50% and suggests a memory capacity of one item. So if the critical item is the first item to be compared a correct response is possible. If one of the distractor items is the first object to be compared the correct answer can only be guessed, because the critical information is already lost and cannot be extracted any more.

Experiment 6

We assumed that in the *detect match* condition of the previous experiment the task could not be solved efficiently, because it was not possible to make use of the *change signal* in order to reliably find the target item. In the following experiment it is tested whether performance in the *detect match* condition would be higher, if the information on the critical item is provided by a location cue. So, similar to using the *change signal* in the *detect change* condition of previous experiments, as a substitute the cue might be used to solve the task in the present experiment. The task of the present experiment was again to decide whether the test display contained an item that has been shown at that location in the sample display or whether all items changed (*detect match*). In part of the trials a cue indicated the location of the critical item. Cue onset time was varied: The cue could occur either at some points within the retention interval, or together with the test display, or after the test display appeared.

Method

Subjects 6 subjects (5 females, 1 male), aged between 19 and 27 years (mean age: 23) participated in the experiment. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment. They were paid for their participation.

Stimuli Except as noted here, the stimuli were the same as in Experiment 1. The sample array consisted of 4 rectangles which all had the same size

($0.34^\circ \times 1.34^\circ$) but differed in colour (red, green, blue, yellow) and orientation (horizontal, vertical, left and right oblique). The test display corresponded to the *detect match* condition of the previous experiment (Experiment 5).

Procedure Except as noted here, the procedure was the same as in Experiment 1. The display time of the sample array was 400 ms. The interval between the sample array and the test array 2000 ms. The test display corresponded to the *detect match* condition of the previous experiment. However in two thirds of the trials a cue appeared. The cue consisted of a dot that marked the location of the critical item. The cue either occurred within the retention time with a cue onset time of -800, -400, -200 or -100 ms with respect to test display, at the same time with the test display (cue onset time: +/- 0 ms) or after the onset of the test display with a cue onset time of 100, 200 or 400 ms. In all cases the cue stayed on the screen until the subject pressed the mouse button for the match-mismatch decision. Subjects were asked to respond as correctly and as quickly as possible. In case they were not sure about the correct response they were instructed to guess. Session duration was approximately 1 hour. In case of a false response subjects received a feedback tone.

Design The nine different conditions were presented at random. One block consisted of 120 trials which were generated at random. In each block the 8 cue conditions in which a matching item was either present or not were repeated 5 times. The conditions without cue in which also either a matching item was either present or not were repeated 20 times. Each block was performed eight times by each subject, yielding 80 data points for each cue condition and 320 data points for the no-cue condition.

Results

The results (% correct) of the experiment are illustrated in figure 4.3. Performance is shown as a function of cue onset asynchrony (COA) with respect to the test display. The vertical dotted line marks the point in time when the test display was shown. Negative COA values refer to cues that are given before the test display appears, positive COA values refer to postcues. At a COA of zero the cue appears at the same time as the test display. Performance for the conditions in which no cue was

presented (60.4 % correct, MSE 2.3) is depicted by the dashed horizontal line. A one-way ANOVA for repeated measures, shows a highly significant main effect of COA, $F(8, 40) = 14.0$; $p < 0.001$. A calculation of simple contrasts between performance at a COA of -800 ms and all other conditions shows no significant difference to performance at a COA of -400 ms ($F(1,5)=1.7$, $p = 0.25$), but between -800 ms and every other conditions ($p < 0.01$ in all cases except for COA -100 and $+200$ where $p < 0.05$). A calculation of simple contrasts between the condition without a cue and the cued conditions shows that there is no significant difference when the cue is presented after the display ($p > 0.05$ in all cases), but a significant effect of the cue for all other cases ($p < 0.01$; except COA = -200 ms: $p < 0.05$).

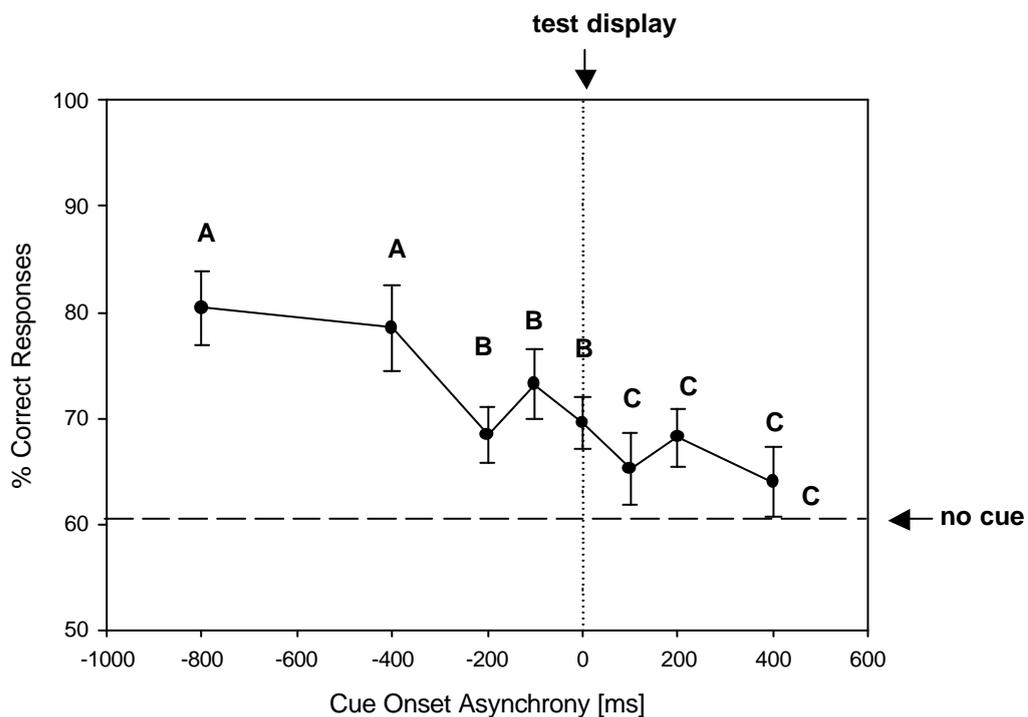


Figure 4.3 Mean accuracy as a function of Cue Onset Asynchrony in experiment 6. ISI between sample and test display was 2000 ms. The vertical dotted line marks the point in time when the test display was shown. The horizontal dashed line indicates memory performance without cue. Data points which are marked with the same letter are statistically not significant from each other. Different letters indicate statistical significance.

In summary, the cue can help to solve the task as long as it is not presented after the test display has appeared. The cue helps more when it is presented some time before the test display (400 ms or more) as when it is presented only shortly before or simultaneously with the test display (−200, −100, or +/- 0 ms).

Experiment 7

The following experiment takes up issues from experiment 5. In the conditions in which only a single test item is presented it was observed that it apparently did not matter, whether this test item was presented at its original location or in the centre of the screen. This has led to the conclusion, that retrieval does not exclusively rely on location information and even may not need location information at all. The comparison of what has been stored in memory and what is currently perceived may be object-based and only relate to properties of objects such as colour, form or texture, but not location. This would also mean that the proposed *change signal* relates to objects. It is elicited when feature information, that could be stored in an object file, of the objects stored in memory does not match the features of the currently perceived object. Therefore, memory performance was tested in a change detection task with a single item located either at its original location (*single test item – old location* condition), or at a location different from its old location, namely at the position of one of the other objects that had been shown (*single test item – changed location* condition) or at a completely new location (*single test item – new location* condition). A difference between a swap of old locations and new locations was made to take into account the possibility that new information could overwrite old information when it appears at previously occupied locations, and in contrast old information would be preserved when new information would appear at different locations. Memory retrieval was tested in three further conditions in which the full set of objects was presented. In one condition, which was labelled the *whole test array – old locations* condition, the items occurred at their old positions. In a further condition, which was labelled the *whole test array – changed locations* condition, the items swapped their locations. In a last condition (*whole test array – new locations*

condition) the items in the test display appeared at completely new locations. (Refer to figure 4.4 for examples of the different test displays.) In all six conditions subjects had to perform a change detection task

Method

Subjects 11 subjects (7 females, 4 males), aged between 22 and 34 years (mean age 27) participated in the experiment. All had normal or corrected-to-normal vision. All subjects were naive with respect to the purpose of the experiment. They were paid for their participation.

Stimuli Except as noted here, the stimuli were the same as in Experiment 1. The sample array consisted of 4 rectangles which all had the same size ($0.34^\circ \times 1.34^\circ$) but differed in colour (red, green, blue, yellow, purple, white) and orientation (horizontal, vertical, left and right oblique). There were two types of test displays, namely a *whole test array*, and a *single test item*. For details see below in the next section on the procedure.

Procedure Except as noted here, the procedure was the same as in Experiment 1. The display time of the sample array was 400 ms. The interval between the sample array and the test array 2000 ms. There were two types of blocks that differed with respect to retrieval conditions (see figure 4.4). In one block the three single test item conditions occurred randomly, in the second block the three whole test array conditions were randomly presented. More specifically the conditions were as follows:

Condition (1) Single test item – old location: The test display contained only one item. In the “same”-condition the test item was exactly the same as the item that had been presented at that location in the sample display. In the “different”-condition the test item differed from the respective item in the sample display either in colour or in orientation.

Condition (2) Single test item – changed location: The test display contained only one item. It occurred at a location that had previously been occupied by the objects of the sample display. In the “same”-condition the test item

was exactly the same as one of the items that had been presented in the sample display. In the “different”-condition the test item differed from the items in the sample display either in colour or in orientation.

Condition (3) Single test item – new location: The test display contained only one item. It occurred at a location that was empty in the sample display. In the “same”-condition the test item was exactly the same as one of the items that had been presented in the sample display. In the “different”-condition the test item differed from the items in the sample display either in colour or in orientation.

Condition (4) Whole test array – old locations: The same number of objects were shown as in the sample array. The objects occurred at the same locations. In the “same”-condition the test display was exactly the same as the sample display. In the “different”-condition the test display differed from the sample display only in one object that changed either in colour or in orientation.

Condition (5) Whole test array – changed locations: The same number of objects were shown as in the sample array. The objects occurred at locations that had been occupied before. However, all objects swapped their locations, so that every object occurred at a new position. In the “same”-condition the test display contained exactly the same objects as the sample display, but they appeared at changed locations. In the “different”-condition again all objects interchanged their locations, in addition one object changed either in colour or in orientation.

Condition (6) Whole test array – new locations: The same number of objects were shown as in the sample array. The objects occurred at completely new locations that had not been occupied before. In the “same”-condition the test display contained exactly the same objects as the sample display, but they appeared at new locations. In the “different”-condition again all objects changed to new locations, in addition one object changed either in colour or in orientation.

In the *single test item* conditions subjects were instructed to press the right mouse button if they have seen the test item anywhere in the sample display before. They were asked to press the left mouse button if the test item had not been shown before. In the *whole test array* conditions subjects were instructed to press the right mouse button, if all the objects that were initially presented were shown again at test irrespective of their location. They were asked to press the left mouse button if a new object occurred in the test display. Subjects were asked to respond as correctly and as quickly as possible. In case they were not sure about the correct response they were instructed to guess. In case of a false response subjects received a feedback tone. Session duration was approximately 1 hour.

Design The six test display conditions were performed in two separate blocks. One type of block contained the three single display conditions (1 – 3), the other type of block contained the three whole test array conditions (4 – 6). In each block trials in which all stimuli occurred at their old positions (1 or 4, respectively) and those in which stimuli either swapped locations or occurred at completely new positions (2 and 3 or 5 and 6, respectively) were presented equally often. Also

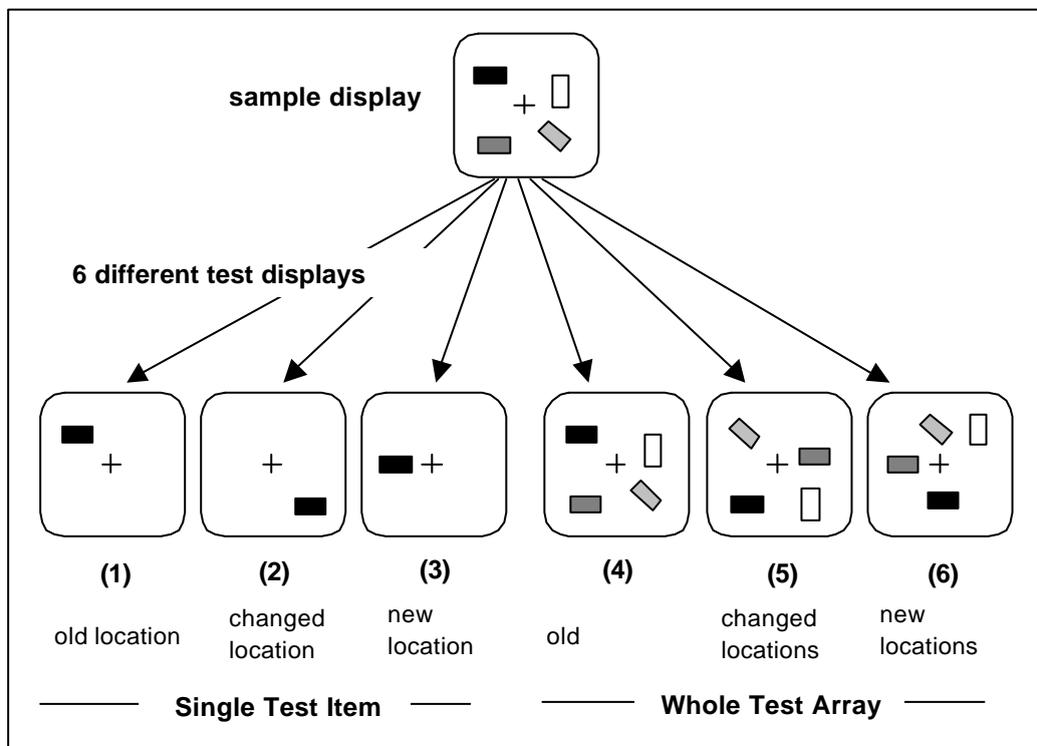


Figure 4.4 Examples of the six different test displays as have been used in experiment 7.

change and non-change trials occurred equally often. Each block consisted of 112 trials which were generated at random. The subject performed each of the two types of block three times with either the three single test item blocks first or whole test array blocks first. This order was balanced among subjects. There were 42 replications of the conditions 2, 3, 5, and 6, in which the stimuli either swapped locations or appeared at new locations. 84 replication of conditions 1 and 3 were run for each subject, in which objects occurred at their original locations. The experiment was performed in one session which lasted approximately 90 minutes.

Results

Results of performance (% correct) are shown in figure 4.5. Firstly, it can be seen that there is no difference in performance between the three *single test item* conditions (conditions 1 – 3). Furthermore, also performance in the *whole test array* condition in which objects occur at their original locations (condition 4) is the same as the *single test item* conditions. However, when locations are changed in the *whole test array* conditions (conditions 5 and 6), memory performance is severely degraded. These results are confirmed by statistical analysis: A one-way ANOVA for repeated measures shows a highly significant main effect of display type, $F(5, 45) = 16.8$; $p < 0.01$. Simple contrasts show no significant difference between condition 4 (*whole test array – old locations*) and the three single test item conditions (conditions 1 - 3, for all comparisons $p > 0.1$). However, simple contrasts show a highly significant difference between the *whole test array* condition in which the items occur at their old locations (condition 4) and the two conditions in which the items occur at other locations, (conditions 5 and 6, for both comparisons $p < 0.01$).

So firstly it can be observed that when only a single test item is presented performance does not depend on the location of this single item. It does not make a difference whether it is presented at its original location or at another position. With this first result the outcome of experiment 5 is confirmed in which also found no difference in performance was found when the location of the single test item was changed. It can be concluded that discrepant location information of a single test item does not disturb retrieval. Information in VSTM is not exclusively accessed by

location information. When only a single item has to be found in memory then object-based information is sufficient to solve the task. However, a second result is that retrieval is indeed disturbed when in a *whole test array* the items from the sample display are shown at different locations when memory is tested. Location changes of remembered objects degrade memory performance for object identity. With this second result the nature of the hypothesized *change signal* can further be specified: If in multi-element displays the objects occur at new locations several *change signals* are induced, so that an efficient comparison of information stored in VSTM and perceptual online information is not possible. This means that irrelevant changes of location cannot be ignored and it is important in the *whole test array* that the objects appear at their original locations. Only when unchanged objects occur at

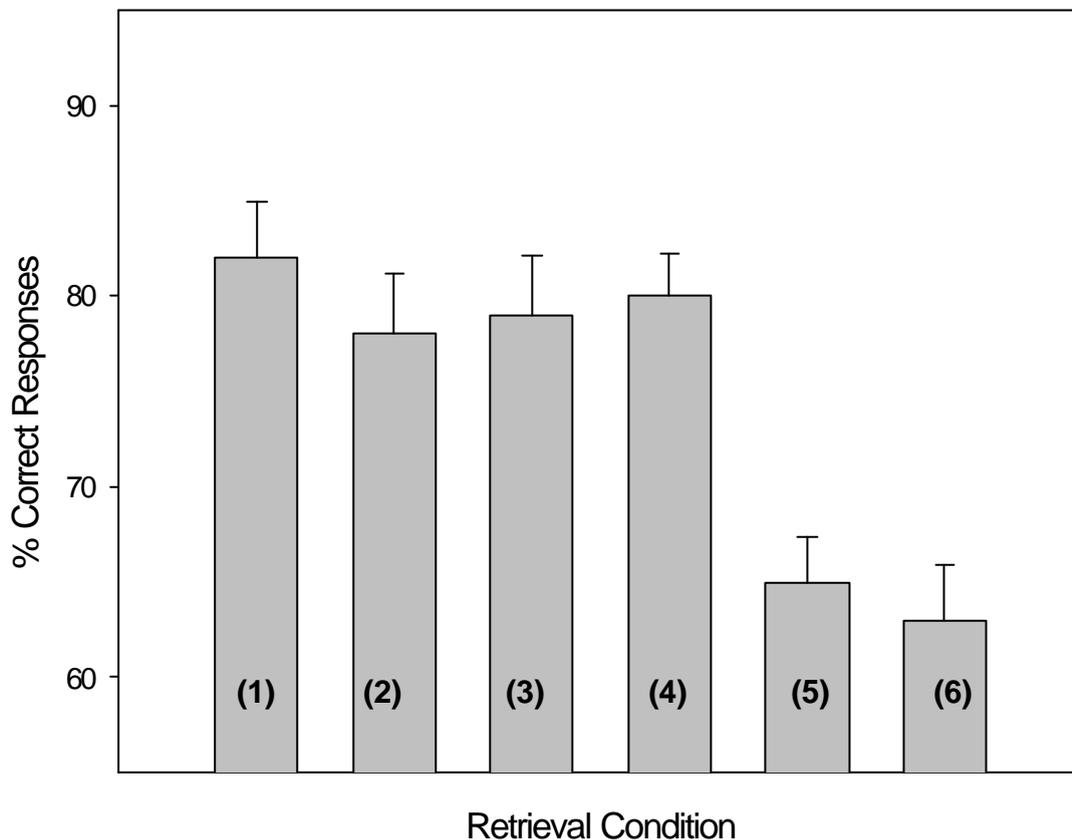


Figure 4.5 Mean accuracy according to the six different retrieval conditions in experiment 7: (1) Single test item – old location, (2) Single test item – changed location, (3) Single test item – new location, (4) Whole test array – old locations, (5) Whole test array – changed locations, (6) Whole test array – new locations.

their original locations an unambiguous change signal occurs for the changed objects.

Experiment 8a

The results of the three previous experiments have led to the assumption that a mismatch between information that is stored in VSTM and perceptual information can elicit a *change signal*. This signal is processed by the visual cognitive system and can be used to efficiently detect a change. There is evidence that in a *whole test array* location discrepancies disturb memory performance even if they are irrelevant for the task. The following experiment aimed at clarifying, whether other irrelevant feature changes like colour and form influence memory performance. Can the *change signal* be modulated by the task so that irrelevant feature changes can be ignored? In a change detection task with a whole test array 2, 4, or 6 rectangles were presented. In a first block the task was to find an item that changed in colour. At the same time changes in the orientation of the objects could occur. These changes were irrelevant for the task and had to be ignored. In a second block the relevant feature was orientation and the irrelevant feature was colour. So the task was to find an item that changed in orientation. However, changes in colour could occur. These were irrelevant for the task and had to be ignored. If the *change signal* is unspecific in that it can be elicited by any change independent of the task, then the irrelevant changes should disrupt performance. If however, irrelevant changes can be suppressed, so that the change signal relates only to relevant changes of colour or form, then performance should not be affected by irrelevant changes.

Method

Subjects 10 subjects participated in the experiment. All had normal or corrected-to-normal vision. All subjects were undergraduate students of Munich University and participated for course credit.

Stimuli Except as noted here, the stimuli were the same as in Experiment 1. The sample array consisted of 2, 4 or 6 rectangles which all had the same size ($0.34^\circ \times 1.34^\circ$) but differed in colour (red, green, blue, yellow, white, light blue) and orientation (horizontal, vertical, left and right oblique). The test display consisted of the same number of stimuli at the same locations as the sample array (cf. *whole test array* condition of Experiment 5).

Procedure Except as noted here, the procedure was the same as in Experiment 1. The display time of the sample array was 400 ms. The interval between the sample array and the test array was 2000 ms. Subjects had to perform a change detection task in which they had to find one item that changed in a specified feature. In one block the change was a change in colour, in a second block it was a change in orientation. In addition to a possible change of the relevant feature also irrelevant changes could occur in all objects. These changes had to be ignored by the subject and therefore served as distractors in the experiment. In the block in which the critical item could change in colour irrelevant changes in orientation could occur. In the block in which the critical item could change in orientation irrelevant changes in colour could occur. An irrelevant change always occurred in all distractors. The distractor items changed in 50% of the trials. Order of blocks was balanced among subjects.

Subjects were instructed to press the right mouse button, when they did not observe a change and the left mouse button, when they observed the change. They were asked to respond as correctly and as quickly as possible. In case they were not sure about the correct response they were instructed to guess. In case of a false response subjects received a feedback tone. Session duration was approximately 1 hour.

Design The relevant feature was either orientation or colour according to the block. “Same” and “different” cases occurred equally often and were randomly varied. The 3 set sizes and the 2 change/non-change conditions required 6 trials for complete replication. One block consisted of 120 trials which were generated at random. The two kinds of block were repeated three times each. I.e. for each subject there were 30 replications of each condition.

Results

Results are shown in figure 4.6. As could be expected a clear set size effect was observed. Performance gradually declines with increasing set size. Moreover and more interestingly, there is no clear effect of irrelevant changes. Performance is not greatly disrupted by a mismatch in a dimension that is irrelevant for the task. There is no difference according to which feature – colour or orientation – is the relevant or irrelevant dimension. These results are confirmed by statistical analysis: A three-way (critical feature \times distractor change/non change \times set size) ANOVA for repeated measures of performance data (% correct) shows a highly significant effect of set size $F(2, 18) = 135.71$; $p < 0.001$, but no effect of the critical feature $F(1, 9) = 0.94$; $p = 0.36$ and no effect whether distractors change or don't change $F(1, 9) = 3.98$; $p = 0.08$. None of the possible interactions were significant.

This experiment provides strong evidence for the fact that the *change signal* can be modulated by the task. However, the results could also be explained by assuming that already during encoding the irrelevant feature is filtered out. Possibly, only the relevant feature is stored in memory, irrelevant features may not be retained and as a consequence in retrieval no disturbing change signals would be generated. In the

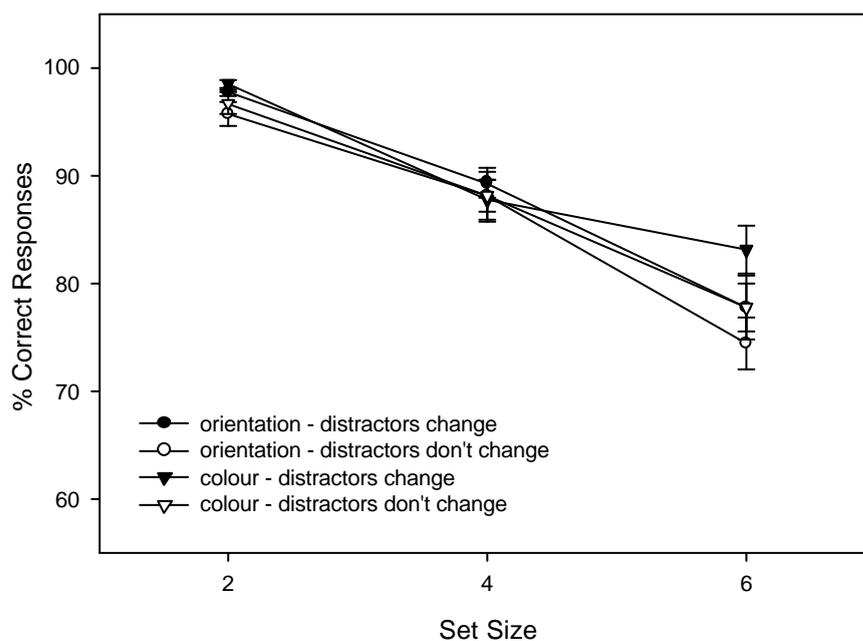


Figure 4.6 Mean accuracy in experiment 8a.

following experiment it was ensured that both dimensions are encoded into memory. The present experiment 8a was repeated, but this time the relevant dimension varied within a block. The information whether subjects had to respond to colour changes or to orientation changes was given during the retention interval by an acoustic signal of high vs. low frequency.

Experiment 8b

Method

Subjects 10 subjects participated in the experiment. All had normal or corrected-to-normal vision. All subjects were undergraduate students of Munich University and participated for course credit.

Stimuli The stimuli were the same as in the previous experiment.

Procedure The procedure was the same as in the previous experiment except for the following: Instead of dividing the relevant changes of colour and orientation into separate blocks they were randomly varied. In order to inform the subject which would be the feature that could change in the critical item a short acoustic cue, a tone of 100 ms duration was introduced that occurred within the retention time, 1000 ms before the test display. A high tone of 200 Hz informed the subject that the colour of the critical item could change. A low tone of 100 Hz informed the subject that the orientation of the critical item could change.

Design Orientation and colour changes of the critical item occurred equally often within the same block. These 2 conditions, the 3 set sizes and the 2 change/non-change conditions required 12 trials for complete replication. One block consisted of 120 trials which were generated at random. Each subject repeated the block 6 times, resulting in 30 replications of each condition for each subject.

Results

Results are shown in figure 4.7. As in the previous experiment there is a clear set size effect. Performance declines with increasing set size. More importantly, also in this experiment performance is not disrupted by the irrelevant changes in object colour nor orientation. This is confirmed by a three-way (critical feature \times distractor change/non change \times set size) ANOVA for repeated measures. It reveals a highly significant effect of set size, $F(2, 18) = 135.71$; $p < 0.001$, but no effect of the relevant feature, $F(1, 9) = 0.94$; $p = 0.36$, and no effect of an irrelevant change, $F(1, 9) = 3.98$; $p = 0.08$. None of the possible interactions were significant. These results show that the *change signal* can be modulated by the task. It can be tuned to certain relevant changes by ignoring others. So, in contrast to an inability to ignore irrelevant location changes it is evident that task irrelevant changes in object features like colour and orientation do not automatically lead to a *change signal*, but can be ignored, depending on the subject's task.

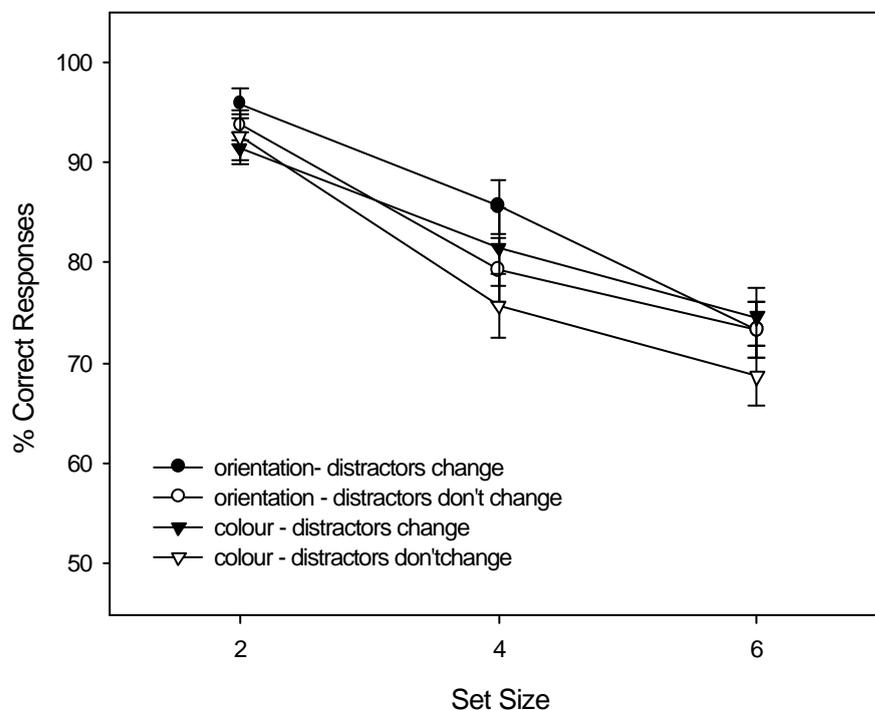


Figure 4.7 Mean accuracy in experiment 8b.

Discussion of Experiments 5 – 8b

The experiments of the present chapter were conducted in order to investigate mechanisms of VSTM retrieval. In order to solve the change detection tasks in the series of the present experiments subjects had to compare the memory representation of visual stimuli with perceptual information. How is this comparison process achieved?

The experiments show firstly, that memory performance does not differ when for memory testing only a single test item is presented compared with presenting the entire test array. With this result a serial item-by-item comparison process in retrieval can be excluded: For each comparison there is a certain probability to make an error. The possibility for a wrong response increases with the number of necessary decisions. So if the task is solved by a serial item-by-item comparison then observed performance should be better in the single test item condition, because only the critical item has to be compared as opposed to multiple necessary comparisons in the whole test array condition. The present results suggest that it does not matter whether the irrelevant, unchanged items are present or absent in the test array. A similar result has been obtained by Vogel, Woodman, and Luck (2001) in experiment 6 of their study on VSTM capacity. In a control experiment using coloured squares the irrelevant items in the test display were replaced by placeholders consisting of black outlined squares. The critical item occurred at its original location with either the same or changed colour. Performance was at the same level as it was when the entire test display was presented in a related experiment. Also Wheeler and Treisman (2002) varied the test display in different change detection experiments on binding in VSTM. They obtained essentially the same pattern of results independent of the test display condition: In one experiment the test display included the irrelevant objects and in a corresponding experiment the critical item was presented in the centre of the screen.

Our results show secondly that performance is profoundly disrupted when the task for memory testing is modified in the following way: In the test display the same number of objects were shown at the same locations as in the sample display. In half of the trials all objects changed in colour or in orientation except for one item, which

was the same as in the sample display. In the other half of the trials all objects changed. Subjects had to look for one item that was the same as the corresponding item in the stored memory representation among other items that all changed (see example (4) in figure 4.1). In this *detect match* condition performance dropped considerably. This result is not in agreement with the assumption that in the detect change and in the detect match condition the same kind of item-by-item comparison is carried out in order to find the target item, because an item-by-item procedure should not depend on the outcome of every single comparison. To find, that two items are the same should be accomplished just as well as to find, that two items are different. Therefore, it was not expected to find a difference in performance between the two tasks. However, the results show a dependence of memory performance from the result of the comparison. A considerable effect by this change of the retrieval condition was observed. To find a single changed object among a number of unchanged distractors is by far easier than to find a single item that matches an item in memory among multiple changed distractors. So this result is additional evidence against the assumption that in retrieval always a serial item-by-item comparison takes place.

These first two results can be explained by assuming that in a change detection task a local mismatch between object representations stored in VSTM and perceptual information is accompanied by a *change signal*. The processing of this *change signal*, which reliably indicates the target item, leads to efficient detection of the local change. Within the limits of VSTM capacity of approximately 4 objects (Bundesen, 1990; Irwin, 1992; Schneider, 1999) it does not make a difference whether irrelevant unchanged objects are present or absent in the display. However, if there are multiple changes the *changes signals* are of no value to find a single matching item. Memory performance is strongly disrupted in this task. The retrieval mechanism which draws on *the change signal* does not work here. The task has to be solved differently. It is suggested here that in order to solve the task an arbitrary item from the display is selected for a single comparison with the respective item that is stored in memory. It is further assumed that this comparison process requires visual attention which has to be disengaged from the current activity, which is holding the remaining memory items active in VSTM. As a consequence these items get lost

from VSTM. If the randomly selected item is the matching item, then the task can be solved successfully. If the comparison reveals a mismatch, further comparisons are necessary. Yet, they cannot be carried out, because the stored information about the sample items is now lost. Therefore, comparison is limited to only one pair of items. Visual attention has an essential role in this view. First of all, attention is assumed to be the mechanism, that is responsible for holding information active in VSTM. In chapter three of the present study the suggestion has already been discussed that visual attention is the rehearsal mechanism for VSTM – a suggestion that has also been put forward by other authors (Awh et al. 1999; Awh, Jonides, & Reuter-Lorenz, 1998; Wheeler & Treisman, 2002; Curtis & D’Esposito, 2003). Furthermore, it is suggested here that visual attention is needed for comparing a pair of elements from a VSTM representation and from a visual lay-out that is currently perceived. By withdrawing attention from rehearsal of the remaining objects in VSTM these objects are lost from the store. And finally, it is claimed that comparison is limited to only one pair of items. This view is in agreement with the claim of Wolfe, Klempe, and Dahlen (2000) that only one link between vision and memory is active at any given moment. And also in the theory of Schneider (1999) it is assumed that there is just one “online object” in VSTM that is directly activated by perceptual input at a time. The remaining three other objects in VSTM need support by the refreshment process for continued activity. Without this support they are lost from VSTM.

Further results of the present experiments demonstrate, thirdly, that providing a location cue greatly improves memory performance in the *detect match* task. This shows that the disrupting effect of multiple changes can be overcome by cueing the relevant item. The cue is most efficient when it is provided a sufficient time before the test array appears, i.e. approximately 400 ms. The level of performance in this condition is comparable to the level of a standard change detection task with four items, namely around 80% correct. The cue still helps when it is provided shortly before the test array or at the same time. The results show that the disrupting effect of the changed task in the *detect match* condition is indeed due to retrieval processes: A memory representation of the sample objects before the onset of test display is available just as it is available in a *detect change* task. This is shown by the high performance with a cue within the retention interval. When the cue is provided the

critical item can be selected from the memory set. When then the test display appears the critical item in memory can immediately be compared with the appropriate object that is present on the computer screen. The fact that the cue helps most, when it is presented some time before the test display may be attributed to the fact that processing the location cue and selecting the relevant item takes some time. Therefore, the task is accomplished more reliably when there is time enough to process the cue and select the relevant item. More than 200 ms seem to be necessary. A further interesting result is that the cue cannot be used once the test display has appeared. The memory representation of the sample items is presumably lost very quickly after the new information has arrived. The following explanation is suggested: As in one third of the trials no cue occurred subjects would not wait for the cue to appear in a postcue condition, but immediately try to solve the task. By the time the cue appears the memory representation is already lost, because visual attention was engaged in the comparison process to find a matching item. Therefore, the cue could not help: The representation of the item at the cue location was not available any more. In agreement with the present results a benefit of cueing during the retention interval was found in other recent studies with change detection and change blindness experiments (Becker, Pashler, & Anstis, 2000; Landmann, Spekreijse, & Lamme, 2003; Scott-Brown & Orbach, 1998; Scott-Brown, Baker, & Orbach, 2000). Landmann, Spekreijse, and Lamme (2003) also tested the effect of a postcue in a change detection task with 8 rectangular figures in a textured display. No advantage was found when the cue was presented after the retention interval. The authors assume that the initial representation was overwritten by the second display. However, in a recent study by Hollingworth (2003) in which a change detection task was applied, a postcue significantly improved performance. This result was taken as evidence for retrieval and comparison failure. But why was a postcue advantage found in this case and not in Landmann et al.'s study and in ours? An important difference between the studies lies in the stimulus material. Hollingworth (2003) used natural scenes and changes consisted of target rotations in depth or target replacements. Referring to his *visual memory theory* (Hollingworth & Henderson, 2002) Hollingworth claims that higher level visual representations of objects are consolidated into long-term memory (LTM), which are preserved even if object

representations are lost from VSTM. These LTM representations are accessed by a postcue in a change detection task and the information needed becomes available. Hollingworth (2003) mentions that these LTM representations may not be established in a similar way for abstract arrays of stimuli. This would mean that LTM cannot be used in the same way in the experiments of Landmann et al. (2003) and in the experiments of the present study as in the experiments of Hollingworth (2003) with concrete objects in natural scenes. Hence the difference between the studies.

Fourthly, the present investigations of retrieval processes from VSTM allows to describe more specifically the nature of the proposed *change signal*. The aim is to find out, whether the *change signal* is elicited by any mismatch that occurs between information stored in VSTM and currently perceived visual information or whether it can be tuned to task relevant object features. In one experiment task irrelevant changes of location are introduced. It was found that performance is largely disrupted by irrelevant location changes in a multi-element display. It is apparently not possible to relate the perceived objects to the respective VSTM representations with discrepant location information. The irrelevant location changes cannot be disregarded. They elicit multiple *change signals* although the relevant features did not change in distractor objects. A situation emerges that is similar to the *detect match* condition: In the presence of multiple changes a local change cannot be processed efficiently, the critical item is not selected easily. Instead, it has to be found by an item-by-item comparison. By engaging visual attention in the comparison process it can no longer be used to hold the remaining objects active in VSTM. As a consequence they are lost from VSTM. The task cannot be solved, unless the changed object is by chance selected for the first comparison. To conclude, irrelevant location changes cannot be ignored, but elicit change signals in a display with multiple abstract elements. However, it was also found that when only the critical item is presented it does not matter whether it is shown at its original location, at the centre of the screen, at a location that was occupied by a different object in the sample display or at a completely new location. Hence, irrelevant location changes of a single test item do not hurt performance. This finding is compatible with the view that the *change signal* is needed for selecting the critical

item from an array of multiple elements. If only the critical item is presented, no such selection is necessary and there is no need to process a *change signal*.

Finally, it was found that contrary to irrelevant location changes it is possible to ignore task irrelevant changes of visual features such as orientation and colour. When distractor items occur at their original locations, but change in the irrelevant feature, performance is not disrupted. It seems that these changes do not elicit a *change signal*. Hence, the *change signal* can be tuned to certain task-relevant features.

The experiments of the present chapter on retrieval clearly show that observed memory performance depends on conditions for retrieval. Limitations in comparison and loss of object representations in VSTM may be responsible for very poor performance when multiple mismatches occur between VSTM representations and currently perceived visual objects. Consequently, when conclusions about the nature of VSTM representations were drawn, such as the amount of information that can be stored, limiting factors that occur during retrieval have to be considered.

Limitations in retrieval and the phenomenon of change blindness

Knowledge of how retrieval of visual representations for further processing is accomplished can provide explanations for observations from related research areas on visual processing. The surprisingly poor ability to detect even large changes in visual scenes has led to various hypotheses about the nature of underlying visual representations. The phenomenon of *change blindness* (see chapter one) has mainly been explained by assuming that only little information about the world is represented in visual short-term memory (O'Regan, 1992; Rensink 2000a, 2000c). There is supposed to be no detailed and precise internal representation of the world, although it is experienced as such. However, this needs not necessarily be the case. Change blindness could occur despite a complete and rich representation. In recent studies it has been suggested that the effect of change blindness might at least in part be due to retrieval failures (Hollingworth, 2003; Scott-Brown & Orbach, 1998; Scott-Brown, Baker, & Orbach, 2000; Simons et al., 2002).

One explanation is that in retrieval it may not be possible to adequately compare the second scene with the memory representation of the initial picture. So, Hollingworth (2003) takes his finding of a postcue advantage in a change detection task in natural scenes as evidence for limitations in retrieval and comparison. He argues that with a cue subjects can limit retrieval and comparison to the target and as a consequence performance is much better. In a real-world change detection study Simons et al. (2002) could show that in the presence of change blindness subjects could after the actual test correctly report the change when specifically questioned about the particular changed object. This was taken as evidence that some representation of the pre-change scene was retained, but it could not successfully be retrieved and compared in order to solve the task. The authors state that people could miss changes if they fail to compare an existing representation of the pre-change scene to the post-change scene. The phenomenon of change blindness was also investigated by Scott-Brown and Orbach (1998) and Scott-Brown, Baker, and Orbach (2000) in experiments in which the two to-be compared stimuli, which were composed of 3 or 5 patches arranged in a circle, were simultaneously presented for contrast discrimination. The authors found an advantage in the task when the critical item was cued. They suggest that it is not necessarily the limitation in memory capacity, that leads to change blindness, but a limitation to make multiple comparisons.

A related explanation of change blindness is that retrieval of the memory representation of the initial scene fails, because it is overwritten by the post-change representation (Becker, Pashler, & Anstis, 2000; Landmann, Spekreijse, & Lamme, 2003). This hypothesis was supported by evidence from change detection tasks in which a cue was introduced. The fact that a cue, which was presented during the retention interval, improved change detection has lead the authors to conclude, that new information at a given location overwrites old information.

These explanations of the phenomenon of change blindness fit very well with the present view on mechanisms of VSTM retrieval. It is also claimed here that it is not possible to make multiple comparisons of the elements of two displays. Multiple comparisons are required under certain conditions. These are conditions in which a *change signal* does not unambiguously relate to a single local change, and therefore

cannot be used to solve a change detection task. This is the case in the presence of multiple changes. So, e.g., in change blindness experiments of multiple transients that are caused by brief visual disruptions such as an eye blink, a saccade, a movie cut, by “mud splashes” or else lead to multiple *change signals*. Instead of simply detecting a *change signal* in order to know that a change has occurred a more detailed comparison of two visual representations becomes necessary: the VSTM representation of the first picture and the perceptual representation of the current picture. The ability to compare two such pictures seems to be severely limited. Visual attention is needed for comparing a first pair of elements of the two representations. It is also needed for holding information active in VSTM from which it is now disengaged for the comparison process. Therefore, the remaining visual representations are presumably lost from VSTM memory. As a consequence no further comparisons are possible, because there is nothing to which the elements of the second picture could be compared.

It is easier to process presence than absence also in perceptual processing of visual information

In experiment 5 of the present study a striking asymmetry between two conditions in the memory task was found. In the first condition subjects had to respond to a change of one element in the display among other elements that did not change (*whole test array - detect change*). In the second condition subjects had to respond to the absence of change in one element in the display among other elements that all changed (*detect match*). Performance is considerably better in the first than in the second condition. This finding is reminiscent of asymmetries found in visual search (Treisman & Souther, 1985; Treisman & Gormican, 1988), in letter scanning (Neisser, 1963), or in texture segmentation (Beck, 1973, 1974; Julesz, 1981).

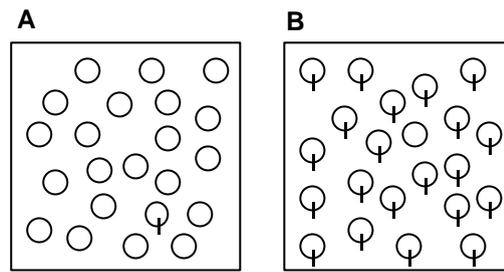


Figure 4.8 A: The target is defined by the presence of a feature, and B: The target is defined by the absence of a feature (Treisman & Souther, 1985).

Treisman and Souther (1985) found a difference between search for the presence and search for the absence of a feature. They carried out a visual search experiment in which subjects had to look for a circle with an added line among distractors that were simple circles without lines (see figure 4.8 A). The target was distinct from the other items by the presence of the feature of a line segment, while in the distractors this feature was absent. Search was efficient in this task, the target was found very quickly not regarding the number of distractors in the display. However, when in reverse subjects had to look for a simple circle among a number of circles with a line through it (see figure 4.8 B) the resulting search slope turned out to be much steeper and response time increased with the number of distractors. The results show that a target that is characterized by the presence of a feature among distractors which do not possess this feature is much easier found than a target that is defined by the absence of the feature among other items that possess the feature. This explanation is put in terms that are related to Treisman's more neuronal concept of feature maps (Treisman & Gelade, 1980): In the example above the crucial feature is the vertical line. When it is perceived subjects check a pooled response from the feature map for vertical lines for the presence of neural activity anywhere in the map. When the target object is a circle with a line then this is a unique feature that exists only in this single object in the search array. Therefore, it pops-out from the background and can quickly be detected. When in the other case the target object is a circle without a line through it then the feature map for vertical lines shows neural activity at all locations in which an object is present except for the relevant item. The absence of the feature cannot be found easily. There is nothing like a feature map for the absence of a line.

Consequently there is no distinct neural activity that can indicate the absence of a feature, and thus the target object in this case does not pop-out and cannot be found easily.

In a visual scanning task (Neisser, 1963) subjects had to search through a list of letter sets, which consisted of two or six letters. The task was to find a critical item, which properties varied according to the condition. In one such condition the critical item contained a target letter, such as the letter Z. In a different condition all the items except the critical one contained a Z. It took much longer to find a row that did not contain a target letter, when all other rows contained that letter, as when a target letter had to be found, when no other row contained that letter. So, this is a further example of an asymmetry between the presence and the absence of features. Neisser (1963) claims that the results show that the process of recognition is hierarchically organized. When subjects had to look for the presence of a target such as the letter Z all the stimuli have to be viewed just long enough to activate the lower-order recognition system when a Z is reached. However, when subjects look for an item that does not contain a Z, then the Z in every item must be identified. Full recognition for Z is needed on each item. (In his later work Neisser distinguished these cases as preattentive vs. attentive processing (Neisser, 1967)). Because of the greater depth of processing, it takes longer to look for the absence of a target than for the presence.

In experiments of texture segmentation similar asymmetries have been found. Texture segregation is usually studied using displays of discrete elements that contain a number of regions which differ according to their elements. Subjects in some tasks have to rate the difference between these regions, in order to identify them. In these experiments it has been found, for example, that complete triangles among incomplete triangles segregate better than incomplete triangles among complete ones. Also it is easier to find an area of long lines among short lines than the reverse (Beck, 1973, 1974). Julesz (1981) discovered that it helps to find an area of targets which lack a certain feature among background items that have it when they are spatially grouped. But the same was not true for the reverse: There was no additional beneficial effect when an area of targets containing a feature was spatially grouped on a background made up of elements that did not contain this feature. Both, Beck and Julesz, explained their findings in a similar way: Texture segregation

depends on the degree of differences in feature density of certain simple textural features, such as line orientation, colour or size (Beck, 1982). Julesz defined what he called *textons* on the basis of these findings. The visual system would be particularly sensitive to these textons and texture segregation takes place through the differential activation of these texton detectors (Julesz, 1981). Hence an explanation that is similar to the one given by Treisman (Treisman & Souther, 1985).

These examples of findings from visual search, letter scanning and texture segregation show an asymmetry between processing of the presence and the absence of features. Items that contain a certain feature are always processed more easily than items that do not have that feature. The explanations of this observation in the three areas do not differ from each other in principle. The critical feature activates the visual cognitive system in a unique way so that it can easily solve the task. When a feature is absent there is no neural response to this absence. This makes more costly processing necessary, e.g., serial as opposed to parallel search, preattentive as opposed to attentive processing, or effortless texture segregation as opposed to “conscious scrutiny” involving sequentially focusing attention on different parts of the display.

Taken together, research on perceptual processing yields results that show a strikingly similar pattern as has been discovered in the present experiments which investigates visual short-term memory.

The role of contextual information in VSTM

An important issue that should be discussed within the framework of the present study is the role of contextual information in VSTM. How relevant is contextual information in VSTM processing? Is it easier to decide that an object has been seen before, when at test the spatial configurational conditions are the same as the conditions when information was encoded? This issue has been investigated in a number of change detection experiments with coloured squares by Jiang, Olson, and Chun (2000). They claim that in VSTM the relational information between separate items is stored on the basis of global spatial configuration. So if an item is encoded into memory, also features of the adjacent items are stored in memory. If the

configuration cues that are formed by neighbouring items are absent or distorted then memory is impaired.

The question on the role of contextual information has also been raised in research on visual stability: It has been shown that transsaccadic localization of objects depends on relational information from before the saccade (Carlson-Radvansky, 1999; Deubel, 2004; Deubel, et al., 1998; Deubel, et al., 2002; Germeys, de Graef, Panis, van Eccelpoel, & Verfaillie, 2004). Distractor objects that surround a target object play a crucial role for the correct transsaccadic localization of that target object. Further studies show that the saccade target is coded in relation to other objects in the display (Carlson et al., 2001, Currie et al., 2000; Verfaillie & De Graef, 2000). This means that accurate information about the relative positions of a few objects in the visual field is stored in a transsaccadic memory and is used after a saccade. These results strongly suggest that also for VSTM retrieval contextual information may play an important role.

The systematic investigation of the role of contextual information in VSTM processing is not within the scope of this study. However, from the present experiments conclusions can be drawn, firstly, on the influence of irrelevant location changes and, secondly, about the effect of removing contextual information. The observations in experiment 6 of the current study show, that information of the spatial relation between objects are indeed represented in VSTM. This can be taken from the finding that irrelevant location changes in a whole test array, which contained four objects with changed locations, retrieval of information on object identity was greatly disrupted. This result can be explained with multiple change signals, that are elicited by multiple irrelevant location changes. The fact that an effect of irrelevant location changes was observed means that contextual information must have been represented in VSTM. In addition, the results show that preserving the spatial configuration in multi-element displays is important for VSTM processing. This finding is an agreement with the claim of Jiang, Olson and Chun (2000) that distorted configuration cues impair VSTM.

However, it could also be shown here, that spatial information is not automatically used in VSTM processing and it is possible to ignore it. This is the

case when spatial information is not needed to solve the task and when at the same time there are no irrelevant location changes of distractor objects. Results from experiment 6 support this view. Firstly, no difference was found in performance between a change detection task with the whole test array condition compared with the single test item condition. In the whole test array condition relational information between objects are provided, but not in the single test item condition. Despite the missing relational information, performance is not worse in the single test item condition. This is the case, because location information is not needed in the task. It is possible to decide whether an object has been seen before irrespective of where it is presented. In line with this result is the second observation that the location of the single test item does not influence performance. So even when the test item is presented at a location different from its original location, memory performance is not affected. Also in this case, it is clear that the only item in the display is indeed the critical item. It cannot be confused with a different item. So, as the information about location is not relevant, it can be disregarded.

These results are not in accord with the strong claim of Jiang, Olson, and Chun (2000) that absent relational information disrupts VSTM processing. However, evidence is provided in which removing the context does not hurt performance. In experiment 1 of the study of Jiang, Olson, and Chun (2000) performance in a whole test array condition was compared with a single test item condition. The stimuli consisted of coloured squares. On change trials the critical item in the test display changed its colour, which had to be detected by the subjects. The results show, that performance in the single test item condition is significantly worse than in the whole test array condition. Apparently, a result that is not in accord with the present result. How can the difference be explained? The spatial organization of the memory display in the present experiments was very simple. There were 8 possible locations in a 3 x 3 matrix around a central fixation (see figure 1.5). Location could be identified unambiguously, the relational position of the objects could be easily retained in memory. In contrast, in the study of Jiang, Olson, and Chun (2000) the structure of the test display was far more complex. It consisted of a 10 x 10 matrix, i.e. with 100 possible locations, and in addition the position of each square inside a cell was slightly jittered (see figure 4.9). As a consequence the spatial relation of one

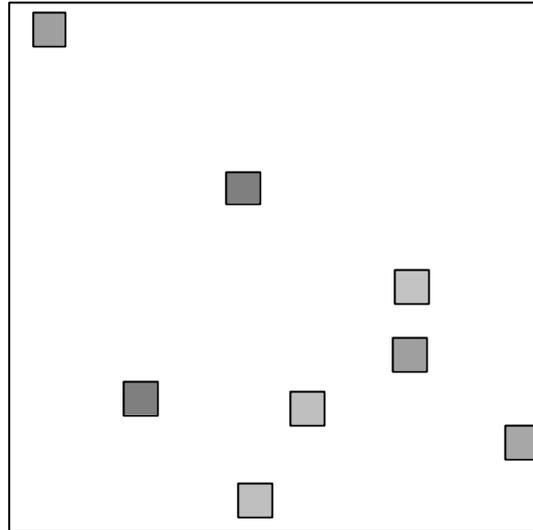


Figure 4.9 Example of a test display as has been used by Jiang, Olson, and Chun (2000). It forms a 10 x 10 matrix, the position of each square inside a cell is slightly jittered.

object to the neighbouring objects are needed to be able to relate the test item to the corresponding item in the sample display. So the strong claim of Jiang, Olson, and Chun (2000) that the representation of a given colour is not independent of the colour of other items in the display should be modified: It is true in displays in which the relational information is necessary to be able to relate an item to the corresponding item in memory. If the correspondence can be determined otherwise, such as in the present experiments with a small number of fixed positions, then the representation for a given colour can be independent of the colour of other items. This means that the reason why in the study of Jiang, Olson, and Chun (2000) the memory task with the single test display turned out to be more difficult than with a whole test array actually cannot merely be attributed to VSTM processing as such, but more rather to the problem of correctly localizing the critical item.

To summarize, it is apparent that contextual information has an important role in VSTM retrieval. When objects change their locations in a multi-element display, memory performance is largely disrupted, even when the memory task concerned only object identity and not location information. Yet, if only one item is presented

for memory testing and location information is not requested in the task, then it is unimportant where the object is presented.

IT cortex and automatic short-term memory processing of non-matching stimuli

There is evidence from neurophysiological research for a short-term memory mechanism that automatically biases visual processing towards test stimuli that do not match a sample item. It has been suggested that certain effects that have been observed in inferior temporal cortex (IT) reflect an automatic storage and retrieval process sensitive to stimulus repetition (Desimone et al., 1995). This evidence fits very well with the hypothesis of a change signal and shall be reported here.

IT cortex is a region in the brain that is critical for visual memory, such that without IT cortex memory of a visual stimulus is impaired. In an influential neurophysiological study the role of IT neurons in working memory was explored by recording the activity of IT cells of two rhesus monkeys while they were performing a delayed matching-to-sample task (Miller, Li, & Desimone, 1991, 1993). In the task first a sample stimulus was presented. Then the monkey viewed a sequence test stimuli (complex, multicoloured pictures) and was rewarded for responding to a matching test stimulus (see figure 4.10). All stimuli were already familiar to the animal and the same stimuli that appeared as sample and matching stimuli on one trial appeared as non-matching stimuli on others. Responses of half the cells did not

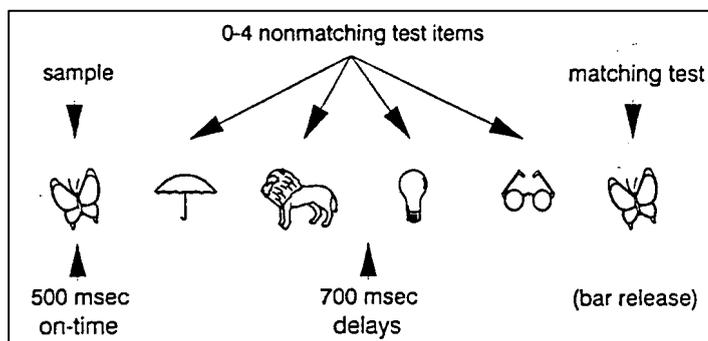


Figure 4.10 Outline of the delayed matching to sample task (from Miller, Li, and Desimone, 1993)

vary significantly depending on whether the stimuli were matching or not. This was interpreted as coding only sensory information. The other half of the recorded IT neurons, however, showed responses to test stimuli that were a joint function of the sensory features of that stimulus and stored memory traces. The majority of those cells showed suppressed responses to matching stimuli compared to non-matching stimuli (see figure 4.11). The comparison of sample and test stimulus appears to be very fast: The suppressive effects begin very shortly after stimulus presentation in IT cortex which is almost at the onset of the visual response, which starts 80 ms after stimulus onset. The mechanism that causes the suppression is therefore seen as a property of IT cortex and cannot be attributed to on-line feedback to IT from other structures.

The observed behaviour of IT cells may be reflected in the results of the present experiments which show very efficient processing of a mismatch between an item that is represented in VSTM and a corresponding item that is currently perceived. The suppressive effect may also occur in the current experimental paradigm when those items that match the corresponding items in VSTM are perceived in the test

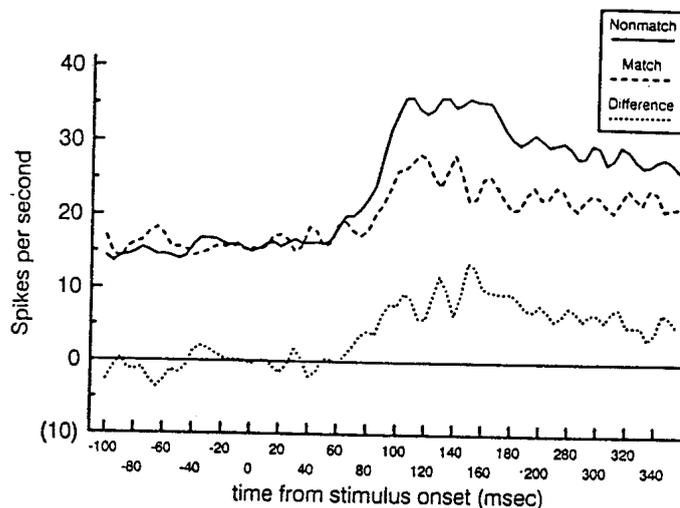


Figure 4.11 Spike density histograms for matching and non-matching stimuli. The „difference line“ plots the difference between the two histograms (from Miller, Li, & Desimone, 1993).

display. As a result the non-matching item is processed very rapidly after presentation of the test display. Hence, the proposed change signal may have its physiological basis in IT cortex.

Chapter 5

SUMMARY AND PROSPECTS

In the previous chapters 2 – 4, three series of experiments were presented, each dealing with a particular aspect of human visual working memory. Their common goal was to characterize the part of visual working memory that is responsible for temporary storage of visual information, namely visual short-term memory (VSTM). More specifically, the property of VSTM to be limited in several respects was addressed. In the following a short summary of each chapter will be given. The basic findings and their implications are briefly reviewed. Resulting questions and issues for further research are presented.

Limitations in VSTM: Retention

In chapter 2 of the present dissertation the empirical goal was to delineate the time-course of VSTM maintenance and describe the temporal limitations of VSTM. A novel kind of visual stimuli was used. It consisted of separable geometrical objects with well defined perceptual attributes, namely rectangles of different size, orientation and colour. The decisive advantage over stimulus material used earlier (e.g. black-and-white matrix patterns in Phillips, 1974) is, that with the new stimulus material it is possible to measure memory decay in terms of the effective memory capacity. As the new kind of stimulus material has been used in all experiments of

the present dissertation, it was important to assess its decay to ensure that it is compatible with observations in earlier studies with visual stimuli of a different type.

In two experiments with a change detection task the time course of information maintenance in VSTM was examined. A sequence of two stimulus displays which were separated by a blank interstimulus interval (ISI) of variable duration was shown to the participants. Memory performance was tested at the varying ISIs as a function of set size. It was expected that at very short ISIs up to ~300 ms a reflection of the visual analog representation, which is a subcomponent of iconic memory (Di Lollo & Dixon, 1988), could be observed. The visual analog representation is of unlimited capacity and has a duration of approx. 300 ms (Irwin & Yeomans, 1986). As a consequence, a very high performance level of more than 90% accuracy for all set sizes was expected for the very short ISIs. After the decay of the visual analog representation, retention has to rely on the capacity-limited VSTM only. Consequently set size dependent storage on a much lower level was expected for the longer ISIs. On the basis of earlier studies (Kikuchi, 1987; Parr, 1992; Pashler, 1988; Phillips, 1974) performance was expected to remain stable with increasing retention intervals up to the longest tested ISI, which was 8000 ms.

Contrary to these expectations, except for an ISI of zero which served as a control, no set size independent, very high level of performance was observed, not even at the shortest ISI of 14 ms. Instead, VSTM maintenance over time turned out to be relatively stable and set size dependent. However, this result is not entirely incongruous with previous research, because the results reported in the literature do not show a fully coherent picture. Phillips (1974), e.g., reports very high, and set size independent performance at an ISI of 20 ms. On the other hand, the studies of Pashler (1988), Becker, Pashler, and Anstis (2000), and Germeys, de Graef, Panis, van Eccelpoel, and Verfaillie (2004) all observed very early decline of performance (< 85 ms) in change detection tasks. It can be taken from these studies and from the present work, that sensory storage in form of visual analog representations could not be used for the task. Two possible explanations were provided in chapter 2 of the present work. Firstly, multiple transients, that are elicited by the onsets of the objects in the second display and that are distributed across the entire visual field, may mask transients that are produced by the local change of the critical object. These

transients could potentially be used to locate the critical object. By specific experimental manipulations in the experiments reported in chapter 2 this explanation could be excluded: Visual analog representations were not disrupted exclusively by the transients that are caused by the onset of irrelevant objects in the second display. An alternative explanation is, that the visual analog representation of the sample stimuli is overwritten by the new visual information contained in the second display. This hypothesis can be tested by applying a cueing technique in presenting a location cue at different times within the retention interval. This approach was pursued in the recent studies by Germeys, de Graef, Panis, van Eccelpoel, and Verfaillie (2004), and by Wesenick (2000), which both showed improved memory performance in the cueing conditions. Because the relevant information can be accessed with the help of the cue, it can be inferred that a visual analog representation does indeed exist, which starts to decay following stimulus offset. The results are in accordance with the hypothesis that new incoming visual information overwrites the current contents of VSTM, which as a consequence is removed from the store. However, there is need for further clarification of the relationship between visual analog representations and VSTM. Furthermore, it is necessary to support the overwriting hypothesis by additional empirical evidence. It remains an open question what factors decide which information is overwritten. So, is always the entire display overwritten by incoming information or is selective overwriting possible? How is the information flow into and out from VSTM controlled? What is the role of the current task set? Both, empirical evidence and theoretical concepts are needed for further specifying these aspects of VSTM processing.

The observation, that after intervals of 4 seconds or longer there is no further significant loss of information is in line with earlier studies (Kikuchi, 1987; Parr, 1992; Pashler, 1988; Phillips, 1974). Memory performance for all set sizes remains at a constant level. From the performance levels according to the different set sizes it could be estimated that the capacity of VSTM is somewhat below 4 objects. It is assumed that the information that is contained in VSTM can be retained for intervals that exceed 15 seconds or more, given the subjects are completely occupied in the retention task. It is generally accepted, that there are active mechanisms that prevent the loss of information from VSTM, which could occur by passive decay or

interference. Such a mechanism has been proposed already in the work by Atkinson and Shiffrin (1968) and also by Baddeley (e.g. Baddeley, 1986), who proposes that within working-memory the visual scratch pad serves as rehearsal system for visuo-spatial information. In the more recent theory of Schneider (1999), a *refreshment process* is responsible for preventing that objects are forgotten. In this theory the objects stored in VSTM have an activation level that is higher than the activation level of objects outside VSTM that compete for entrance in the store. By refreshment the stored objects are kept at the level of activation, that is necessary to remain in the store. Refreshment is postulated to be selective for specific object attributes. Extra activation to a particular dimension, such as location, will increase the activation level only of the location attribute of the concerning object, but not the activation of other attributes.

How can rehearsal or refreshment be described on a functional level? What could be the underlying mechanism? Is it possible to describe the mechanism on a neuroanatomic level, to identify the responsible brain areas and establish a neural network? In recent studies it has been suggested that it is an attentional mechanism that is responsible for holding information active in short-term memory. More specifically, it has been proposed that focal shifts of spatial selective attention mediate the maintenance of location-specific representations (Awh et al. 1999; Awh & Jonides, 2001; Awh, Jonides, & Reuter-Lorenz, 1998). Starting out from the well established effect of spatial selective attention to improve visual processing at attended locations (e.g. Posner, 1980), the authors developed the hypothesis that a similar effect should be observed in working memory: If spatial selective attention is directed towards a location stored in working memory, then improved processing should be observed at that location. This effect has indeed been observed in behavioural experiments (Awh, Jonides, & Reuter-Lorenz, 1998). Also, the underlying neural mechanism has been specified by the same research group. In addition to an anatomical overlap they observed also a functional overlap in the mechanisms of spatial working memory and spatial selective attention (Awh et al., 1995; Awh & Jonides, 1998). Both processes are driven by a right-hemisphere dominant network of frontal and parietal brain areas. Data suggest that spatial

rehearsal recruits top-down processes that modulate early sensory processing in the visual areas that represent the memorized locations (Awh & Jonides, 2001).

The assumption of a strong overlap between mechanisms of visual attention and visual working memory, as suggested by Awh and colleagues, is extremely appealing. In the context of the present study the role of visual attention in VSTM has not only been identified for holding information active in VSTM. It has also been suggested that it is crucially involved in the process of retrieval (see chapter 4). The issue of the role of visual attention in VSTM processing will be taken up again later in this section. Yet, already at this point it has become evident that it is surely a challenging task for future research to provide more empirical evidence on the issue and further develop the idea of a strong connection between the processes of visual attention and visual working memory.

Limitations in VSTM: Capacity and how it is related to the format of VSTM

The issue of chapter 3 of the present dissertations was the relation between the storage format of VSTM and the limit of VSTM capacity. This relation is important in order to determine how much information can be maintained in VSTM. Only if the format of the stored visual representations is specified, is it possible to determine the capacity. The more specific question here was, whether visual information is stored in terms of the number of whole objects, or of the object's features. An important claim on this matter has been made by Luck and Vogel (1997) on the basis of their experimental results (see also chapter 1). In their view, the unit of VSTM is the integrated object. Only the number of objects determines the capacity of the visual short-term store and not the number of features. According to Luck and Vogel (1997) this should be true even when objects consist of feature combinations of the same dimension. Importantly it follows, that binding the different features in one object has no memory costs whatsoever. The experiments of the present dissertation provide further evidence on this issue and lead to a view that is not fully consistent

with neither, the empirical data nor the conclusions, described in the study by Luck and Vogel (1997).

The present experiments 3a and 3b provide evidence that basically the capacity of VSTM is indeed related to the number of stored objects and not to the number of stored features. However, the data also show that memory performance is significantly lower when a conjunction of features has to be retained in one object compared to only one feature. Yet the costs for binding an additional feature in a stored object are not as high as they would be if an additional object had to be retained. An exception is the case of binding features of the same dimension in one object, such as two colours. In experiment 4 of the present study, retention of objects that are composed of two colours is considerably worse than retention of the same number of objects that have only one colour. In fact, memory performance for two compound objects is about the same as for four simple objects. This means that the costs for an additional feature from the same dimension are comparable to costs for a new object. This is clearly not in accordance with the results of Luck and Vogel (1997). An attempt from a different laboratory to replicate this part of the study by Luck and Vogel (1997) also failed (Wheeler & Treisman, 2002), thereby confirming the present data, which have been reported earlier (Schneider, Deubel, & Wesenick, 2001). In brief, from the present data it can be concluded that,

- ✓ the capacity of VSTM is basically determined by the number of objects that have to be retained;
- ✓ binding a number of features in one object has some costs, even though the costs for binding are not as large as the costs for storing a whole new object;
- ✓ if features of the same dimension are combined in the same object, binding costs are considerably larger. They are compatible with the costs for storing an additional object;
- ✓ memory for different features apparently is not exactly the same, but varies according to the dimension.

These results have important implications for a conception of VSTM storage and have to be taken into account by any theory of VSTM. Some theoretical suggestions have been outlined in chapter 3 (Wheeler & Treisman, 2002; Schneider, 1999).

Further empirical questions are created on the issue of the binding mechanism in VSTM, which are subject to prospective studies. Empirical questions are whether the observed results are true for other kinds of visual features. Are binding costs comparable for combinations of other visual features? There may be larger storage costs for feature combinations other than the tested combinations of colour, orientation or length. This could for example be the case for a combination of the features of motion and orientation as opposed to the tested conjunction of colour and orientation. Or on the contrary, there could be features that make the retention of objects much easier, which could be the case for the feature of location in a 3-dimensional space in combination with surface features. Is there a storage limitation according to the number of features that can be integrated in one object? Is retention dependent on the combinations of particular features, so that some feature combinations are retained more easily than others?

A further aspect that is pertinent for the understanding of VSTM processing is the effect of the current task on bound objects in VSTM. Binding is normally conceived as a process which takes place on a neural level and which can be described in neurophysiological terms. Binding theories typically propose the neural mechanism, such as synchronized neural firing, that provides the information on which features belong to the same visual object (e.g. Milner, 1974; von der Malsburg, 1981; Singer, 1989; Singer et al., 1997). It is not clear, whether and how this low-level process can be modified by higher level processing and top-down control. It is possible, that higher-level mechanisms operate on bound objects in such a way, that specific features selectively receive enhanced processing resources and other features do not, such that processing single features of bound objects may be selectively modulated by a given task. One such higher level mechanism, that has an influence on lower-level processes in VSTM, could be an attentional mechanism. As has been reported above, feature integration theory (FIT) of Treisman and colleagues (e.g. Treisman & Gelade, 1980; Treisman, 1988, 1998, 1999) proposes that attention is crucial for binding object features in visual perception. It certainly will be fruitful to determine

the relationship between binding in visual perception and binding in VSTM. It may turn out, that there is in fact the same underlying mechanism of attention.

Limitations in VSTM: Retrieval

The experiments of the present chapter 4 address the aspect of retrieval of information from VSTM, that up till now has received only little attention in VSTM research. To empirically investigate the retrieval mechanism the same change detection task was used as in the experiments of the previous chapters of the present work. Aiming at retrieval, the structure of the test display was varied. It turned out that performance in the task was the same, no matter whether the entire display of objects was presented at test (*whole test display*) or just the critical item (*single item test*), which was the item that would change in change-trials. This result is surprising, if one expects that in order to solve the task it is necessary to serially compare each object that is stored in VSTM with each object that is currently perceived. In case of the *single item test* the location of a potential change is already known; if there is a change, then it will be in the presented item. In contrast, this information is not available in the *whole test display*. The change can occur at any of the occupied locations. How can it be explained that the task with a *whole test array* can be solved equally well than the task with a *single item test*? It has been proposed here, that the cognitive system makes use of a *change signal* in order to solve the task. This *change signal* is elicited by a mismatch between the information stored in VSTM and corresponding information that is currently perceived. It can be used to very efficiently locate the mismatch and so in the *whole test array* condition a mismatch can easily be located, although other – unchanged – irrelevant distractor objects are present on the screen. The suggestion of the *change signal* is central to the view on VSTM retrieval proposed here. The subsequent experiments all aimed at elaborating this hypothesis and providing evidence for further specification of the notion of the *change signal*.

In a further condition, supportive evidence for the hypothesised *change signal* was obtained. In a *detect match* task performance was considerably lower than in the *detect change* task and appeared to be just above chance level. By assuming a *change signal*, the results can be explained in the following way: In the *detect match* condition the changing distractor objects all elicit change signals, but obviously the critical unchanged object does not. In this situation the change signal is not useful to solve the task, because there are multiple signals that all relate to locations of irrelevant changes and no signal that leads to the relevant location. So, instead of using the efficient change signal, the task had to be solved in a different way. It is suggested that now one item from VSTM is compared with the respective item that is currently perceived. It is further assumed that for this comparison process visual attention is needed. As a consequence the limited attentional resources are withdrawn from the currently active process, which is to maintain the stored objects in VSTM. So now the remaining stored objects are lost from VSTM and no other comparisons can be carried out. Hence, the very low performance in this task.

In a *detect match* task the change signal cannot be used to locate the critical item as it is possible in a *detect change* task. It could be shown in experiment 6 that a location cue that indicates the critical object has the effect of making the task much more easier. The point in time when the cue was presented was varied and it turned out that the cue helps in a detect match task as long as it is presented at the same time with the test display and not after. It helps most when it is presented some time before the test display. So here the cue could be used in the same way as the change signal can be used in the detect match task. Both mark the location of the critical item so that the task can be solved very reliably.

Performance in further experimental conditions show, that when only a single item is presented, it does not matter at which location it occurs. The task can be solved at a high level of performance. Obviously there are no disturbing change signals of irrelevant distractors. However, when the entire display with multiple objects is presented, then location changes of the objects are critical. Apparently, irrelevant location changes elicit change signals and it does not matter, whether the objects change to completely new locations or whether they exchange their locations. In any case, location changes of irrelevant objects lead to low performance.

Experiments 8a and 8b were designed to test, whether the occurrence of the change signal can be modulated by the task. Changes in colour or orientation, that were irrelevant for the task were introduced. The results show that if changes in a whole test array occur in the irrelevant dimension of colour or orientation performance is not affected. This means that in this case no multiple change signals occurred. It has to be concluded that the change signal can be modulated by the task and is not entirely automatic.

In brief, from the empirical data the following conclusions are drawn:

- ✓ a change signal is elicited by a mismatch between information stored in VSTM and respective information which is currently perceived;
- ✓ the change signal can be used to efficiently locate a changed object, if irrelevant distractor objects do not change their locations;
- ✓ in particular change signals occur when relevant or irrelevant objects change location;
- ✓ irrelevant changes in orientation or colour do not elicit a change signal;
- ✓ if a change cannot be detected by using the change signal, it is proposed that an error-prone serial process is initiated that compares an item from memory with the respective item that is currently perceived;
- ✓ this comparison process requires visual attention, which is then withdrawn from keeping the other objects active in VSTM. As a consequence they are lost from VSTM and not more than only one comparison is possible.

There are major issues for subsequent research. One is, for example, to scrutinize the involvement of visual attention in the comparison process. Another issue is to clarify the nature of the proposed change signal and whether it is indeed such a fast and efficient process as has been proposed here. To approach this topic, the method of electrophysiology can be employed. On the one hand it provides information on the temporal course of the potential change signal, and on the other hand pattern of results may be obtained that can be related to previous research on attention. It seems reasonable in this context to analyse the N2pc component of the event-related potential (ERP) waveform, which has been analysed in studies on attention (Eimer,

1996; Heinze et al., 1990; Luck & Hillyard, 1994a, 1994b; Luck et al., 1997b; Woodman & Luck, 1999). The N2pc is typically observed in visual search tasks contralateral to the visual field in which an object is attended within the search array. Previous studies have concluded that the N2pc reflects covert orienting of visual attention before the completion of object recognition and that it reflects a process of attentional selection when a target object has to be filtered out from surrounding distractor objects (Luck & Hillyard, 1994a; b, Luck et al., 1997b). The N2pc occurs at a latency of 200 – 300 ms poststimulus. It consists of an increase in negative voltage at posterior scalp sites, mainly over the occipital cortex. The N2pc has a highly contralateral scalp distribution, which means that within a bilateral stimulus array the N2pc is more negative at left electrode sites for target objects occurring in the right visual field and more negative at right electrode sites for targets occurring in the left visual field. It is hence labelled the *N2pc*, which denotes *negative voltage, 200 ms poststimulus, at posterior contralateral electrodes* (Heinze et al., 1990; Luck et al., 1997b; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999).

The conditions in visual search resemble the present change detection task in a specific way. In visual search tasks the target is defined perceptually. So it may carry certain physical features, for example “the small green vertical rectangle”. The target can also be defined by a relation to other objects present in the search array, being the one deviant item that is different from the rest, as it is the case in inhomogeneous search arrays with pop-out stimuli. This description is also purely perceptual. In a change detection paradigm a search takes place in the test display. In this case the target is not perceptually defined, but by a relation to corresponding VSTM contents: The target object is that object in the test display, which does not match the respective object in VSTM. So in this case, not the physical feature characterizes the target, but the fact that it is not currently contained in VSTM. Because of this parallel it seems reasonable to analyse the data with respect to a potentially existing N2pc which could be related to the postulated *change signal*. So if a process of attentional selection is involved for finding a mismatch between an object in VSTM and a currently perceived object, the N2pc component is very likely to be observed. This was indeed the case in a pilot study which investigated the change signal by using the N2pc component of the ERP waveform (Wesenick, Deubel, & Reimann, 2003). In

the experiment the present change detection paradigm was used with a sample display that contained two items left and right from fixation. The N2pc component was observed on change-trials, time-locked to the onset of the test display. It occurred approximately 200 ms after orientation changes and 300 ms after colour changes (see figure 5.1). This result is nicely in accord with the assumption that an attentional mechanism is involved in detecting a mismatch between objects that are represented in VSTM and corresponding objects that are currently perceived: Local differences between memorized items and perceptual information are processed by using the mechanism of visual attention. In addition, the change detection process is very fast as it shows a reflection in the ERP as early as 200 ms after stimulus presentation.

The analysis of eye-movements in change detection may also help to clarify whether a mechanism of visual attention is involved in change detection. It makes use of the fact, that the attentional system is closely connected to the mechanism that controls eye movements (Deubel & Schneider, 1996). Saccades are often caused by items or events that attract attention. They are not as much in our control as manual reactions and are executed much faster. So, as a first step, to learn more about the time that is needed to detect a change, eye-movements were recorded in a change

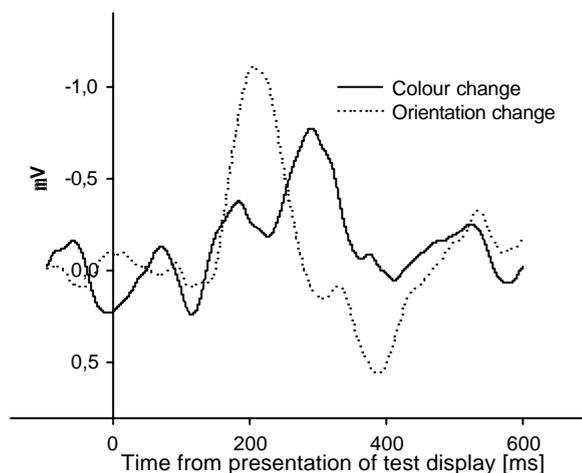


Figure 5.1 The N2pc component observed after the presentation of a test item that differed from the sample in colour or in orientation (Wesenick, Deubel, & Reimann, 2003).

detection paradigm as has been used in the reported experiments of the present dissertation (Wesenick, Schneider, Deubel, 2003). The empirical goal was to find out at which saccade latency subjects could respond to a changed item by directing an eye-movement to the target item. With a set size of four objects it was found that ~80% change trials were correctly indicated by the subjects. More importantly, on these trials saccades were directed with high reliability to the critical item at a latency of approx. 330 ms after the orientation of a presented item changed with respect to the orientation of the corresponding item stored in VSTM. Correct saccades had a latency of approx. 450 ms after the presentation of an item with a changed colour (see figure 5.2).

The observed latencies in the eye-movement analysis fit with the time course of the observed ERP-component, where the N2pc after an orientation mismatch occurs about 100 ms earlier than the N2pc after a mismatch in colour. In addition there is a difference between the electrophysiological latency and the saccade latency of about 150 ms. It is known that the very fast saccades have a duration of at least 120 ms (Fischer, 1986). So, the most part if not all of the difference in latency of 150 ms may be attributed to the programming and execution of the saccade in the eye-

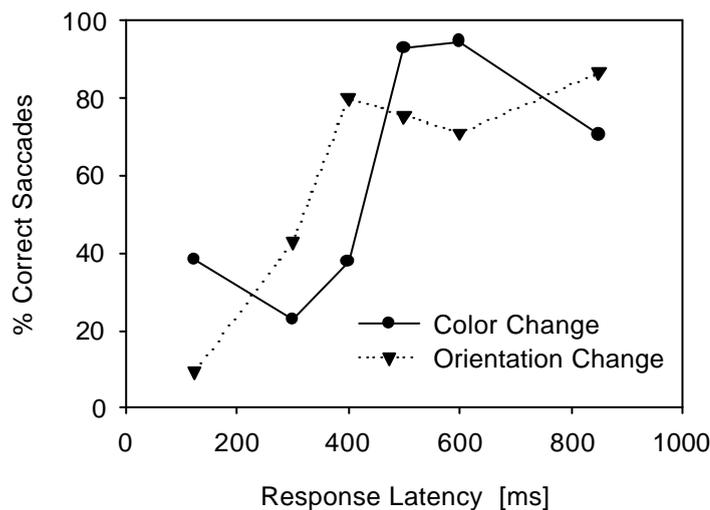


Figure 5.2 Mean accuracy of saccades as a function of eye movement latency to an item that does not match the sample, either in colour or in orientation (Wesenick, Deubel, & Schneider, 2003).

movement experiment (Becker & Jürgens, 1979). This result means that the two experiments are at least qualitatively in accord with each other in pointing at roughly the same processing durations of the mismatch.

In conclusion, the methods of electrophysiology and the analysis of eye-movements have shown to be useful for a more detailed understanding of the VSTM process of retrieval. There is preliminary evidence, that in retrieving information from VSTM a mismatch with currently perceived information is processed very efficiently and fast. There is also evidence that a mechanism of visual attention is involved in VSTM retrieval. It will be subject to future research to pursue this line of research and to investigate in more detail the mechanism that has here been termed the *change signal*.

Closing Remarks

The present dissertation has shown that limitations of the human temporary storage system for visual material cannot be described in a simple way. VSTM is limited in several respects, which is not only due to a limited capacity or storage duration, as it is generally believed. Limitations are to an important extent also based on retrieval conditions. Furthermore, the different types of limitations are always complex and can only be described, when multiple factors are taken into account. So, for example, to be able to specify the limitations in VSTM maintenance, the nature of visual analog representations has to be understood. The limitation in storage duration, moreover, is dependent on active rehearsal or refreshment. It has to be taken into account that they presumably rely on the mechanism of visual attention. A further example for the complexity of the limitation is, that the storage capacity cannot be described by referring to a simple and generally valid number. Although it is now generally acknowledged that the integrated object is the basic unit which determines the capacity of VSTM, storage capacity is also contingent on the number of features that have to be retained in one object. Furthermore, the additional storage costs seem to be determined by the respective feature dimension. The fact that the

specific amount of storage costs is not yet known for the different feature dimensions and feature combinations, illustrate the intricacy of the matter. As a final example, the retrieval process also appears to depend on several factors. Retrieval is efficient and fast when a change signal can be used to detect a mismatch between representations in VSTM and perceptual information. But retrieval can also appear to be extremely limited, if in the presence of multiple changes a less efficient strategy has to be adopted for the task.

In the course of the present dissertation it has become evident that there are various interactions between VSTM processes and visual attention: Firstly, visual attention seems to be crucially involved in the mechanism of refreshing the stored information during maintenance in VSTM. Furthermore, attention is presumably important for processes of binding in VSTM. And finally, visual attention seems to have an important role in retrieval of information from VSTM. The present dissertation provides some suggestions how VSTM and visual attention act in combination. A comprehensive and more detailed description of the multiple relationships and interactions between VSTM and visual attention remains subject to future research.

References

- Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (pp. 89-145): Academic Press.
- Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell System Technical Journal*, *40*, 309-328.
- Awh, E., Smith, E. E., & Jonides, J. (1995). Human rehearsal processes and the frontal lobes: PET evidence. In J. Grafman, K. Holyoak, & F. Boller (Eds.), *Annals of the New York Academy of Science: Vol. 769. Structure and functions of the human prefrontal cortex* (Vol. 769, pp. 97-119). New York: New York Academy of Sciences.
- Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 780-790.
- Awh, E., & Jonides, J. (1998). Spatial selective attention and spatial working memory. In R. Parasuraman (Ed.), *The attentive brain* (Vol. 12, pp. 353-380). Cambridge, MA: MIT Press.
- Awh, E., Jonides, J., Smith, E. E., Buxton, R. B., Frank, L. R., Love, T., Wong, E. C., & Gmeindl, L. (1999). Rehearsal in spatial working memory: Evidence from neuroimaging. *Psychological Science*, *10*(5), 433-437.
- Awh, E., Anllo Vento, L., & Hillyard, S. A. (2000). The role of spatial selective attention in working memory for locations: Evidence from event-related potentials. *Journal of Cognitive Neuroscience*, *12*(5), 840-847.
- Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*(3), 119-126.

- Baddeley, A. D. (1966). Short-term memory for word sequences as a function of acoustic, semantic and formal similarity. *Quarterly Journal of Experimental Psychology*, *18*, 302-309.
- Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation* (Vol. 13, pp. 47-89). New York: Academic Press.
- Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *14*, 575-589.
- Baddeley, A. D., Grant, S., Wight, E., & Thomson, N. (1975). Imagery and visual working memory. In Rabbitt & Doring (Eds.), *Attention and performance V* (pp. 205-217). London, New York, San Francisco: Academic Press.
- Baddeley, A. D., & Lieberman, K. (1980). Spatial working memory. In R. Nickerson (Ed.), *Attention and Performance Volume:8* (pp. 521-539). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Pub.
- Baddeley, A. D. (1986). *Working memory*. New York: Oxford University Press.
- Baddeley, A. D. (1990). *Human memory. Theory and practice*. Hove: Laurence Erlbaum.
- Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417-423.
- Beck, J. (1973). Similarity grouping of curves. *Perceptual and Motor Skills*, *36*, 1331-1341.
- Beck, J. (1974). Relation between similarity grouping and perceptual constancy. *American Journal of Psychology*, *88*, 397-409.
- Beck, J. (1982). Textural segmentation. In J. Beck (Ed.), *Organisation & representation in perception* (pp. 285-317). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double-step stimuli. *Vision Research*, *19*, 967-983.
- Becker, J. T. (1994). Working memory (Special Issue). *Neuropsychology*, *8*(4).

- Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception, 29*, 273-286.
- Brandimonte, M. A., Hitch, G. J., & Bishop, D. V. (1992). Influence of short-term memory codes on visual image processing: Evidence from image transformation tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(1), 157-165.
- Broadbent, D. (1958). *Perception and communication*. London: Pergamon Press.
- Brooks, L. R. (1967). The suppression of visualization by reading. *Quarterly Journal of Experimental Psychology, 19*(4), 289-299.
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97*(4), 523-47.
- Carlson, L. A., Covell, E. R., & Warapius, T. (2001). Transsaccadic coding of multiple objects and features. *Psychologica Belgica, 41*(1/2), 9-27.
- Carlson-Radvansky, L. A. (1999). Memory for relational information across eye movements. *Perception and Psychophysics, 61*(5), 919-934.
- Catell, J. M. (1886). The time taken up by cerebral operations. *Mind, 11*, 220-242; 377-392; 524-538.
- Cermak, G. W. (1971). Short-term recognition memory for complex free-form figures. *Psychonomic Science, 5*(4), 209-211.
- Clark, H. J. (1965). Recognition memory for random shapes as a function of complexity, association value, and delay. *Journal of Experimental Psychology, 69*(6), 590-595.
- Cohen, J. D., Perlstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., & Smith, E. E. (1997). Temporal dynamics of brain activation during a working memory task. *Nature, 386*, 604-608.
- Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics, 27*, 183-228.
- Cornoldi, C., Cortesi, A., & Preti, D. (1991). Individual differences in the capacity limitations of visuospatial short-term memory: Research on sighted and totally congenitally blind people. *Memory and Cognition, 19*(5), 459-468.

- Courtney, S. M., Ungerleider, L. G., Keil, K., & Haxby, J. V. (1997). Transient and sustained activity in a distributed neural system for human working memory. *Nature*, *386*(10), 608-611.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87-185.
- Currie, C. B., McConkie, G. W., Carlson-Radvansky, L. A., & Irwin, D. E. (2000). The role of the saccade target object in the perception of a visually stable world. *Perception & Psychophysics*, *62*, 673-683.
- Curtis, C. E., & D'Esposito, M. (2003). Persistent activity in the prefrontal cortex during working memory. *Trends in Cognitive Science*, *7*(9), 415-423.
- Della Sala, S., & Logie, R. D. (1993). When working memory does not work: The role of working memory in neuropsychology. In F. Boller & H. Spinnler (Eds.), *Handbook of neuropsychology* (Vol. 8, pp. 1-63). Amsterdam: Elsevier.
- Desimone, R., & Ungerleider, L. G. (1989). Neural mechanisms of visual processing in monkeys. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (pp. 267-299). New York, NY: Elsevier Science Publishers B.V. (Biomedical Division).
- Desimone, R., Miller, E. K., Chelazzi, L., & Lueschow, A. (1995). Multiple memory systems in the visual cortex. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 475-486). Cambridge, MA: MIT Press.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*, 1827-1837.
- Deubel, H., Bridgeman, B., & Schneider, W. X. (1998). Immediate post-saccadic information mediates space constancy. *Vision Research*, *38*(20), 3147-3159.
- Deubel, H., Schneider, W. X., & Bridgeman, B. (2002). Transsaccadic memory of position and form. In J. Hyönä, D. Munoz, W. Heide, & R. Radach (Eds.), *The brain's eye: Neurobiological and clinical aspects of oculomotor research* (pp. 165-180). Amsterdam: Elsevier Science.

- Deubel, H. (2004). Localization of targets across saccades: Role of landmark objects. *Visual Cognition*, *11*(2-3), 173-202.
- DeYoe, E. A., & Van Essen, D. C. (1988). Concurrent processing streams in monkey visual cortex. *Trends in Neurosciences*, *11*, 219 - 226.
- Di Lollo, V., & Dixon, P. (1992). Inverse duration effect in partial report. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1089-1100.
- Dixon, P., & Di Lollo, V. (1994). Beyond visible persistence: An alternative account of temporal integration and segregation in visual processing. *Cognitive Psychology*, *26*, 33-63.
- Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*(4), 501-517.
- Ebbinghaus, H. (1885). *Über das Gedächtnis*. Leipzig: Dunker.
- Eckhorn, R., Bauer, R., Jordan, W., Brosch, M., Kruse, W., Munk, M., & Reitboeck, H. J. (1988). Coherent oscillations: A mechanism of feature linking in the visual cortex? *Biological Cybernetics*, *60*, 121-130.
- Egly, R., Driver, J., & Rafal, R. (1994). Shifting visual attention between objects and locations: evidence for normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, *123*, 161-177.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225-234.
- Eriksen, C. W., & Yeh, Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception & Performance*, *11*, 583-597.
- Fischer, B. (1986). Express saccades in man and monkey. *Progress in Brain Research*, *64*, 155-160.
- Frick, R. W. (1985). Testing visual short-term memory: Simultaneous versus sequential presentations. *Memory and Cognition*, *13*(4), 346-356.
- Funahashi, K. (1989). On the approximate realization of continuous-mappings by neural networks. *Neural Networks*, *2*(3), 183-192.

- Fuster, J. M. (1973). Unit activity in prefrontal cortex during delayed-response performance: neuronal correlates of transient memory. *Journal of Neurophysiology*, 36, 61-78.
- Fuster, J. M., & Jervey, J. P. (1981). Inferotemporal neurons distinguish and retain behaviorally relevant features of visual stimuli. *Science*, 212, 952 - 955.
- Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, 3(11), 410-419.
- Gegenfurtner, K. R., & Sperlin, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance*, 19(4), 845-866.
- Germeys, F., de Graef, P., Panis, S., van Eccelpoel, C., & Verfaillie, K. (2004). Transsaccadic integration by bystander locations. *Visual Cognition*, 11(2-3), 203-234.
- Germeys, F., De Graef, P., Van Eccelpoel, C., & Verfaillie, K. Visual change detection within and across fixations. *Manuscript submitted for publication*.
- Goebel, R. (1991). The role of visual perception, selective attention, and short term memory for symbol manipulation: A neural network model that learns to evaluate simple LISP expressions. In K. F. Wender, F. Schmalhofer, & H. D. Boecker (Eds.), *Cognition and computer programming*. University of Braunschweig, Department of Psychology: Ablex Publishing Corporation.
- Goldman-Rakic, P. S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In F. Plum (Ed.), *Handbook of physiology* (pp. 373-417). Bethesda, Maryland: American Physiological Society.
- Goldman-Rakic, P. S. (1996). Regional and cellular fractionation of working memory. *Proceedings of the National Academy of Sciences, USA*, 93, 13473-13480.
- Gray, C. M., König, P., Engel, A. K., & Singer, W. (1989). Oscillatory responses in the cat's visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. *Nature*, 338, 334-337.

- Harvey, L. D. (1986). Visual memory: what is remembered? In F. Klix (Ed.), *Human memory and cognitive capabilities* (pp. 173-187): Elsevier Science.
- Hebb, D. O. (1949). *Organization of behavior*. New York, NY: John Wiley & Sons, INC.
- Hecht, S., & Schlaer, S. (1936). Intermittent stimulation by light: V. The relation between intensity and critical frequency for different parts of the spectrum. *Journal of General Physiology*, 19, 965-979.
- Heinze, H. J., Luck, S. J., Mangun, G. R. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays: I. Evidence for early selection. *Electroencephalography and Clinical Neurophysiology*, 75(6), 511-527.
- Henderson, L. (1972). Spatial and verbal codes and the capacity of STM. *Quarterly Journal of Experimental Psychology*, 24(4), 485-495.
- Henderson, J. M., & Hollingworth, A. (1999). High level scene perception. *Annual Reviews in Psychology*, 50, 243-271.
- Hines, D. (1975). Immediate and delayed recognition of sequentially presented random shapes. *Journal of Experimental Psychology: Human Learning and Memory* 1 (5), 634-639.
- Hines, D., & Smith, S. (1977). Recognition of random shapes followed at varying delays by attended or unattended shapes, digits, and line grids. *Journal of Experimental Psychology: Human Learning and Memory*, 3(1), 29-36.
- Hitch, G. J. (1990). Developmental fractionation of working memory. In G. Vallar & T. Shallice (Eds.), *Neuropsychological impairments of short-term memory* (pp. 221-246). Cambridge, UK: Cambridge University Press.
- Hollingworth, A., Henderson, J. M. (2002). Accurate visual memory for previously attended objects in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance*, 28, 113-136.
- Hollingworth, A. (2003). Failures of retrieval and comparison constrain change detection in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance*, 29(2), 388-403.

- Hummel, J. E., & Biedermann, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review*, *99*, 480-517.
- Irwin, D. E., Yantis, S., & Jonides, J. (1983). Evidence against visual integration across saccadic eye movements. *Perception & Psychophysics*, *34*, 49-57.
- Irwin, D. E., & Yeomans, J. M. (1986). Sensory registration and informational persistence. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 343-360.
- Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cognitive Psychology*, *23*, 420-256.
- Irwin, D. E. (1992). Memory for position and identity across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(2), 307-317.
- Irwin, D. E., & Andrews, R. V. (1996). Integration and accumulation of information across saccadic eye movements. In T. Inui, McClelland, J. L., et al. (Eds.), *Attention and performance 16: Information integration in perception and communication*. (pp. 125-155). Cambridge, MA, USA: MIT Press.
- Irwin, D. E. (1996). Integrating information across saccadic eye movements. *Current Directions in Psychological Science*, *5*(3), 94-100.
- Jacobs, J. (1887). Experiments on 'prehension'. *Mind*, *12*, 75-79.
- James, W. (1890). *Principles of psychology* (Vol. 1). New York: Holt.
- Jiang, Y., Olson, I., Chun, M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition* *26* (3), 683-702.
- Jonides, J., Irwin, D. E., & Yantis, S. (1982). Integrating visual information from successive fixations. *Science*, *215*, 192-194.
- Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S., & Mintun, M. A. (1993). Spatial working memory in humans as revealed by PET. *Nature*, *363*(623-625).
- Julesz, B. (1981). Textons, the elements of texture perception, and their interactions. *Nature*, *290*, 91-97.

- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*(2), 175-219.
- Kanwisher, N., & Driver, J. (1992). Objects, attributes and visual attention: Which, what, and where. *Psychological Science*, *1*, 26-31.
- Kelly, R. T., & Martin, D. W. (1974). Memory for random shapes: A dual-task analysis. *Journal of Experimental Psychology*, *103*(2), 224-229.
- Kerr, N. H. (1987). Locational representation in imagery: The third dimension. *Memory and Cognition*, *15*(6), 521-530.
- Kikuchi, T. (1987). Temporal characteristics of visual memory. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(3), 464-477.
- Kyllingsbaek, S. (2003). *Variations in visual short-term memory capacity within individuals*. Paper presented at the XIII Conference of the European Society of Cognitive Psychology (ESCOP), Granada, Spain.
- Landmann, R., Spekreijse, H., Lamme, V. A. F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research*, *43*, 149-164.
- Levin, D. T., & Simons, D. J. (1997). Failure to detect changes to attended objects in motion pictures. *Psychonomic Bulletin and Review*, *4*, 501-506.
- Levin, D. T., Momen, N., Drivdahl, S. B., & Simons, D. J. (2000). Change blindness: The metacognitive error of overestimating change-detection ability. *Visual Cognition*, *7*(1-3), 397-412.
- Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth - anatomy, physiology, and perception. *Science*, *240*(4853), 740-749.
- Loftus, G. R., Duncan, J., & Gehrig, P. (1992). On the time course of perceptual information that results from a brief visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 530-549.
- Logie, R. H., Zucco, G. M., & Baddeley, A. D. (1990). Interference with visual short-term memory. *Acta Psychologica*, *75*(1), 55-74.

- Logie, R. H., & Marchetti, C. (1991). Visuo-spatial working memory: visual, spatial or central executive? In R. H. Logie & M. Denis (Eds.), *Mental images in human cognition* (pp. 105-115). Amsterdam: Elsevier.
- Logie, R. H. (1995). *Visuo-spatial working memory*. Hove, UK: Erlbaum.
- Luck, S. J., & Hillyard, S. A. (1994a). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*(3), 291-308.
- Luck, S. J., & Hillyard, S. A. (1994b). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1000-1014.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279-281.
- Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas v1 v2, and v4 of macaque visual-cortex. *Journal of Neurophysiology*, *77*(1), 24-42.
- Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, *33*(1), 64-87.
- Macmillan, N. A., & Creelman, C. D. (1990). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.
- Matin, E. (1974). Saccadic suppression: A review and analysis. *Psychological Bulletin*, *81*, 899-917.
- McConkie, G. W., & Rayner, K. (1976). Identifying the span of the effective stimulus in reading: literature review and theories of reading. In H. Singer & R. Ruddell (Eds.), *Theoretical models and processes of reading (2nd edition)* (pp. 137-162). Newark, DE: International Reading Institute.
- Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *The Psychological Review*, *63*(2), 81-97.

- Miller, E. K., Li, L., & Desimone, R. (1991). A neural mechanism for working and recognition memory in inferior temporal cortex. *Science*, *254*(5036), 1377-1379.
- Miller, E. K., Li, L., & Desimone, R. (1993). Activity of neurons in anterior inferior temporal cortex during a short-term memory task. *Journal of Neuroscience*, *13*(4), 1460-1478.
- Miller, E. K., Erickson, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *The Journal of Neuroscience*, *16*, 5154-5167.
- Milner, P. (1974). A model for visual shape recognition. *Psychological Review*, *81*, 521-535.
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. New York: Oxford University Press.
- Miyake, A., & Shah, P. (Eds.). (1999). *Models of working memory*. Cambridge: Cambridge University Press.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, *229*(4715), 782-784.
- Moutoussis, K., & Zeki, S. (1997). Functional segregation and temporal hierarchy of the visual perceptive systems. *Proceedings of the Royal Society of London Series B*, *264*(1387), 1407-1414.
- Mozer, M. C., Zemel, R. S., Behrmann, M., Williams, C. K. (1992). Learning to segment images using dynamic feature binding. *Neural Computation* *4*(5), 650-665.
- Neisser, U. (1963). Decision-time without reaction-time: Experiments in visual scanning. *American Journal of Psychology*, *76*, 376-385.
- Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.
- Niebur, E., Koch, C., & Rosin, C. (1993). An oscillation-based model for the neuronal basis of attention. *Vision Research*, *33*, 2789-2802.
- O'Regan, J. K., & Levy-Schoen, A. (1983). Integrating visual information from successive fixations: Does transsaccadic fusion exist? *Vision Research*, *23*, 765-768.

- O'Regan, J. K. (1992). Solving the 'real' mysteries of visual perception: The world as an outside memory. *Canadian Journal of Psychology, 46*(3), 461-488.
- O'Regan, J. K., Rensink, R. A., & Clark, J. J. (1999). Change-blindness as a result of 'mudsplashes'. *Nature, 398*, 34.
- O'Regan, J. K., Deubel, H., Clark, J. J., & Rensink, R. A. (2000). Picture changes during blinks: Looking without seeing and seeing without looking. *Visual Cognition, 7*(1-3), 191-211.
- Oyama, T., Kikuchi, T., & Ichihara, S. (1981). Span of attention, backward masking, and reaction time. *Perception & Psychophysics, 29*, 106-112.
- Palmer, J. (1990). Attentional limits on the perception and memory of visual information. *Journal of Experimental Psychology: Human Perception and Performance, 16*(2), 332-350.
- Palmer, J., Ames, C. T., & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception and Performance, 19*(1), 108-130.
- Palmer, J. (1995). Attention in visual search: Distinguishing four causes of a set-size effect. *Current Directions in Psychological Science, 4*(4), 118-123.
- Palmer, S. E. (1999). *Vision Science: Photons to phenomenology*. Cambridge, Massachusetts: The MIT Press.
- Parr, W. (1992). Delayed matching-to-sample performance as a measure of human visuospatial working memory. *Bulletin of the Psychonomic Society, 30*(5), 369-372.
- Pashler, H. (1988). Familiarity and visual change detection. *Perception and Psychophysics, 44*(4), 369-378.
- Petrides, M. (1996). Specialized systems for the processing of mnemonic information within the primate frontal cortex. *Philosophical Transactions of the Royal Society of London: Biological Sciences, 351*, 1455-1462.
- Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception and Psychophysics, 16*(2), 283-290.

- Phillips, W. A., & Singer, W. (1974). Function and interaction of on and off transients in vision. I. Psychophysics. *Experimental Brain Research*, *19*, 493-506.
- Phillips, W. A., & Christie, D. F. (1977). Components of visual memory. *Quarterly Journal of Experimental Psychology*, *29*(1), 117-133.
- Posner, M. I., & Konick, A. F. (1966). Short-term retention of visual and kinesthetic information. *Organizational Behavior and Human Decision Processes*, *1*(1), 71-86.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3-25.
- Postman, L., & Phillips, L. W. (1965). Short-term temporal changes in free recall. *Quarterly Journal of Experimental Psychology*, *17*(2), 132-138.
- Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory*, *2*(5), 509-522.
- Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*(3), 179-197.
- Rafal, R. D. (1997). Balint syndrome. In T. E. Feinberg & M. J. Farah (Eds.), *Behavioral neurology and neuropsychology* (pp. 337-356). Berkshire, UK: McGraw-Hill, UK.
- Rao, S. C. R. G., & Miller, E. K. (1997). Integration of what and where in the primate prefrontal cortex. *Science*, *276*, 821-824.
- Rayner, K., & Pollatsek, A. (1983). Is visual information integrated across saccades? *Perception and Psychophysics*, *34*, 39-48.
- Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, *81*(2), 275-280.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1995). Image flicker is as good as saccades in making large scene changes invisible. *Perception*, *24* (suppl.), 26-28.
- Rensink, R. A. (1997). *How much of a scene is seen? The role of attention in scene perceptiom*. Paper presented at the ARVO 97, Ft. Lauderdale, FL.

- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science*, 8(5), 368-373.
- Rensink, R. A. (2000a). The dynamic representation of scenes. *Visual Cognition*, 7(1-3), 17-42.
- Rensink, R. A. (2000b). Visual search for change: A probe into the nature of attentional processing. *Visual Cognition*, 7(1-3), 345-376.
- Rensink, R. A. (2000c). Seeing, sensing, and scrutinizing. *Vision Research*, 40(10-12), 1469-1487.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (2000). On the failure to detect changes in scenes across brief interruptions. *Visual Cognition*, 7(1-3), 127-145.
- Rensink, R. A. (2002). Change detection. *Annual Reviews of Psychology*, 53, 245-277.
- Romo, R., Brody, C. D., Hernandez, A., & Lemus, L. (1999). Neuronal correlates of parametric working memory in the prefrontal cortex. *Nature*, 399, 470-473.
- Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition, and space-based motor action. *Visual Cognition*, 2, 331-375.
- Schneider, W. X., Wesenick, M.-B., Deubel, H., & Bundesen, C. (1999). A study on visuo-spatial working memory. *Perception*, 28(supplement), 5.
- Schneider, W. X. (1999). Visual-spatial working memory, attention, and scene representation: a neuro-cognitive theory. *Psychological Research*, 62, 220-236.
- Schneider, W. X., Wesenick, M.-B., Deubel, H., & Bundesen, C. (1999). A study on visuo-spatial working memory. *Perception*, 28(supplement), 5.
- Schneider, W. X., Deubel, H., & Wesenick, M.-B. (2001). Characterizing chunks in visual short-term memory: Not more than one feature per dimension? *Behavioral and Brain Sciences*, 24(1).
- Scott-Brown, K. C. & Orbach, H. S. (1998). Contrast discrimination, non-uniform patterns and change blindness. *Proc. R. Soc. Lond. B*, 265, 2159-2166.

- Scott-Brown, K. C., Baker, M. R. & Orbach, H. S. (2000). Comparison blindness. *Visual Cognition*, 7 (1-3), 253-267.
- Shaffer, W., & Shiffrin, R. M. (1972). Rehearsal and storage of visual information. *Journal of Experimental Psychology*, 92(2), 292-296.
- Shaw, M. L. (1980). *Identifying attentional and decision-making components in information processing*. Paper presented at the Attention and Performance, Hillsdale NJ.
- Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance*, 14(4), 591-600.
- Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in Cognitive Sciences*, 1, 261-267.
- Simons, D. J., & Levin, D. T. (1998). Failure to detect changes to people during a real-world interaction. *Psychonomic Bulletin and Review*, 5, 644-649.
- Simons, D. J., Chabris, C. F., Schnur, T. (2002). Evidence for preserved representations in change blindness. *Consciousness and Cognition*, 11, 78-97.
- Singer, W. (1989). Search for coherence: A basic principle of cortical self-organization. *Concepts in Neuroscience*, 1, 1-26.
- Singer, W., & Gray, C. M. (1995). Visual feature integration and the temporal correlation hypothesis. *Annual Review of Neuroscience*, 18, 555-586.
- Singer, W., Engel, A. K., Kreiter, A. K., Munk, M. H. J., Neuenschwander, S., & Roelfsema, P. R. (1997). Neuronal assemblies: necessity, signature and detectability. *Trends in Cognitive Sciences*, 1(7), 252-261.
- Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology*, 33(1), 5-42.
- Smyth, M. M., Pearson, N. A., & Pendleton, L. R. (1988). Movement and working memory: Patterns and positions in space. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 40(3-A), 497-514.

- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, 74, 1-29.
- Stelmach, L. B., Bourassa, C. M., & Di Lollo, V. (1984). Detection of stimulus change: The hypothetical roles of visual transient responses. *Perception & Psychophysics*, 35(3), 245-255.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97-136.
- Treisman, A., & Souther, J. (1985). Search asymmetries: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, 114, 285-310.
- Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology*, 40, 201-237.
- Treisman, A., & Gormican, S. (1988). Feature analysis in early vision - evidence from search asymmetries. *Psychological Review*, 95(1), 15-48.
- Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society, B* 353, 1295-1306.
- Treisman, A. (1999). Solutions to the binding problem: Progress through controversy and convergence. *Neuron*, 24, 105-110.
- Treue, S. (2001). Neural correlates of attention in primate visual cortex. *Trends in Neurosciences*, 24(5), 295-300.
- Ungerleider, L. G., & Haxby, J. V. (1994). 'What' and 'where' in the human brain. *Current Biology*, 4, 157-165.
- Vecera, S. P., & Farah, M. J. (1994). Does visual attention select objects or locations? *Journal of Experimental Psychology: General*, 123(146-160).
- Verfaillie, K., & De Graef, P. (2000). Transsaccadic memory for position and orientation of saccade source and target. *Journal of Experimental Psychology: Human Perception and Performance*, 26(4), 1243-1259.
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, 27(1), 92-114.

- von der Malsburg, C. (1981). *The correlation theory of brain function*. Göttingen, Germany: Max-Planck-Institute for Biophysical Chemistry.
- Wesenick, M.-B. (2000). *Retrieval of information from visual working memory* (unpublished master's thesis). München: Ludwig-Maximilians Universität.
- Wesenick, M.-B., Deubel, H., & Reimann, B. (2003). *Effective processing of change in visual working-memory retrieval*. Poster presented at the XIII Conference of the European Society of Cognitive Psychology (ESCOP), Granada.
- Wesenick, M.-B., Deubel, H., & Schneider, W. X. (2003). *Detection of change in retrieval from visual short-term memory*. Poster presented at the Munich Visual Search Symposium, Holzhausen am Ammersee.
- Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, 131(1), 48-64.
- Wilson, J. L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology*, 5(3), 249-255.
- Wolf, W., Hauske, G., & Lupp, U. (1980). Integration of pre- and postsaccadic patterns having the same coordinates in space. *Vision Research*, 20, 117-124.
- Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 13-73). Hove, East Sussex, UK: Psychology Press.
- Wolfe, J., M., Klempen, N., & Dahlen, K. (2000). Postattentive vision. *Journal of Experimental Psychology: Human Perception and Performance*, 26(2), 693-716.
- Woodman, G. F., & Luck, S., J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, 400(6747), 867-869.
- Wyant, S., Banks, W. P., Berger, D., & Wright, P. W. (1972). Verbal and pictorial similarity in recognition of pictures. *Perception and Psychophysics*, 12(2-A), 151-153.
- Zeki, S. M. (1993). *A vision of the brain*. Oxford: Blackwell Scientific Publications.

Begrenzungen des menschlichen Arbeitsgedächtnisses

(deutsche Zusammenfassung)

Einleitung

In der kognitiven Psychologie haben sich Forscher von Beginn an für die Untersuchung des menschlichen Gedächtnisses interessiert. Insbesondere sind als Vertreter des 19. Jahrhunderts Herrmann Ebbinghaus mit seinem berühmten Werk *Über das Gedächtnis* (1885) und William James zu nennen, der in seinem klassischen Buch *Principles of Psychology* (1890) zwei Gedächtnisspeicher unterschied. Die Idee einer genaueren Beschreibung verschiedener Gedächtnissysteme wurde Mitte des 20. Jahrhunderts im Rahmen des Informationsverarbeitungsansatzes von Broadbent (1958) weiter entwickelt. Eine detaillierte Darstellung des menschlichen Gedächtnisses gaben bald darauf auch Atkinson und Shiffrin (1968). Sie beschrieben ein Gedächtnismodell, das aus mehreren Komponenten besteht. Eine dieser Komponenten ist das Kurzzeitgedächtnis, andere sind das sensorische Register und das Langzeitgedächtnis.

Ein sehr einflussreiches Modell der temporären Speicherung ist das Arbeitsgedächtnismodell von Baddeley und Hitch (1974). Dieses Modell ist wichtig für die Forschung zum visuellen Kurzzeitgedächtnis, weil es das Arbeitsgedächtnis nicht als einheitliches System annimmt, sondern mehrere Bestandteile beschreibt. Es unterscheidet einen räumlich-visuellen Speicher und einen verbalen Speicher von der Kontrollinstanz einer zentralen Exekutive.

Klassische Studien zum visuellen Kurzzeitgedächtnis wurden von Phillips (z.B. Phillips, 1974) durchgeführt. Er entwickelte eine Methode zur Erforschung des visuellen Kurzzeitspeichers und beschrieb dessen zentralen Eigenschaften. Obwohl Phillips keine umfassende Theorie entwickelte, so war man zunächst doch der

Auffassung, dass nun die relevanten Fragen zu diesem Forschungsgebiet weitgehend geklärt seien.

Erst mit der Entwicklung des neuen Paradigmas der kognitiven Neurowissenschaften und mit Fortschritten in Neurobiologie, Neurophysiologie und Gehirnforschung sind wichtige Themen der kognitiven Psychologie unter neuen Sichtweisen wieder aufgegriffen worden. Ein solches neues Gebiet in der kognitiven Psychologie zum menschlichen Sehen widmet sich dem Phänomen der „Veränderungsblindheit“ (z.B. O'Regan, 1992; Rensink, 2000a, 2000b). Es entstand eine neue Auffassung darüber, wie der Mensch seine visuellen Umwelt im Gehirn repräsentiert. Das visuelle Kurzzeitgedächtnis spielt darin eine zentrale Rolle.

Als weitere wichtige Beiträge für ein Verständnis des menschlichen visuellen Kurzzeitgedächtnisses und wesentlich für die vorliegende Arbeit seien die Untersuchungen zum transsakkadischen Gedächtnis genannt (z.B. Irwin, 1991), die Studien über das räumlich-visuelle Arbeitsgedächtnis von Luck und Vogel (1997) und die neurokognitive Theorie des visuell-räumlichen Arbeitsgedächtnisses von Schneider (1999).

Fragestellung

Die vorliegende Dissertation knüpft an die genannten Arbeiten an und trägt zum Verständnis des visuellen Arbeitsgedächtnisses bei. Die meisten Arbeitsgedächtnistheorien unterscheiden verschiedenen Funktionen wie z. B. die Funktion der temporären Speicherung oder die aktive Organisation und Modifikation gespeicherter Information. In der vorliegenden Arbeit werden Aspekte der Kurzzeitspeicherung untersucht, wobei das visuelle Kurzzeitgedächtnis (VKZG) als Teil des visuellen Arbeitsgedächtnisses aufgefasst wird. Eine definierende Eigenschaft des VKZG ist es, in mehrerer Hinsicht Begrenzungen aufzuweisen. Allgemeines Ziel der vorliegenden Arbeit ist es, diese Begrenzungen detaillierter zu beschreiben. Die Begrenzungen dreier Aspekte des VKZG werden untersucht:

RETENTION: Zunächst werden Begrenzungen in der Dauer des Gedächtnisspeichers für eine neue Art von Stimulusmaterial untersucht, welches in

den Experimenten der gesamten vorliegenden Arbeit verwendet wurde. Wie kann die Speicherung im VKZG in seinem Zeitverlauf beschrieben werden? Wie sieht der Übergang von ikonischer Repräsentation der Information zur Speicherung, die allein auf das VKZG zurückgeht, aus? Wie lange kann die Information insgesamt im Speicher verbleiben, bevor sie vergessen wird?

FORMAT: Der zweite Aspekt betrifft Begrenzungen in der Kapazität des VKZG. Wie viel Information kann das VKZG speichern? Diese Frage kann nicht adäquat beantwortet werden, ohne dass das Speicherformat spezifiziert ist, in dem die Information im VKZG repräsentiert wird. Wird die Information in Form von ganzen Objekten gespeichert oder ist die Anzahl der Objektmerkmale ausschlaggebend für die Kapazität? Die vorliegende Dissertation untersucht, ob das Binden von Merkmalen Kosten für die Speicherung im VKZG hat. Diese Frage wurde auch von Luck und Vogel (1997) untersucht, welche jedoch zu Ergebnissen gelangten, die in der vorliegenden Arbeit nicht vollständig bestätigt werden konnte. Eine modifizierte Sichtweise und die zugrundeliegenden empirischen Befunde werden dargestellt.

ABRUF: Drittens werden Begrenzungen der Verarbeitung im VKZG beschrieben, die auf limitierte Abrufbedingungen zurückzuführen sind. Begrenzungen der Gesamtleistung des VKZG haben ihre Ursache demnach nicht ausschließlich in der eingeschränkten Kapazität. Die vorliegende Arbeit zeigt, dass der Prozess des Abrufs äußerst begrenzt sein kann. Dieser Aspekt ist von der Forschung bislang nur wenig beachtet worden. Bisher liegen keine systematischen Untersuchungen zum Abruf und keine theoretischen Vorstellungen darüber vor, wie der Abrufprozess konzeptualisiert werden kann. Empirische Ergebnisse und eine theoretische Beschreibung über den Abruf vom VKZG werden in der vorliegenden Dissertation präsentiert.

In allen Experimenten der vorliegenden Arbeit wird visuelles Stimulusmaterial verwendet, das sehr abstrakt und von sehr einfacher Struktur ist. Es handelt sich um einfache geometrische Figuren, nämlich Rechtecke verschiedener Farbe, Länge und Orientierung. Zwei Eigenschaften der Stimuli sind besonders hervorzuheben. Zum einen ist von einer weitgehend visuell-räumlichen Speicherung auszugehen, zum anderen besteht das Material aus abgegrenzten, gut definierten einzelnen Objekten,

deren Komplexität leicht zu kontrollieren ist. Es ist somit möglich die Kapazität durch die Anzahl von Objekten und die Anzahl ihrer Merkmale, die gespeichert werden können, anzugeben.

Das verwendete experimentelle Paradigma besteht aus einer Aufgabe der Veränderungsdetektion. Es wird zunächst eine Gedächtnisvorlage mit den zu merkenden Stimuli gezeigt (400 ms). Diese Gedächtnisvorlage wird wieder ausgeblendet, und die Stimuli müssen für ein bestimmtes Behaltensintervall so gut wie möglich memoriert werden (z.B. 2000 ms). Anschließend wird eine Testvorlage präsentiert. Sie enthält entweder exakt dieselben Stimuli wie die Gedächtnisvorlage oder eines der Objekte unterscheidet sich von dem entsprechenden vorherigen Objekt in einem Merkmal. Die Aufgabe ist, durch Drücken der entsprechenden Maustaste anzuzeigen, ob eine Veränderung vorliegt oder nicht.

Ergebnisse

Retention

In Experimenten 1 und 2 wurde der Zeitverlauf der Speicherung im VKZG untersucht. Die Gedächtnisleistung wurde in dem oben beschriebenen experimentellen Paradigma und der Aufgabe der Veränderungsentdeckung getestet. Dazu wurde das Retentionsintervall systematisch variiert (zwischen 14 ms und 8000 ms). Es wurde erwartet, dass sich bei sehr kurzen Retentionsintervallen bis zu etwa 300 ms die Speicherung in Form von visuell analogen Repräsentationen in der Gedächtnisleistung zeigen würde. Visuell analoge Repräsentationen sind ein Teil des ikonischen Gedächtnisses (Di Lollo & Dixon, 1988). Sie haben eine unbegrenzte Speicherkapazität und eine Dauer von ca. 300 ms (Irwin & Yeomans, 1986). Folglich wurde für Behaltensintervalle bis etwa 300 ms eine sehr hohe Gedächtnisleistung von mehr als 90% Genauigkeit unabhängig von der zu merkenden Informationsmenge erwartet. Nach dem Zerfall der visuell analogen Repräsentationen würde sich die Speicherung allein auf das VKZG gründen. Für die längeren Speicherdauern müsste nun eine deutlich niedrigere Gedächtnisleistung zu beobachten sein, die zudem von der zu speichernden Informationsmenge abhängt. Ausgehend von früheren Studien müsste diese Gedächtnisleistung über alle längeren

Behaltensintervalle hinweg stabil bleiben (Kikuchi, 1987; Parr, 1992; Pashler, 1988; Phillips, 1974).

Im Gegensatz zu diesen Annahmen wurde keine von der Informationsmenge unabhängige, sehr hohe Gedächtnisleistung beobachtet. Stattdessen zeigte sich eine relative stabile, von der Informationsmenge abhängige Leistung auf niedrigerem Niveau. Diese Ergebnisse zeigen, dass von visuell analogen Repräsentation kein Nutzen für die Lösung der Aufgabe gezogen werden kann. Zwei mögliche Antworten werden in Kapitel 2 der vorliegenden Arbeit vorgeschlagen. Erstens könnten Transienten, die durch den Onset der Stimuli in der Testvorlage verursacht werden und über das gesamte Sehfeld verteilt sind, diejenigen Transienten maskieren, welche durch die lokale Veränderung des kritischen Objekts verursacht werden. Die Transienten der lokalen Veränderungen hätten ansonsten zur Lösung der Aufgabe ausgenutzt werden können. Spezifische experimentelle Manipulationen führten zur Zurückweisung dieser Vermutung. Eine zweite Erklärung könnte sein, dass die visuell analogen Repräsentationen der zu merkenden Stimuli nicht ausschließlich durch den Onset der irrelevanten Objekte in der Testvorlage unzugänglich waren. Es könnte sein, dass die visuell analogen Repräsentationen durch neue Information überschrieben wird, die in der Testvorlage enthalten ist. Diese Hypothese scheint sich durch stützende Evidenz zu bestätigen.

Dass nach Intervallen von 4 Sekunden oder länger kein weiterer Informationsverlust zu beobachten ist, stimmt mit früheren Studien überein (Kikuchi, 1987; Parr, 1992; Pashler, 1988; Phillips, 1974). Die Kapazität des VKZG beläuft sich auf mehr als zwei und weniger als vier Objekte. Es kann angenommen werden, dass die im VKZG gespeicherte Information für eine Dauer von 15 Sekunden oder länger aufrechterhalten werden kann, wenn die Versuchsperson vollständig mit dieser Aufgabe befasst ist. Aktive Retentionsmechanismen verhüten den Informationsverlust durch passiven Zerfall oder Interferenz. In der neurokognitiven Theorie von Schneider (1999) ist ein Auffrischungsmechanismus verantwortlich dafür, ein Vergessen zu verhindern. In dieser Theorie haben die Objekte, die im VKZG gespeichert sind, ein höheres Aktivationsniveau als die Objekte, die im Wettbewerb um den Eintritt ins VKZG stehen. Durch den

Auffrischungsmechanismus werden die gespeicherten Objekte auf einem Aktivationsniveau gehalten, der notwendig für den Verbleib im VKZG ist.

Speicherformat

Thema des dritten Kapitels ist die Relation zwischen dem Speicherformat des VKZG und dessen Begrenzung in der Kapazität. Luck und Vogel (1997) stellen fest, dass sich die Kapazität des VKZG aus der Anzahl ganzer Objekte bestimmt, unabhängig von der Zahl ihrer Merkmale. Diese Behauptung kann aufgrund der experimentellen Befunde, die im Rahmen der vorliegenden Arbeit erhoben wurden, nicht voll bestätigt werden. Die hier durchgeführten Experimente 3a und 3b weisen zwar darauf hin, dass tatsächlich ganze Objekte die grundlegende Einheit des VKZG darstellen. Dennoch zeigt sich, dass die Gedächtnisleistung größer ist, wenn nur einzelne Merkmale von Objekten memoriert werden sollen als wenn die Konjunktion mehrerer Merkmale behalten werden muss. Dies lässt darauf schließen, dass das Binden von Objektmerkmalen Speicherkosten hat. Die Kosten für das Binden eines zusätzlichen Merkmals in einem Objekt sind jedoch nicht so groß wie die Kosten für die Speicherung eines völlig neuen Objekts. Eine Ausnahme bildet die Speicherung von Objekten, die sich aus Merkmalen derselben Merkmalsdimension zusammensetzen. In Experiment 4 war die Gedächtnisleistung für Objekte, die aus zwei Farben bestehen erheblich schlechter als die Gedächtnisleistung für einfarbige Objekte. So war die Gedächtnisleistung für zwei zweifarbige Objekte vergleichbar mit der Gedächtnisleistung für vier einfarbige Objekte. Das bedeutet, dass die Speicherkosten für ein zusätzliches Merkmal derselben Dimension vergleichbar ist mit den Speicherkosten für ein zusätzliches Objekt. Diese Beobachtung widerspricht klar den Befunden von Luck und Vogel (1997), die keine zusätzlichen Speicherkosten im Fall von zweifarbigen Objekten beobachten konnten. Ein weiteres Labor konnte die Befunde von Luck und Vogel (1997) ebenfalls nicht bestätigen (Wheeler & Treisman, 2002) und stimmt somit mit den Befunden der vorliegenden Arbeit überein, die bereits an anderer Stelle berichtet wurden (Schneider, Deubel, & Wesenick, 2001). Die vorliegenden Befunde lassen sich wie folgt zusammenfassen:

- ✓ Die Kapazität des VKZG bestimmt sich durch die Anzahl der zu speichernden Objekte.

- ✓ Das Binden mehrerer Objektmerkmale in einem Objekt hat Speicherkosten, wobei die Kosten für das Binden nicht so hoch sind wie für die Speicherung eines neuen Objekts.
- ✓ Wenn jedoch Merkmale derselben Dimension in einem Objekt kombiniert werden, dann sind die Speicherkosten sehr viel größer. Sie sind vergleichbar mit den Kosten für die Speicherung eines neuen Objekts.
- ✓ Die Gedächtnisleistung ist nicht für alle Merkmale gleich, sondern variiert je nach Merkmalsdimension.

Diese Ergebnisse haben wichtige Implikationen für eine Konzeption der Speicherung im VKZG und müssen in jeder Theorie des VKZG Berücksichtigung finden. Einige theoretische Vorstellungen werden in Kapitel 3 berichtet. Darin wird visuelle Aufmerksamkeit als zentraler Mechanismus bei der Merkmalsbindung in der visuellen Wahrnehmung postuliert. In Kapitel 3 werden darüber hinaus Forschungsbefunde dargestellt, die zum Ziel haben, Bindungsmechanismen auf physiologischer Ebene zu beschreiben.

Abruf

Kapitel 4 der vorliegenden Arbeit beschäftigt sich mit dem Thema des Abrufs von Informationen aus dem VKZG. Zur Untersuchung dieses Aspekts wird im verwendeten experimentellen Paradigma sowohl die Struktur des Gedächtnistests als auch die Abrufaufgabe variiert. In Experiment 5 zeigt sich, dass es keinen Einfluss auf die Gedächtnisleistung hat, ob im Test die gleiche Anzahl vorher präsentierter Objekte gezeigt wird oder nur ein einzelnes kritisches Objekt. Dieses Ergebnis ist sehr überraschend, wenn man von einem seriellen Vergleich der im VKZG gespeicherten Objekten mit den wahrgenommenen Objekten ausgeht. Im Fall der Präsentation eines einzigen Objekts im Test, muss nur dieses eine Objekt verglichen werden, d.h. der Ort des kritischen Objekts ist bekannt. Dagegen ist dies bei mehreren Testobjekten nicht der Fall. Multiple Vergleiche wären unter dieser Annahme zur Lösung der Aufgabe notwendig. Die experimentellen Ergebnisse erfordern die Entwicklung einer alternativen Erklärung. Hierzu wird die Hypothese eines Veränderungssignals gebildet, welches von einer lokale Inkongruenz von

Gedächtnisinhalt und wahrgenommener Information generiert wird. Es kann dazu ausgenutzt werden, um eine solche Inkongruenz schnell und effizient zu verarbeiten.

Experiment 5 zeigt auch, dass es einen gravierenden Abfall in der Gedächtnisleistung gibt, wenn die ursprüngliche Aufgabe in bestimmter Weise verändert wird. In der ursprünglichen Aufgabe kann im Test ein Objekt vorhanden sein, das sich von dem entsprechenden Objekt der Gedächtnisvorlage unterscheidet, während die anderen Objekte gleich geblieben sind. Es soll beurteilt werden, ob ein verändertes Objekt im Test enthalten ist (*detect change* Aufgabe). In einer anderen Aufgabe ändern sich alle Objekte im Vergleich zur Gedächtnisvorlage. Es kann jedoch sein, dass eines der Objekte gleich geblieben ist. Hier soll beurteilt werden, ob ein kongruentes Objekt vorhanden ist oder ob alle Objekte anders sind als in der Gedächtnisvorlage (*detect match* Aufgabe). Die Gedächtnisleistung in der *detect match* Aufgabe ist deutlich schlechter als in der *detect change* Aufgabe. Auch dieser Befund kann mit der Annahme eines Veränderungssignals erklärt werden: Drei veränderte Objekte verursachen Veränderungssignale, das eine nicht veränderte Objekt hingegen nicht. Es gibt in diesem Fall kein eindeutiges Signal, das effektiv und schnell für die Lösung der Aufgabe ausgenutzt werden kann. Möglicherweise wird nun stattdessen ein serieller Vergleich initiiert, der langsam und fehleranfällig ist. Dieser Vergleichsprozess, so die Hypothese, verlangt Ressourcen der visuellen Aufmerksamkeit, welche ihrerseits mit der Aufrechterhaltung der Information im VKZG beschäftigt ist. Sie wird nun von dieser Aufgabe für den Vergleichsprozess abgezogen. Da jetzt keine Aktivierung des gespeicherten Materials möglich ist, geht es verloren und ist nun nicht mehr verfügbar. Falls in dem ersten Vergleich das richtige Objekt nicht ausgemacht werden konnte, sind keine weiteren Vergleiche zur Lösung mehr möglich. Daher die sehr viel schlechtere Gedächtnisleistung als in der Bedingung mit der Aufgabe der lokalen Veränderungsdetektion.

Alle folgenden Experimente haben zum Ziel, weitere Evidenz zur Stützung dieser Hypothese zu sammeln und Eigenschaften des Veränderungssignals näher zu spezifizieren. So wird in Experiment 6 gefunden, dass in der *detect match* Aufgabe ein lokaler Hinweisreiz zur Lösung beitragen kann, wenn dieser im Behaltensintervall oder gleichzeitig mit dem Test präsentiert wird. Er hilft nicht, wenn er erst etwas nach dem Test gezeigt wird. In Experiment 7 zeigt sich, dass das

Veränderungssignal durch irrelevante Änderung der Orte ausgelöst werden kann, wenn der Test multiple Objekte enthält. Die Ortsänderung eines einzelnen Testitems hat keinen Effekt. Experimente 8a und 8b zeigen, dass für die Aufgabe irrelevante Änderungen in den Dimensionen Farbe und Orientierung nicht zu einer Störung der Leistung führen. Das wird als Evidenz dafür angenommen, dass das Veränderungssignal hier nicht auftritt und daher in gewissem Maße durch die Aufgabe modulierbar ist.

Die Befunde werden zusammenfassend folgendermaßen erklärt:

- ✓ Das Veränderungssignal wird durch eine Inkongruenz zwischen Gedächtnisinhalt und wahrgenommener Information hervorgerufen.
- ✓ Das Veränderungssignal kann dazu ausgenutzt werden, um ein verändertes Objekt zu lokalisieren, wenn irrelevanter Distraktorobjekte nicht ihre Orte ändern.
- ✓ Veränderungssignale entstehen speziell auch dann, wenn relevante oder irrelevante Objekte ihre Orte ändern.
- ✓ Wenn eine Änderung nicht unter Ausnutzung des Veränderungssignals verarbeitet werden kann, dann wird ein fehlerträchtiger serieller Vergleichsprozess initiiert.
- ✓ Dieser Vergleichsprozess benötigt die Beteiligung von visueller Aufmerksamkeit. Diese wird vom gegenwärtigen Prozess der Auffrischung von Information im VKZG abgezogen, so dass diese Information verloren geht. Das bedeutet, dass nur jeweils ein einziger Vergleich von einem Objekt im VKZG und einem wahrgenommenen Objekt möglich ist.

Schlussbemerkung

Die vorliegende Arbeit zeigt, dass sich Begrenzungen des VKZG nicht in einfacher Weise beschreiben lassen. Zum einen bestehen seine Limitierungen nicht nur, wie gemeinhin angenommen, in der Kapazität oder in einer begrenzten Speicherdauer. Limitierungen sind wesentlich auch auf Bedingungen des Abrufs

zurückzuführen. Zum anderen ist die jeweilige Art der Limitierung von komplexer Art und nur unter Beachtung verschiedener Faktoren zu beschreiben.

Limitierungen in der Speicherdauer können nur in Bezugnahme auf eine weitere Art der Gedächtnisrepräsentation beschrieben werden, nämlich auf die der visuell analogen Repräsentationen. Die Abgrenzung der beiden Speichersysteme ist nur unter Berücksichtigung von Bedingungen des Informationsflusses, wie z.B. Mechanismen des Überschreibens möglich. Die Begrenzung der Speicherdauer hängt zudem von dem aktiven Mechanismus der Aufrechterhaltung oder der Auffrischung der gespeicherten Information ab. Dieser Mechanismus involviert vermutlich visuelle Aufmerksamkeit. Es muss spezifiziert werden, in welcher Weise hier VKZG und Aufmerksamkeit zusammenwirken.

Eine Limitierung in der Speicherkapazität ist ebenfalls nicht einfach durch eine simple und allgemeingültige Angabe der Größe des Speichers zu beschreiben. Obwohl es als erwiesen anzunehmen ist, dass ganze visuelle Objekte die grundlegende Einheit zur Kapazitätsbemessung bilden, so ist die Speicherkapazität dennoch von der Anzahl der zu merkenden Merkmale pro Objekt abhängig. Zudem scheinen die zusätzlichen Speicherkosten je nach Merkmalsdimension verschieden zu sein. Es ist ungeklärt, wie im einzelnen zusätzliche Speicherkosten für die verschiedenen Merkmale und Merkmalskombinationen zu veranschlagen sind.

Auch die Limitierungen des Abrufprozesses sind recht komplex. Der Abruf kann unter Ausnutzung eines Veränderungssignals effektiv vonstatten gehen, wenn es gilt, eine lokale Inkongruenz zwischen im VKZG gespeicherter und wahrgenommener Information auszumachen. Der Abruf ist extrem limitiert, wenn aufgrund multipler Änderungen eine weniger effektive Strategie zur Lösung der Aufgabe eingesetzt werden muss. Möglicherweise muss ein aufwendiger Vergleichsprozess unter Einbezug visueller Aufmerksamkeit herangezogen werden, welche dann nicht mehr für andere Aufgaben zur Verfügung steht. Die Rolle von visueller Aufmerksamkeit beim Abruf von Informationen aus dem VKZG ist nur im Ansatz geklärt.

Im Zuge der vorliegenden Arbeit haben sich komplexe Zusammenhänge zwischen Prozessen des VKZG und der visuellen Aufmerksamkeit gezeigt. Visuelle Aufmerksamkeit scheint entscheidend am Mechanismus der Auffrischung

gespeicherter Information zu sein. Weiterhin ist visuelle Aufmerksamkeit möglicherweise wichtig für Bindungsprozesse im VKZG. Und schließlich wird ihr eine wichtige Rolle beim Abruf von Information aus dem VKZG zugewiesen. Die vorliegende Dissertation konnte Hinweise zur Klärung der Zusammenhänge von VKZG und visueller Aufmerksamkeit liefern. Die weitere und detaillierte Beschreibung und Aufklärung der vielfältigen Beziehungen wird Aufgabe zukünftiger Forschung sein.

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