The boundaries of attention

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Elkan Gamzu Akyürek

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Promotiecommissie:

Promotor: Prof. dr. B. Hommel

Referent: Prof. dr. K. R. Ridderinkhof

Overige leden: Prof. dr. A. H. C. van der Heijden

Prof. dr. K. L. Shapiro

Dr. G. Wolters
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Chapter 1: The boundaries of attention

Introduction

The study of human attention is a major force in cognitive psychology. Attention is a factor in many aspects of cognition and as a consequence, researchers have been studying this broad topic for decades. While attention is a concept that is intuitive and seemingly natural, its science is not without difficulty. In everyday life, there seems to be little mystery associated with focusing one’s attention on reading a letter or watching a car drive by—and switching back between those tasks. It seems equally obvious that some other events are ignored, even if to varying degrees. For example, imagine sitting in an office and someone walks down the corridor past your door. This whole event can be ignored fully if the circumstances call for it (e.g. being hard at work), so that any perception and recollection of the walk-by event does not enter consciousness. At the same time, a tune playing on the radio may be only partially ignored; it does not seem to interfere with any task that is being performed, yet it is also not completely suppressed—there is a sense of music playing and a particular melody may be remembered. In essence then, attention appears to be firmly under our control, at least in most situations. However, there are at least as many instances in which it is not. Attention is not an effortless process, as witnessed when it fails and stray events enter the mind. In such cases we become distracted and unable to focus on the event or task that we had set ourselves to. Why does this happen?

Presumably, the answer to that question has something to do with the (unconscious) analysis of incoming sensory information. Certain properties of this information might determine whether the event attracts attention. If someone gives a firm knock on your office door, the sound is sure to draw attention. The sensory properties of a sudden relatively loud sound in your vicinity indicate at least a salient event and potentially a threat. There is
another reason for this almost automatic response, however. You also possess knowledge about this type of situation; for example that it is customary to knock on someone’s door before entering and that it would not be appropriate to ignore the event and leave the person standing. This knowledge acts together with sensory perceptions, providing a perspective on their importance. The importance of this knowledge-embedded process is illustrated by our uncanny ability to hear our own name being uttered in a conversation that is otherwise drowned out by the noise of a cocktail party. Apparently the reference to our own person carries such great importance that we are able to attend instantly even if the sensory ‘footprint’ of the name is modest.

There are more mysteries to attention than the issue of how and what we attend. Attention is close to consciousness and the ability to remember. Paying attention to something is almost synonymous with being aware of that event. The match is not perfect, however. Awareness extends beyond consciously attended events; you are aware of your surroundings without constantly focusing on individual items in it. In fact, the only instance in which attention might play a role is when something in the environment changes. Change can only be registered if the previous situation is known, so in other words, memory is needed to provide context to perception. Attention also actively modifies the contents of short- and eventually long-term memory. It does so by selecting information to attend to and by determining the amount of time and elaboration it receives. The relationship between attention and memory is by no means exclusive though; various things can be remembered implicitly or without conscious effort. While it is obvious that attending to something will increase the quality and likelihood of remembering it, there are many occasions on which attended events are forgotten anyway and unattended events remembered to a good degree. This latter phenomenon can be cleverly exploited when you’re being accused of not listening to your conversation partner; you’re often able to re-iterate the last few sentences straight
from memory—even though you were in fact distracted at the time they were spoken. This brings up the question of how attention and memory interact to result in such varied performance. To answer questions such as this has been an ultimate goal of psychologists.

**Research on attention and memory**

An effective method of studying attention is to seek out the limits on attention and memory by examining the amount of information that can be processed over fixed time intervals and perceptual domains. In a typical experiment participants are presented with multiple stimuli for limited amounts of time and are asked to identify these as quickly as possible. Indices of the amount of information that is processed are measures of response error rates and reaction times. When the time interval becomes too short or when there are too many events that require attention, reaction times slow and (identification) errors are made.

Of particular interest in the temporal domain is the rapid serial visual presentation (RSVP) paradigm. It entails the presentation of a number of (usually) visual stimuli in rapid succession at rates of 6 to 18 items per second. While it is possible to add a spatial component to the RSVP paradigm, its main strength is the demand it places on the speed of attentional processing. At intervals as short as those used in RSVP, basic cognitive processes like stimulus recognition and identification can produce measurable delays when they are stacked. In turn, delays can lead to increased difficulty with successfully completing aforementioned processes. It is at that point that limits on the amount of information that one can process at any given time can be observed. Figure 1 shows a typical RSVP trial.
Figure 1: Events in an RSVP trial. Time is represented from front to back. Stimulus displays replace each other rapidly (~10 items per second). Target displays are pictured in gray for clarity. The temporal distance between targets is referred to by lag.

Early RSVP studies

One of the first studies using RSVP was done on a tachistoscope by Lawrence (1971). He conducted two experiments, in which participants viewed words flashed briefly after each other. The first experiment compared the identification rate of a single uppercase word amidst lowercase distractor words with a presentation that used simple dots as distractors. The study showed that the presence of an embedding stream of similar items (words) made it much more difficult to detect the target word. Essentially, this means that the visual perception of the target itself does not pose the main bottleneck; it is the process of selecting it among other candidates that does. This form of selection by identification is presumed to require at least some degree of attention. The differentiation between target word and distractors was further reduced in the second experiment. All words were presented in the same way, and the defining feature of the target was of a semantic nature; i.e. the target word was either an animal and the distractors were not or vice versa. Again, difficulty with identifying the target
words was observed. Errors were most frequent when the target was not an animal, presumably because of the skewed set size of these categories (there are more non-animal words than animal words). This result affirms the idea that the identification of the target word requires substantial processing. If this was not the case one would not expect a semantic set size difference to show up.

Subsequent research on target processing in RSVP further examined abstract semantic dimensions of the target item. Schneider & Shiffrin (1977) presented participants with a more complex RSVP sequence of up to four letters and digits per display. Their study revealed an important difference between target-related distractor sets and sets that were unrelated. In Schneider & Shiffrin’s study distractors were always letters, while target items were either digits or letters. In the former case there was no apparent relation between targets and distractors, but in the latter case the targets were drawn from the same range of letters as the distractors and hence considered related. Note that in this condition the actual identity of the target items was defined on a per-trial basis; a target letter on one trial could be a distractor on the next. Clearly different accuracy and reaction time profiles were obtained for related and unrelated conditions in highly practiced subjects. Unrelated sets resulted in little task difficulty and generally high identification accuracy, while related sets proved much more challenging and showed substantial increases in reaction time and decreases in accuracy. As display size was increased and display duration was shortened, difficulty with the related sets became more severe. Schneider and Shiffrin concluded at the time that the unrelated conditions could be performed effortlessly, automatically. This automatic detection was supposedly not sufficient for the related conditions, which required another processing step of controlled serial search. Although the unrelated conditions proved not to be completely insensitive to frame size and duration manipulations and were therefore probably unlikely to
be completely effortless, the general contrast between these two types of detection mode holds virtue.

Schneider and Shiffrin continued to expand their paradigm and added a second target to their presentation. Interestingly, a notable effect of temporal spacing between targets appeared. When targets were presented rapidly after each other, identification rate of both targets was poor. Performance recovered when temporal delay was increased. In line with their previous results, the increased difficulty was most apparent with related sets. The detection of multiple targets and the temporal restraints resulting from this task were eventually to be the focus of a number of studies.

The attentional blink

Initially, the RSVP procedure pointed researchers to an impressive proficiency with detecting and identifying stimuli under adverse conditions, in particular of practiced participants. It is therefore perhaps somewhat paradoxical that a striking limitation of attentional processing has become the most well-known phenomenon in RSVP. This phenomenon is known as the attentional blink (AB). Broadbent & Broadbent (1987) were among the first to specifically demonstrate the phenomenon in their experiments. In their study participants were asked to report two target words within a rapidly presented list of distractor words. When the first of the two targets was detected the chance of also detecting the second target dropped below what would have been expected by chance, but only if the second target followed the first within approximately half a second. Missing the first target resulted in much improved detection of the second target word. These findings lead to the important notion that identifying and reporting a stimulus of some complexity (e.g. not of a binary type) requires a detectable amount of time, during which new input cannot be processed successfully.

Raymond, Shapiro and Arnell (1992) coined the term “attentional blink” in analogy to a blink of the eyelids, which obviously also limits processing by blocking visual input for a
short time. In most of Raymond et al.’s experiments, the second target was a relatively easy letter detection task requiring only a present/absent response. They observed that even under these conditions the detection of the second target was still impaired by the identification of the first. The full extent of the bottleneck caused by the dual-target task remained controversial, however. In Raymond et al.’s task, the present/absent response to the second target required the perception of an “X” among letter distractors. Presumably, some form of in-depth identification of the target was necessary in order to distinguish it from its competitors as the target shares the semantic category and global visual appearance of the distractors. Even if identification of the first target would have been relatively easy, the processing required for the second target might have been more extensive than expected.

**Mechanisms of attention**

Given a challenging amount of information coming in within a sufficiently short time, a processing impairment is not hard to imagine. Beyond that global assessment, it has proved to be quite difficult to localize and define the source of a deficit like the attentional blink in functional terms. In work by Reeves and Sperling (1986), who used a slightly atypical RSVP “attention shift” paradigm for their experiments, the authors argued that the entry of items in visual short-term memory (VSTM) caused a loss of temporal order information. In particular, the quick opening and closing of an attentional gate that allows entry of items into VSTM was considered crucial. The idea of selected input entering short-term memory has remained fairly common, although details of the concept may differ. An example of such a difference is the theory of visual selection proposed by Duncan & Humphreys (1989). Consisting of three components, rather than two (i.e. an attentional gate and memory), the principal feature of the model was that the attentional selection phase was split up between an initial parallel stage of perceptual description and a subsequent (limited capacity) selection process that matches input against internal templates. The third component remained the storage of information in
VSTM. It can perhaps be argued that the initial parallel stage could be matched to a form of sensory storage, as discussed by Phillips (1974). Either way, all of these models conform to a fairly universal structure, in which initially abundant information enters the system, after which a relevant selection is made and subsequently stored. Two hypotheses regarding these models are noteworthy; 1) attention is the process that selects information, and 2) this is where the system is likely to stall when overloaded. If these hypotheses hold true, then a framework for understanding the attentional blink as one of many attentional phenomena emerges.

Whether these hypotheses are valid is a matter of debate, however. Some authors have explained limitations in divided-attention performance by demonstrating the presence of a bottleneck at a stage before the attentional filter. Joseph, Chun & Nakayama (1997) presented participants with a RSVP of black letters that contained a single white target. The second target was a circular array of Gabor items surrounding the central RSVP. All items were oriented in the same way with the exception of one potentially deviating item. Participants had to report the identity of the colored letter and indicate whether a deviating item was present or not. A clear dual-task performance deficit was found. The presence of this deficit is surprising given the supposedly pre-attentive nature of the Gabor patch task—when participants are presented with large sets performance remains constant. When any number of items can be processed at once, a strong case for parallel (not-selective) processing can be made. The presence of an attentionally demanding task should not matter to the limited sensory processing of incoming information, yet the opposite was observed. The authors argued that this result indicates the presence of a bottleneck at an earlier stage than supposed by attentional filter models. Support for this hypothesis was lent by Ross & Jolicœur (1999) who instanced a similarly pre-attentive detection RSVP task and found an attentional blink for color information. However, an alternative account for the results of Joseph et al. could be
given on the basis of findings of Visser, Bischof & Di Lollo (1999). In their meta-study, a number of attentional blink studies were compared and examined for category and task switches. Visser et al. found a positive correlation between the presence of a task switch and the difficulty of target identification. There certainly was a task switch between the identification of the white letter and the detection of an orientation oddball in Joseph et al.’s study. Perhaps it was not the (pre-attentive) task itself that caused the performance deficit, but the need to switch from one task to the other. As this example demonstrates, the debate between competing accounts of attentional processing is not over yet.

A memory bottleneck

The idea that STM (or working memory) is central to many processes including attention is widespread. A demonstration of the interaction between memory and selective attention was given by Downing (2000). He first presented participants with a stimulus that had to be remembered. Then, after a substantial delay, a pair of stimuli was shown, on opposite sides of a central fixation point. One of these matched the memorized stimulus, the other did not. Quickly after that a speeded single-stimulus task was given, such as the detection of motion or a judgment of orientation. This stimulus was presented either on the side of the memorized stimulus or on the opposite side. Participants proved to be faster and more accurate at this task when it was presented on the same side than when it was not. Apparently, the contents of STM guided the allocation of attentional resources to a particular location and facilitated processing there. If the contents of memory are able to facilitate performance in congruent conditions, then impairment in other situations is likely; the link between memory and attention works both ways.

In an elegant experiment by de Fockert, Rees, Frith & Lavie (2001), an increasing load on working memory was shown to impair the ability to ignore distracting stimuli. Their paradigm required participants to memorize a set of digits and to perform a ‘famous name’
classification task in the mean time. During this task, a picture of a famous person was displayed in the background. The picture sometimes was congruent with the name, and sometimes not. After the display of the name and picture a memory probe was presented, requiring a speeded response. When the digit set was difficult (e.g. “3 1 4 2” compared to “1 2 3 4”), and load on working memory was assumed to be high, reaction times to the probe item were slower when a incongruent face was displayed, than when memory load was low. That result suggests that working memory was needed to effectively perform the classification task. As soon as memory was taxed, and fewer resources were available, the guidance of attention deteriorated and performance suffered.

In line with the findings of Downing and de Fockert et al., Vogel & Luck (2002) performed an experiment investigating the link between working memory consolidation and the attentional blink using event-related potentials (ERP). In particular, they studied the P3; the third major positive ERP component, which peaks around 400 milliseconds after stimulus presentation and which is assumed to represent working memory consolidation. The authors measured brain activity during RSVP after the presentation of the second target. In their paradigm, the second target was presented at two points in time; 1) within the stream of items, and 2) at the end of the stream. When a target is presented without an item succeeding it and masking its appearance, no attentional blink is observed. Vogel & Luck observed that the P3 was completely suppressed during the attentional blink, whereas no such pattern was observed in the no-blink condition at the end of the stream. Further specification and support was provided by Kranczioch, Debener & Engel (2003), who observed a P3 for detected targets during the blink-critical period and an absence of it when those targets were missed. The authors argued on the basis of the behavioral outcome and the occurrence of the P3 that the missed targets did not reach memory, whereas the detected targets did.
Given the potential importance of short-term or working memory for attention, its functional structure deserves some description. The capacity of STM can be probed in fairly straightforward ways, for example by first presenting a variable number of stimuli and then examining recall performance at some later point in time. Many experiments have shown that STM capacity is limited; it typically holds only a single-digit number of items, although it may vary slightly per individual and for different types of information (Baddeley, 2000; Luck & Vogel, 1997; Smith & Jonides, 1998). The limits of STM can be shown empirically by decreasing recall performance when the number of items to be remembered is increasing. The logic here dictates that STM can hold only so much and any given item presented that makes the set exceed that limit will lead to one being forgotten. Despite this limitation, the available ‘space’ is used effectively by storing information in chunks. The four digits 1, 9, 7, and 8 can be stored as one chunk, 1978, by thinking of it as a date. Recent experiments by Luck & Vogel (1997) and Vogel, Woodman & Luck (2001) have shown that complex visual objects can be stored in visual working memory for the same ‘price’ as simple (single-featured) objects.

STM does not comprise the total of human memory. Sensory information travels through STM and is tied in with the knowledge and experience that was previously learned. The repository of this sort of information is often referred to as long-term memory (LTM) and provides for an extended context in perception. Naturally, not everything that is perceived activates long-term information in a more elaborate way. It is conceivable, however, that stimuli that are attended and that enter consciousness do. The interaction of LTM and conscious processing has been hypothesized to be short-term memory. In this way, LTM and STM combined provide a fluid semantic interaction between conscious experience and sensory impressions. The link between attention, temporary storage and LTM within
working memory has been modeled somewhat more explicitly by Baddeley (2000). Figure 2 shows his multi-component model of working memory.

Figure 2: The multi-component model of working memory, adapted from Baddeley (2000). Unshaded components accommodate fluid cognitive capacities like attention and temporary storage.

The multi-component model of memory features a clear distinction between crystallized (gray) and fluid (white) components of memory. While long term storage is considered to be fairly static, the components of memory that are generally considered to form working memory are all fluid cognitive systems, and as such involved in temporal storage and attention. If STM is indeed closely tied to conscious processing, or attention, then it could theoretically be possible to manipulate its contents and by doing so influencing the process of attention itself. There are several ways to implement such manipulations, focusing on different aspects of STM. Examples of these aspects are memory processing modes like retrieval, consolidation and updating, and specific memory subsystems such as the phonological loop.
A response-selection bottleneck

An alternative account of the limits of attention can be given that roughly holds that the problem does not lie with visual processing or memory storage alone, but also with the selection of the appropriate response to a stimulus. Pashler (1989; 1991) proposed a two-component model of divided attention. The first component consisted of general visual processes that can occur largely in parallel that do show mutual interference, while the second component was the response selection stage, which required discrete queuing and formed a bottleneck in the system. In a series of experiments, Pashler used a relatively easy tone-discrimination task that preceded a more complex second task. The stimulus onset asynchrony (SOA) between tasks was varied to examine dual-task costs. He found large intertask interference with short asynchronies only when the response to the second task was speeded, highlighting a bottleneck at the response stage since the interference was absent when the response to the second task could be made at leisure. When the first task was a more complex visual one (like the second), interference was present regardless of response modes. The interference in this condition was attributed to the visual processing stage of the two-component model. Some caution should be taken with the interpretation of these results, however. It has been shown that the response selection bottleneck may be specific to the psychological refractory period (PRP) paradigm that Pashler and others have used and that other dual-task paradigms may produce different sources of task interference (Arnell, Helion, Hurdelbrink & Pasieka, 2004).

An alternative framework

It is possible to think about attention from a slightly different perspective. The theory of event coding (TEC; Hommel, Müsseler, Aschersleben & Prinz, 2001) attempts to sketch a general framework for perception and action, and it does so primarily by defining both feature codes and event files. A feature code is a representation of distal properties of an event that is not
Chapter 1

necessarily limited to a sensory percept. A feature code may be an action affordance ("can-be-grasped"), or a specific tone of red ("crimson"). The TEC emphasizes a common coding system that bridges sensory and motor systems, which is potentially relevant to the issue of memory and response-related processing (Hommel, 2004). The integration of feature codes is the important second step in the model. One might imagine a bunch of feature codes activated at a particular moment in the mind. For example “red”, “roundish”, and “fruit”—this set may well pose a perceptual problem if the environment contains both an apple and a cherry. With just these feature codes being activated, there is no way of knowing which feature belongs to which actual object. In order to obtain this knowledge, features have to be integrated into more meaningful events representations (e.g. “apple”, “cherry”). The combination of feature codes into event files is not just a second step in the process; it also means that feature codes behave differently when bound together in an event file. The TEC is in a way an extension of the binding theory proposed by Treisman and others (e.g. Kahneman, Treisman & Gibbs, 1992; Treisman, 1996). Although the latter was mostly involved with perception alone, the general idea that simple properties are integrated into meaningful wholes is similar. While the TEC and the binding theory were not specifically formulated in the context of the attentional blink, their common framework could apply in this domain as well.

Allowing for differences in terminology, the TEC and the binding theory are consistent with the two-stage model of the attentional blink, detailed (amongst others) by Chun & Potter (1995). The first stage in this model is a rapid detection of incoming stimuli. By nature, the processing in this stage is only sufficient to allow for selection of relevant (target) stimuli on the basis of feature cues such as color or outline. In essence then, this stage is reminiscent of the loose feature codes activated in the binding models. The second stage of Chun & Potter’s model is a form of capacity-limited processing. In this stage, the representations from the earlier processing operations are transferred to a more durable type.
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This transfer is assumed to require additional processing and result in full stimulus identification and consolidation. Again, these concepts are conceptually not far from integrated events. The second stage is presumed to be the locus of the bottleneck associated with dual-task performance, although it should be noted that this is not necessarily equated to either selection or consolidation. One instance of support for the two-stage model was provided by a study of Arnell & Jolicœur (1999), in which cross-modal stimuli were used and a central limitation to attention was proposed. The authors argued that the limitation was due to a post-perceptual stage of processing, similar to the second stage of the Chun & Potter model (although with more emphasis on the consolidation of information). Taking that post-perceptual stage of integrated events one step further, it is conceivable that this stage can be thought of as a specific form of memory that might well incorporate response codes. Doing so would bridge considerable distance between the models of attention presented above.

The suggestion of convergence is of a primarily conceptual kind. Defining different types of models can be helpful to theorize about particular phenomena in the study of attention, yet in practice bits and pieces of each have often been blended together in the literature (e.g. Shapiro, Raymond & Arnell, 1994). In this thesis, an attempt will be made to maintain specificity derived from separate models while integrating their ideas on a loosely compatible level.

Outlook

In the context of the array of ideas about visual attention and dual-task performance discussed above, the following chapters are dedicated to testing a select set of model-derived predictions. Chapters 2 and 3 are centered on the relation of short-term memory and attention. A number of experiments are reported that vary demands on memory and attention in a combined multi-task paradigm. In chapters 4, 5 and 6 attentional performance within the attentional blink task is examined, in an attempt to characterize the different phases in the
process. Early processes that are triggered at the onset of target stimuli are studied as well as late processes that involve meta-knowledge about experimental tasks. The final experimental chapter 7 deals with the impact of response factors by using a partially speeded RSVP design. Taken together, the experimental chapters provide various insights about the topics of attention and memory, which are summarized in chapter 8.

The experimental chapters in this thesis are based on manuscripts that are accepted by or are (to be) submitted to international refereed journals. To acknowledge the important contributions of co-authors, a reference list is provided below.


In addition, although not included as a separate entity, some ideas discussed in this thesis were inspired by the following manuscript:

Chapter 2: Short-term memory and the attentional blink:

Capacity versus content

When people monitor the Rapid Serial Visual Presentation (RSVP) of stimuli for two targets (T1 and T2), they often miss T2 if it falls into a time window of about half a second after T1 onset, a phenomenon known as the Attentional Blink (AB). We found that overall performance in an RSVP task was impaired by a concurrent Short Term Memory (STM) task, and furthermore that this effect increased when STM load was higher and when its content was more task-relevant. Loading visually defined stimuli and adding articulatory suppression further impaired performance on the RSVP task but the size of the AB over time (i.e., T1-T2 lag) remained unaffected by load or content. This suggested that at least part of the performance in an RSVP task reflects interference between competing codes within STM, as interference models have held, while the AB proper reflects capacity limitations in the transfer to STM, as consolidation models have claimed.

Introduction

Human attention is limited: with respect to space, a broadly investigated dimension, and with respect to time, as demonstrated in tasks with a Rapid Serial Visual Presentation (RSVP) of stimulus sequences. When people monitor a visual stream for two targets (T1 and T2), they often miss T2 if it falls into a time window of about 100-600 msec after T1 onset (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). In analogy to an overt blink of the eyes, Raymond et al. have coined this insensitivity to the second of two sequential targets an Attentional Blink (AB).

Available accounts of the AB have linked the effect to short-term memory (STM). Consolidation models assume that to report a target its sensory representation needs to be consolidated into STM, which requires the allocation of attentional resources (Chun & Potter, 1995; Jolicœur, Dell'Acqua, & Crebolder, 2000). If resources are allocated to consolidating T1—to a degree and duration that depends on how severely T1 is masked by following
items—fewer resources are left to consolidate T2. This makes T2 codes vulnerable to inhibition from other items competing for access to STM, so that it is less likely to be maintained and reported later on. From a slightly different perspective, interference models assume that it is not the transfer of sensory codes to STM that provides the bottleneck but, rather, the competition between candidate items within STM for being selected for action control (e.g., Duncan, Ward, & Shapiro, 1994; Shapiro & Raymond, 1994). Items are thought to be encoded in STM if they match the template representing the current selection goal, where they receive selection values reflecting that degree. The item with the highest value is then selected for action control, such as verbal report. As T1 will always receive a high value, T2 is likely to lose the competition for selection against T1 and/or distractor items that erroneously received high selection values by virtue of appearing briefly before or after T1—at least if T2 appears before the selection of T1 is completed.

In view of the strong emphasis available models place on STM we asked in the present study whether RSVP performance and the AB in particular would be affected by the content and load of STM induced by a concurrent task. Accordingly, we embedded standard RSVP trials into an STM task in which we had participants retain varying numbers of items. Moreover, as interference models assume that competition within STM is modulated by similarity (with more similar items being thought to compete more strongly: cf., Raymond, Shapiro, & Arnell, 1995; Shapiro & Raymond, 1994), we loaded STM with various types of items: items that were taken from the same category as either the targets or the distractors of the RSVP task, or items that were unrelated to that task.

From a consolidation point of view, one might speculate that consolidating sensory traces into STM gets more difficult, or takes longer, the more filled-up STM already is. This would be expected to decrease performance overall but to affect the AB (i.e., the performance drop at lags of 100-600 msec) in particular, because the more attentional resources are
allocated to T1 processing the less is available to consolidate T2 before it decays. In contrast, the way STM is filled-up (i.e., which kind of items STM contains) should not play a major role, so that an impact of STM-item type would not be expected. Interference models assume that competition increases with the number of items in STM, suggesting again that performance in general, and around lags of 100-600 msec in particular, decreases with an increasing number of items in the STM task. Moreover, given their reliance on similarity, interference models strongly suggest that such decrements vary with the similarity between the RSVP target set and the item set of the STM task. If so, load effects should be more pronounced if STM items match the category of T1 and T2 in the RSVP task. By contrast, finding no effect of increasing secondary task difficulty would point to a multiple-channel processing mechanism (Awh, Serences, Laurey, Dhaliwal, van der Jagt & Dassonville, 2004).

**Experiment 1**

In Experiment 1 we asked participants to identify and report two digits (T1 and T2) presented within a stream of letter distractors. Before each RSVP stream a memory set containing 2, 4 or 6 items was presented, and this set was probed after the RSVP stream. In different conditions, the set comprised (a) symbols that were unrelated to the AB task; (b) letters, i.e., items from the same category as RSVP distractors (although set members never matched any actual distractor of a given trial); and (c) digits, i.e., items from the same category as targets of the AB task (although, again, set members never matched any actual target of a given trial). These conditions allowed us to assess the effects of absolute STM load and the content of that load separately.
Chapter 2

Method

Design

Experimental and analytical variables of the 4x3x3 mixed factorial design were T2 lag (1, 3, 5, or 8), STM load (2, 4, or 6 items), and STM content (neutral, distractor-related, or target-related). Lag and load was varied within, and content was varied between participants. Dependent measures were accuracy on the STM task, accuracy on T1, and conditional accuracy on T2 (T2|T1).

Participants

A total of 90 students participated for pay, 30 in each STM-content group. They reported having normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Apparatus and procedure

Participants were seated behind a standard PC in a small, dimly lit cubicle. Stimuli were presented using the E-Prime© experimental software package on a 17" monitor, refreshing at 85Hz. Viewing distance was not strictly fixed, but amounted to about 50 cm. Each participant completed 288 experimental and 32 practice trials, which took about 1h. Instructions emphasized performing both the STM and the RSVP task as accurately as possible.

Trials were self-paced and began with the presentation of 2, 4, or 6 STM items for 1,000 msec. Neutral STM items were taken from a set of symbol characters ("!", "@", ",#", "$", ",%", ",^", ",&", and ",*"). Distractor-related STM items were chosen from a random set of uppercase letters, and target-related STM items were randomly chosen digits. In order to equate set sizes to the eight-symbol pool used in the neutral condition, the other two sets were constructed in a similar fashion. STM letters were randomly selected from the eight letters left after filling the RSVP stream (26 letters in total, minus 18 for the RSVP task). The set of possible STM items in a trial consisted of the six digits that remained after selecting the two
RSVP targets (8 in total, minus 8) plus the two digits not used in the RSVP task, 0 and 5. Due to this procedure, STM items never appeared in the RSVP task in the same trial. The current STM set was presented in a row centered on the screen.

After a delay of 2,000 msec, a fixation mark (+) appeared for 200 msec in the center of the screen, followed by the RSVP stream. The stream consisted of 2 targets and 18 distractors. Each item appeared for approximately 59 msec, followed by a 35 msec blank (five and three screen refreshes, respectively). T1 appeared as the $7^{th}$, $8^{th}$, or $9^{th}$ item of the stream, randomly chosen. T2 appeared with a lag of 1 (i.e., as the next item), 3, 5, or 8 items. Lag 8 was specifically chosen so as to fall outside the critical AB interval of about half a second, so that performance on this lag can be taken to represent baseline level¹. Target items were always digits (1-9 excluding 5) and distractor items were always capital letters. Items were randomized except that they never appeared twice in the same trial. A further constraint was that response category (being even or odd) was evenly distributed across trials. Both STM and RSVP items were presented in 16pt. Times New Roman font in black (RGB 0, 0, 0) on a gray (RGB 128, 128, 128) background.

After the offset of the RSVP stream and a 1,000-msec blank interval a single item was presented for 1,000 msec to assess STM performance. Depending on the content group, this was a symbol, a letter, or a digit that had a 50% probability of being part of the STM set for that trial. After another 500-msec delay a response screen appeared, prompting an unspeeded yes (was part of the set) or no (was not part) decision by pressing the "J" or "N" key of the computer keyboard. Then participants were to indicate at leisure whether T1 and T2 were even or odd by using the "E" and "O" keys. Thus, chance level for the STM task as well as T1 and T2 was 50%. The instructions of the experiment stressed the importance of accuracy on each dependent variable and explicitly discouraged 'strategic' response modes focusing on a specific part of the task.
Chapter 2

Results and discussion

A significance level of $p < .05$ was adopted for all analyses, Greenhouse-Geisser adjusted wherever appropriate. First we analyzed performance in the STM task. Accuracy varied with T2 lag, $F(2.8,240.1) = 3.17$, $MSE = 0.0041$, $p < .05$, STM load, $F(1.9,162) = 168.89$, $MSE = 0.0080$, $p < .001$, and STM content, $F(2.87) = 22.95$, $MSE = 0.0547$, $p < .001$. Load and content were also involved in a two-way interaction, $F(2.174) = 40.02$, $MSE = 0.0075$, $p < .001$.

The lag effect reflected a slight drop in performance if T2 appeared with the longest lag (88.6%, 88.4%, 89.3%, and 87.7% for lag 1, 3, 5 and 8), presumably due to the fact that the longest lag between T1 and T2 implies the shortest interval between T2 storage and STM test, that is, the shortest time to consolidate T2. Importantly, however, performance for two STM items was very good and about the same in all three groups, suggesting that the participants were motivated and comparable². The interaction between load and content indicated that in correspondence with the purpose of the load manipulation, accuracy decreased with an increasing number of items, but this decrease was more dramatic with abstract symbols, as can be seen from Table 1.
Table 1. Mean STM performance in Experiment 1 in percent correct as a function of STM content, STM load (number of items), and temporal lag between T1 and T2.

<table>
<thead>
<tr>
<th>Content</th>
<th>Load</th>
<th>Lag 1</th>
<th>Lag 3</th>
<th>Lag 5</th>
<th>Lag 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>symbols</td>
<td>2</td>
<td>93.5</td>
<td>93.6</td>
<td>94.9</td>
<td>93.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>79.2</td>
<td>81.1</td>
<td>81.0</td>
<td>81.0</td>
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<tr>
<td></td>
<td>6</td>
<td>72.8</td>
<td>69.9</td>
<td>72.4</td>
<td>68.1</td>
</tr>
<tr>
<td>letters</td>
<td>2</td>
<td>94.3</td>
<td>93.6</td>
<td>95.3</td>
<td>92.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>94.3</td>
<td>92.9</td>
<td>93.3</td>
<td>92.1</td>
</tr>
<tr>
<td></td>
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<td>86.3</td>
<td>86.9</td>
<td>89.3</td>
<td>88.8</td>
</tr>
<tr>
<td>digits</td>
<td>2</td>
<td>94.4</td>
<td>95.7</td>
<td>94.4</td>
<td>94.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>94.4</td>
<td>93.8</td>
<td>93.3</td>
<td>92.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>87.9</td>
<td>88.1</td>
<td>90.1</td>
<td>87.5</td>
</tr>
</tbody>
</table>

Performance on T1 depended on lag, $F(2.3,201.5) = 119.09$, $MSE = 0.012$, $p < .001$, load, $F(2,174) = 7.79$, $MSE = 0.0071$, $p < .001$, and content, $F(2,87) = 3.60$, $MSE = 0.106$, $p < .05$. Figure 1 shows mean T1 response accuracy in all conditions.

Figure 1: Percentage correct (+/- 1 SE) of the first target, as a function of STM content, STM load, and T2 lag in Experiment 1.
The lag effect indicated that performance was particularly poor at Lag 1 compared to the other lags. This is a familiar effect—at least in RSVP tasks where T1 and T2 are defined according to the same selection criteria (thus enabling direct competition)—that is likely to reflect an attentional trade-off with T2 (Hommel & Akyürek, in press; Potter, Staub, & O'Connor, 2002). The load effect showed that T1 accuracy was worse the more items were to be maintained in STM (83.0%, 81.6%, and 80.5%, with 2, 4, and 6 STM items, respectively). The content effect was due to better performance if the STM task used neutral symbols than if letters or digits were used.

Our central measure, conditional T2 accuracy, showed a significant effect of T2 lag, $F(2.6,225.7) = 38.82$, $MSE = 0.0139$, $p < .001$, reflecting a standard AB with the typical dip in between Lag 1 ("Lag-1 sparing": Chun & Potter, 1995; Potter, Chun, Banks, &
Muckenhoupt, 1998; Potter et al., 2002) and longer lags (see Figure 2). The lag effect was small, presumably due to the rather high 50% chance level, but robust: e.g., it survived dropping a random 50% of the participants, $F(3,132) = 7.17, MSE = 0.0072, p < .001$. Further main effects were obtained for STM load, $F(2,174) = 10.17, MSE = 0.0056, p < .001$, and STM content, $F(2,87) = 4.17, MSE = 0.113, p < .05$, which were both involved in an interaction that was marginally significant, $F(4,174) = 2.35, MSE = 0.0056, p < .06$. As Figure 2 shows, performance on T2 decreased with increasing STM load (86.4%, 85.5%, and 83.9%, for 2, 4, and 6 items, a linear trend, $F(1,87) = 20.42, MSE = 0.0055, p < .001$), and this effect tended to be most pronounced with the target-related STM set. T2 performance was also better with neutral STM items (89.4%) than with distractor- or target-related items (83.4% and 82.9%). Of particular interest for our purposes, there was no evidence that any of the above or other effects depended on lag, all $F$’s $< 1$. To be certain that there were no isolated interactions of lag and load within the content groups, we looked at these separately and found no significant interactions there either, $p > .24$. We also checked whether the opposite roles of neutral items (impairing STM performance but facilitating T2 report) might indicate a trade-off. This can be ruled out, however, as the correlations between overall performance in the two tasks were positive in all three content groups (for symbols $r^2 = .42, p < .05$, for letters $r^2 = .54, p < .001$, and for digits $r^2 = .40, p < .05$). Furthermore, content affected T2 report significantly even in the 2-item condition, $F(2,87) = 3.48, MSE = 0.0393, p < .05$, where STM performance was the same for all contents, $F(2,87) < 1$.

To summarize, Experiment 1 produced three results of theoretical relevance: (1) Performance on T2 decreased with increasing memory load and (2) did so depending on task relevance of the memory set, but (3) neither of these effects interacted with lag.

Interference models have assumed that the AB reflects interference in STM (Duncan, Ward, & Shapiro, 1994; Shapiro & Raymond, 1994), which in the present context suggested
two predictions: First, performance on T2 should decrease under conditions that are likely to increase competition in STM. Experiment 1 showed performance to be impaired as STM load increased and/or as STM content was more task-relevant and, thus, was more easily confused with targets in the RSVP task. However, a second, related prediction is that the degree of competition in STM should be particularly important for the time interval following T1 presentation. For instance, Shapiro and Raymond (1994) assumed that T2 processing is affected by competition with other elements in STM for only about half a second from T1 appearance on. Statistically, this amounts to an interaction of competition-inducing variables (here: STM content and load) with lag, and this is an effect that we did not observe in Experiment 1. This might indicate that interference models are correct to assume that competition in STM affects T2 processing but may be insufficient to account for the drop of T2 performance at short lags, hence, the AB proper. However, as this conclusion was based on a null effect, that is, on the absence of an interaction, we sought converging evidence in two additional experiments.

Experiment 1 used alphanumeric stimulus materials in both the RSVP and the STM tasks, that is, material that could be coded visually as well as verbally. This might have introduced the possibility for participants to code STM and RSVP items in different ways, thus eliminating crosstalk. In a way, the fact that we obtained main effects of STM content and STM load speaks against the possibility that participants had coded the stimuli differently in the two tasks (e.g., verbally in the STM task and visually in the RSVP task), which would have eliminated mutual interference, e.g., by running the STM task in the phonological loop (Baddeley, 1986) and the RSVP task in visual STM (Logie, 1995). This means that the absence of a load-by-lag interaction is unlikely to be the result of differential-coding strategies. Moreover, if that were to have happened, one would expect less interference for the easier to name letters and digits than for the symbols. If anything, however, RSVP
The boundaries of attention

performance was affected more by letters and, in particular, by digits as STM items than it was by symbols. Thus, the two tasks must have shared some sort of processing resources (as the consolidation approach suggests) and/or have suffered from some sort of direct cross talk (as the interference approach suggests). And yet, we thought it would strengthen the case against the interference account of AB if we were able to replicate the null interaction between lag and load under conditions that minimize the opportunity to code STM items and RSVP targets differently.

**Experiment 2**

In Experiment 2 we employed arbitrary, meaningless visual symbols that were unlikely to invite verbal coding. Previous studies have shown that substantial ABs can be obtained with nonverbal material, such as symbols (<, >, #, %, ?, /, and *: Chun & Potter, 1995), visual patterns (Kellie & Shapiro, 2004), meaningless visual shapes (Chun & Jiang, 1999; Raymond, 2003), colors (Ross & Jolicœur, 1999), and time intervals (Sheppard, Duncan, Shapiro, & Hillstrom, 2002). Here we used “letters” from two “Star Trek” alphabets (see Figure 3). To the degree that the absence of load-by-lag interactions in Experiment 1 was due to differential coding (verbal vs. visual) in the RSVP and the STM task, preventing differential coding in Experiment 2 by eliminating the verbal option should yield a substantial interaction.

**Method**

Another 46 students participated for pay or course credit. The method and procedure were as in Experiment 1, with the following exceptions. The STM content variable was dropped; only target-relevant STM items were used. STM load was reduced to 1, 2 or 3 items, because pilot runs indicated that the new stimuli made the task much more difficult—so difficult that performance often dropped to near chance level with the original set sizes of 2, 4 and 6 items. The visual symbols serving as both STM items and targets for the RSVP stream consisted of
a set of 10 letters from the "Cardassian alphabet" used in the fictional "Star Trek" television series (taken from [http://www.voyager.fsworld.co.uk/voyfont.htm](http://www.voyager.fsworld.co.uk/voyfont.htm)). These symbols were chosen because they have no apparent meaning, yet do offer a letter-like appearance and a suitable variety at the same time. As in Experiment 1, a symbol never appeared both in the STM and the RSVP task on any given trial. The distractors of the RSVP stream were selected from a set of 26 letters from the "Klingon" font of the Star Trek series. Both complete symbol sets are shown in Figure 3.

![Figure 3: Complete symbol set used in Experiment 2; STM/RSVP target set on top, RSVP distractor set below.](image)

The inter-task interval was eliminated to save session time, a modification that according to pilot testing did not affect task performance. Thus, the RSVP stream started off immediately after the STM set had been presented. Each symbol in the stream was presented for 75 msec, followed by a 50 msec blank. T2 appeared with a lag of 1, 2, 3, 4, 5, or 8 items. The background color was changed from gray to white, to increase the discriminability of the stimuli. Font size was set to 24pts with spacing proportional to Experiment 1, to ease identification of the symbols. After the offset of the last RSVP symbol a 250 msec blank interval ensued, followed by the presentation of the STM probe for 1,000 msec. After another 250 msec participants were prompted to judge whether the probe was part of the STM set. Then, participants were asked to identify the RSVP targets by pressing the corresponding keys on a re-labeled keyboard. As a result of changes in the tested conditions, the total number of trials for each participant was 232, 16 of which were practice trials and not included in the analyses.
**Results and discussion**

Performance on the STM task showed a main effect of load, $F(1.7,75) = 219.03$, $MSE = 0.0242$, $p < .001$, similar to that found in Experiment 1: Accuracy was best with one item, followed by two and three items. The interaction of lag and load also proved to be significant, $F(10, 450) = 2.20$, $MSE = 0.0129$, $p < .05$. While load tended to have a linear impact on performance, the 2-item load condition showed some fluctuation. Performance on Lags 1, 3 and 5 was slightly better than on Lags 2, 4 and 8. The relevant means are shown in Table 2.

Table 2. Mean STM performance in Experiment 2 in percent correct as a function of STM load (number of items) and temporal lag between T1 and T2.

<table>
<thead>
<tr>
<th>Load</th>
<th>Lag</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>8</th>
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</thead>
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<tr>
<td>2</td>
<td></td>
<td>89.1</td>
<td>89.7</td>
<td>88.0</td>
<td>89.9</td>
<td>91.3</td>
<td>88.4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>78.8</td>
<td>71.4</td>
<td>78.1</td>
<td>72.6</td>
<td>78.8</td>
<td>71.6</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>62.1</td>
<td>64.9</td>
<td>63.9</td>
<td>66.1</td>
<td>64.1</td>
<td>63.8</td>
</tr>
</tbody>
</table>

T1 and T2 responses were scored as correct whenever the identity of the respective target was retained, independent of the order of report—a procedure that has the advantage of being consistent with common scoring practice in AB research but the disadvantage of ignoring the possible loss of order information (Hommel & Akyürek, in press). Note that this method of analysis is not meaningful for binary category judgments as used in Experiment 1, because identical responses cannot be ordered. Since experiments 2 and 3 (see below) did require full target identification, the same method was used for both. In addition, we ran control analyses with identity and order as accuracy criteria and found the pattern of outcomes more or less unchanged, especially with regard to the crucial interactions involving load and lag.
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T1 performance (see Figure 4) was affected by main effects of T2 lag, $F(5,225) = 17.63$, $MSE = 0.021$, $p < .001$, and STM load, $F(2,90) = 10.81$, $MSE = 0.028$, $p < .001$. The lag effect reflected a drop of performance on T1 at Lag 1, just as in Experiment 1 (cf., Hommel & Akyürek, in press; Potter et al., 2002). The load effect indicated better performance when one item (64.3%) than when two (58.2%) or three (59.1%) items were to be retained. The difference between conditions here was not very large, but may still suggest that more effort is needed to identify a target when the STM load is more than a single item.

![Figure 4: T1 performance in Experiment 2 as a function of T2 lag; separate lines represent different STM loads.](image)

Our crucial measure was again T2 performance, contingent on T1 (see Figure 5). As expected, lag had a significant effect, $F(4,179) = 35.97$, $MSE = 0.053$, $p < .001$, which represented a typical AB with performance dipping as low as 33.1% at Lag 2 and recovering
to 62.1% at Lag 8. There was also a hint of Lag-1 sparing, but it was a modest difference at best. A possible explanation for this small sparing effect may be the fact that both target discrimination (from the stream) and identification must have been much more difficult than in a usual RSVP task, which again is likely to motivate the investment of more attentional resources into T1 processing—leaving less for T2 to take advantage of the close temporal distance. T2 performance also decreased with increasing STM load (48.6%, 45.0%, and 44.7%), $F(2,90) = 3.77$, $MSE = 0.034$, $p < .05$—a linear trend, $F(1,45) = 5.87$, $MSE = 0.035$, $p < .05$. The most important outcome is, however, that the interaction between lag and load was far from significance, $p > .58$, and even the qualitative pattern does not suggest that shorter lags would be more affected by STM load than longer lags. In fact, all three load functions were more or less parallel across lags.

Figure 5: Experiment 2: T2 performance (given T1 correct) as a function of T2 lag; separate lines represent different STM loads.
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To summarize, Experiment 2 showed that even if both the STM and the RSVP task require visual encoding (since there are no preexisting phonological representations for the stimuli that were used), the impact of STM load did not increase with decreasing lag. This was true in spite of the visual task being much more difficult for participants to perform accurately (therefore leaving more room for error). Thus, Experiment 2 provided further evidence that there is no impact of STM load on the RSVP task that interacts with lag. However, two concerns with Experiment 1 were not addressed; 1) the magnitude of the AB was rather modest, possibly reducing the chance of finding additional modulation, and 2) the limited impact of increasing load on STM accuracy, which could mean that STM was not fully taxed. In Experiment 3 we attempted to address these two remaining while employing a manipulation similar to the one in Experiment 2 concerning encoding strategy. This was done by using the same stimulus set as in Experiment 1 but combining the hybrid RSVP-STM task with a third, verbal suppression task that should prevent verbal coding in both the RSVP and STM tasks.

Experiment 3

Method

Forty new participants took part in the experiment for pay or course credit, 20 in the suppression group and 20 in the no-suppression group. The procedure was almost identical to the target-related condition of Experiment 1 with the addition of the articulatory suppression variable. The differences in procedure included changing the RSVP task to full target identification instead of a category judgment and using the inter-task intervals from Experiment 2. Participants in the articulatory suppression group were required to repeat the word "Maandag" (Monday) out loud during each trial.
Results and discussion

The data were analyzed as a function of T2 lag, STM load, and verbal suppression. STM performance depended on lag, $F(3,114) = 4.55, \text{MSE} = 0.0037, p < .005$, and load, $F(1.7, 64.9) = 115.5, \text{MSE} = 0.0203, p < .001$. The lag effect was again limited to a very slight (~2%) drop at the longest lag, that is, when the time to consolidate was shortest (means of 77.7%, 77.9%, 78%, and 75.5%, for the four lags). As intended, increasing the number of STM items made the task more difficult (88.6%, 77%, and 66.2%, for loads of 2, 4, and 6 items, respectively). The suppression variable was also significant, $F(1,38) = 20.36, \text{MSE} = 0.108, p < .001$, as was its interaction with load, $F(2,76) = 5.62, \text{MSE} = 0.0174, p < .005$. The complete set of means is given in Table 3.

Table 3. Mean STM performance in Experiment 3 in percent correct as a function of verbal suppression, STM load (number of items), and temporal lag between T1 and T2.

<table>
<thead>
<tr>
<th>Suppression</th>
<th>Load</th>
<th>Lag 1</th>
<th>Lag 3</th>
<th>Lag 5</th>
<th>Lag 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>2</td>
<td>83.9</td>
<td>85.3</td>
<td>86.4</td>
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<td></td>
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<td>74.6</td>
<td>74.2</td>
<td>74.7</td>
<td>74.4</td>
</tr>
</tbody>
</table>

Unsurprisingly, articulatory suppression added to task difficulty, suggesting an increase of stimulus- and load-independent task-coordination costs (Miyake, Emerson, Padilla, & Ahn, 2004). The finding that suppression also produced what seems to be a slight increase of the load effect needs to be taken with caution, however: This interaction was entirely due to a modest reduction of the suppression effect with the lowest load, while the two conditions with higher loads were equally affected by suppression—a pattern that looked very much like a ceiling effect.
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T1 performance varied with lag, \( F(3,114) = 21.7, \text{MSE} = 0.005, p < .001 \), due to a drop in performance at Lag 1 (see Figure 6). As in Experiment 1, the competition between T1 and T2 at this lag was somewhat biased towards T2 at the expense of T1 identity, presumably because our targets were again defined according to the same selection criteria. There was also a main effect of load, \( F(2,76) = 8.78, \text{MSE} = 0.011, p < .001 \), replicating the findings from Experiments 1 and 2. Interestingly, this load effect was modified by suppression, \( F(2,76) = 6.56, \text{MSE} = 0.011, p < .005 \). As Figure 6 shows, articulatory suppression reduced the overall performance and leveled out the load effect. Hence, even if the small load effect obtained in Experiments 1 and 2, and in the present no-suppression group, could be taken to point to the use of verbal-coding strategies in the STM task, no such hint remained in the suppression group.

**Figure 6: T1 performance in Experiment 3 as a function of T2 lag for each STM load. Left pane shows performance with articulatory suppression, right pane shows performance without.**
Conditional T2 performance yielded the usual main effect of T2 lag, \( F(1.8,68.5) = 40.7, \text{MSE} = .04, p < .001 \), showing a standard, AB-type dip at Lag 3 and Lag-1 sparing, shown in Figure 7. The interaction of load and suppression, \( F(2,76) = 2.61, \text{MSE} = .011, p < .08 \) was marginally significant, which reflected a similar pattern as obtained for T1 performance. Most importantly, there was no hint of any interaction involving lag, \( p > .57 \), despite the rapid decline in STM performance observed with increasing load, which suggested that STM capacity was at its limit. Since no main effect of load or suppression was significant, a separate analysis on the no-suppression group was done that showed a main effect of load, \( F(1.4,27.4) = 3.94, \text{MSE} = 0.0151, p < .05 \), thus replicating the previous experiments. Mean
percent correct went from 85.8% to 82.1% and finally to 81.6% for loads of 2, 4 and 6 items, respectively.

Compared to Experiment 1, the concerns regarding AB magnitude and the difficulty of STM load increase were successfully addressed. A blink of sizeable proportion was obtained and STM performance decreased steadily with increasing load—an indicator of task difficulty. At the same time, the pattern of results remained similar. T2 lag and STM load had effects similar to those observed in the experiments described above; and again an interaction between them did not show up. One additional observation concerned the reduced impact of STM load on T1 and T2 accuracy in the articulatory suppression condition. While somewhat mysterious at first glance, this phenomenon could be explained by assuming that a performance floor level was being reached. Suppression caused substantially lower RSVP performance, which in turn can have lead to reduced room for additional variance as participants coded stimuli with reduced but stable efficiency. In sum, Experiment 3 provided additional support for the conclusions tentatively drawn in Experiments 1 and 2.

**General discussion**

Though for different reasons, interference and consolidation accounts of AB have suggested that performance in a RSVP task is hampered by a concurrent STM task. In the current studies, STM load impaired both T1 and T2 report, and it did so with both alphanumeric stimuli and meaningless symbols. This provided strong evidence that the STM task and the RSVP task shared some sort of processing resources (as the consolidation approach suggests) and/or suffered from some sort of cross talk (as the interference approach suggests).

A second important observation is that both T1 and T2 performance were affected by the task-relevance of STM items: memorized items belonging to the same category as RSVP distractors or targets hampered performance more than neutral items did. This is inconsistent with a pure capacity approach, unless one assumes that maintaining overlearnt digits and
letters requires more capacity than maintaining abstract symbols. But this assumption received little support from STM performance which, instead, provided evidence that symbols were the most difficult items. Given that consolidation approaches have not much to say about what goes on after consolidation has taken place, we hesitate to consider the observation of content effects as necessarily incompatible with such an approach. What is clear, however, is that such effects provide ample support for the general assumptions of the interference approach that 1) RSVP performance reflects competition between pre-selected event codes and 2) the degree of competition depends on similarity between the codes involved (or their match with the template used for pre-selection). Moreover, the finding that category relations were sufficient to induce competition is consistent with Isaak, Shapiro, and Martin's (1999) claim that what counts most is similarity defined at a conceptual or categorical, but not purely visual, level—even if our findings did not show that physical similarity has no impact.

Although we hesitate to draw strong conclusions from the marginally significant interaction between content and load on T2 performance in Experiment 1, we do point out that this tendency is also consistent with an interference approach. In most RSVP tasks both targets and distractors are repeated over and over again which should lead to a strong priming of their codes above their normal base level. Moreover, as target codes receive both bottom-up activation from the target stimuli presented and top-down activation in order to maintain them for later test, these codes must be particularly primed. Accordingly, items that had served as targets in previous trials and that are expected to appear as targets in later trials should represent particularly strong competitors for selection in STM. If the activation of these codes is further enhanced by making them an item in the STM task, it is not surprising to see that they impair T2 report more strongly than others, and that this impairment is stronger the more target-related items are currently memorized in STM.
Chapter 2

With regard to the AB effect proper, the theoretical implications of our findings are clear as well: We did not find any interaction of either load or content effects with lag, which we take to speak against an interference account of AB. That is, besides any competition within STM there needs to be some additional capacity bottleneck that excludes the entry of new information while the processing of older information is not yet completed—just as the consolidation account proposes. Obviously, the effects of increasing difficulty within and between tasks show that task overlap is a reality, which speaks against a multiple channel approach as far as the present paradigm is concerned.

It also seems clear that specific loading of visual STM and phonological subsystems does not change the overall picture, despite indications of increased task difficulty. It is unlikely that either visual STM or a phonological subsystem can account for any substantial part of the AB deficit. Although it must be kept in mind that in the case of articulatory suppression, there were several interactions that did show an effect, none of these involved T2 Lag.

All in all, our findings provided support for both consolidation and interference models of RSVP performance: while the AB proper seems to be caused by a temporal capacity problem, as consolidation models hold, the overall performance level is considerably influenced by competition from other contents of STM, the more so the more task-relevant these competitors are.
Footnotes

1. Consistent with common practice in dual-task and task-switching research, we prefer comparing long and short lags to determine the AB effect (e.g., Chun & Potter, 1995; Visser, Bischof, & Di Lollo, 1999) over comparing single- and dual-target conditions (e.g., Shapiro, Arnell, & Raymond, 1997) because the latter invites possible confounds associated with pro- and retroactive interference, task-switch costs, task-coordination overhead, working-memory load, etc.

2. It may also be taken into account that STM accuracy is not an exclusive measure of (added) task difficulty. Our STM task was similar to the one used by Schneider & Shiffrin (1977), who reported finding little evidence for increased task difficulty as a function of number of items in accuracy although there was an effect on reaction time. Although we did not employ RT measures, this study does lend support to the idea that having more items is indeed more difficult.

3. Two pilot experiments were run to see whether the methodological changes from Experiment 1 to 2 might have mattered. The first pilot (N = 20) was as Experiment 1 (target-related condition), with the following exceptions: the initial inter-task interval was done away with and the ending pauses were as in Experiment 2, and RSVP responses now required an identification instead of categorization. Results were very similar to Experiment 1, with main effects of load and lag, but no interaction between the two. Mean T2|T1 performance was 82.4%, 78.4% and 76.9% for 2, 4 and 6 items, respectively. The second pilot (N = 20) was identical to the first, except for the stimulus material, which was replaced by the visual symbols as used in Experiment 2. Here, only lag reached significance. Mean performance was 18.1% for 2 items, 21.1% for 4, and 15.7% for 6 items (statistically equal, with a chance level of 12.5%). Neither experiment produced a qualitatively deviant result (compared to the reported experiments).
Chapter 3: Memory operations in rapid serial visual presentation

Short-term memory (STM) has often been considered to be a central resource in cognition. This study addresses its role in rapid serial visual presentation (RSVP) tasks tapping into temporal attention—the Attentional Blink (AB). Various STM operations are tested for their impact on performance and, in particular, on the AB. Memory tasks were found to exert considerable impact on general performance but the size of the AB was more or less immune to manipulations of STM load. Likewise, the AB was unaffected by manipulating the match between items held in STM and targets or temporally close distractors in the RSVP stream. The emerging picture is that STM resources, or their lack, play no role in the AB. Alternative accounts assuming serial consolidation, selection for action, and distractor-induced task-set interference are discussed.

Introduction

One of the most intriguing demonstrations of humans’ limitations in processing rapid sequences of visual information (Rapid Serial Visual Presentation or RSVP) is the Attentional Blink (AB) phenomenon (Raymond, Shapiro & Arnell, 1992). Commonly described as the decrease in the accuracy of identifying the second of two targets (T2) when it follows the first (T1) at a lag shorter than about 500 milliseconds, it has been studied intensively for some years now. Despite the accumulation of an impressive body of research, numerous questions regarding how the phenomenon comes about remain unanswered, partly due to the lack of a comprehensive model of the attentional processes underlying it. However, virtually all accounts of the AB (for overviews, see Shapiro, Arnell & Raymond, 1997; Visser, Bischof & Di Lollo, 1999) have linked the capacity limitation expressed as AB to working memory or Short-Term Memory (STM; Baddeley, 2000), by assuming either rate limitations in the consolidation of target-related information into STM (e.g., Chun & Potter, 1995) or interference within STM (e.g., Shapiro & Raymond, 1994). Accordingly, the aim of
the present study was to investigate the relation and possible interactions between STM and the attentional processes responsible for the AB in more detail.

In a previous study, we had participants perform an AB task while concurrently holding information in STM, to see whether the number of items held would affect the size of the AB (Akyürek & Hommel, in press). However, even though increasing STM load tended to decrease general performance in the RSVP task, there was no evidence that this decrease would be more pronounced at shorter lags, that is, in cases where T1 and T2 processing overlaps in time. Moreover, we found that using more task-related items to load STM (i.e., items from the same category as the targets or the distractors) led to a stronger drop in performance on the RSVP task but, again, this drop was independent of the lag between T1 and T2. These observations suggest that STM load and content affect T1 and T2 maintenance—presumably by modulating the amount of competition in STM (Duncan, Ward, & Shapiro, 1994; Shapiro & Raymond, 1994)—but not the processes underlying the AB proper. Given the central role STM plays in the majority of AB models suggested so far this is an astonishing finding. Consolidation accounts would lead one to expect that consolidating sensory traces of targets into STM gets more difficult, or takes longer, the more filled-up STM already is. Likewise, interference models suggest that competition increases with the number of items held in STM. Hence, from either point of view, increasing STM load should have a considerable impact on the size of the AB.

However, one may argue that the Akyürek & Hommel (in press) study provided a rather conservative and limited test of the interaction between STM and RSVP tasks. We identified two aspects with regard to which this may have been the case and, accordingly, carried out two experiments addressing these concerns in the present study. The first aspect relates to the STM loads employed, which were 2, 4, and 6 items. Considering the drop of almost 23% from the easiest to the most difficult condition, the range of these loads seems to
be sufficiently broad to expect some impact on AB size. However, as no baseline without any STM-related extra activity was obtained, Akyürek & Hommel may have missed the impact of the presence of the STM task as such. The need to deal with a concurrent STM task and to coordinate it with the RSVP task may be considered to increase demands on what Baddeley (1986) calls the “central executive”. It may be the presence or absence of these task-coordination demands—but not the number of STM items—that make the difference, so that the theoretically most important contrast may not be that between 2 and 6 items but between zero and 2. The present Experiment 1 tested this prediction.

A second aspect with regard to which Akyürek & Hommel (in press) test may have been rather conservative concerns the choice of STM items. Although they used items from the same category as targets or distractors of the RSVP task, none of the STM items could occur as target or distractor in the RSVP stream. This makes sense for a test of merely capacity-related interactions between attention and STM but may underestimate content-related interactions. Several studies have shown that the AB is sensitive to the similarity between targets and distractors in the RSVP stream, with more similarity producing a greater AB (e.g., Isaak, Shapiro & Martin, 1999; Maki, Bussard, Lopez & Digby, 2003; Maki, Couture, Frigen & Lien, 1997). This suggests that distractors compete with targets for selection to a degree that depends on their match with the implemented target template, that is, with the cognitive representation of the task-relevant stimuli held in STM (cf., Bundesen, 1990; Duncan & Humphreys, 1989)—a mechanism that Desimone and Duncan (1995) called “biased competition”. If we assume that the similarity between targets and distractors is not all or none but a matter of degree (considering that both always share at least some task-relevant features, such as location or appearance by abrupt onset; see Maki et al., 2003), it seems possible that STM impacts the processing of RSVP streams (and the AB in particular) not only in a capacity-related fashion, as tested in Experiment 1, but (also) in a more specific,
content-related fashion. The present Experiment 2 tested whether these kinds of interactions might play a role in the AB.

To summarize, we carried out two experiments to tap into possible interactions between the AB and STM. In particular, we considered task coordination (Experiment 1), and competition bias (Experiments 2A and 2B). To the degree that these aspects play a role in creating the attentional bottleneck reflected by the AB we would expect that taxing them by means of appropriate experimental manipulations has a specific impact on the AB. That is, increasing the load on a particular STM operation should impair performance in the RSVP task more the shorter the lag between T1 and T2.

**Experiment 1: Task coordination**

The first experiment was carried out to compare performance on a RSVP task of participants who performed a concurrent STM task and those who did not. Since the inclusion of an STM task will present additional difficulty, performance in the dual-task group is likely to be worse compared to the single-task group. If so, this might be due to either of two factors: One potential source of difficulty results from limits on STM capacity, as the STM items were to be maintained while the RSVP task was performed. Capacity problems should increase with STM load, so that the contribution of this factor was expected to grow with the number of to-be-maintained STM items. The other possible source derives from the executive overhead and coordination demands in the dual-task situation, so that this factor was expected to show up as a main effect of experimental group. The central question was, however, whether the effect of load and/or group would interact with the AB, that is, whether increased load and/or executive costs would boost the lag effect expected in the RSVP task. As Akyürek and Hommel (in press) found little evidence for interactions between load and lag, our main focus was on the group or task effect.
Both groups of participants received an identical RSVP task that in one group was embedded into a STM task. The design included the presentation of a set of items, followed by the RSVP stream with two targets, and a comparison item to probe STM. There were only two differences between the two groups: (1) The single-task group was told to ignore the STM items presented at the beginning of each trial and the comparison item at the end, whereas both of these stimuli were to be attended to in the dual-task group. (2) The dual-task group received an additional prompt to decide whether the comparison item was a member of the STM set or not.

Method

Design

Within-subjects factors in the repeated measures ANOVA were (1) the temporal distance between RSVP targets expressed in the number of intervening distractors, which is referred to as lag, and (2) the size of the STM set, referred to as load. The former consisted of four levels: Lags 1, 3, 5 and 8; and the latter of three levels: 2, 4 and 6 items. Group was the only between-subjects factor: the dual-task group performed the RSVP task together with the STM task and the single-task group the RSVP task only. Accordingly, the load factor refers to the number of presented and to-be-recalled items in the dual-task group but to the number of presented items only in the single-task group. Dependent measures were T1 accuracy, T2 accuracy given T1 was correct (T2|T1), and accuracy in the STM task (in the dual-task group only).

Participants

Thirty-eight Leiden University students (19 per group, 32 female and 6 male) participated for pay or course credit. All participants reported having normal or corrected-to-normal vision and were not aware of the purpose of the experiment. Mean age was 20.9 years.
Chapter 3

Apparatus and procedure

All experimental sessions took place in a standardized environment. Participants were seated in a small, dimly-lit room. Stimuli were presented on an Intel Pentium III computer using the Intel i815 onboard graphics system. The E-Prime™ runtime component controlled presentation and data logging. The LG FlatTron 776FM screen diameter was 17” with contrast and brightness fixed at 75%. Using a resolution of 800 by 600 pixels, the screen refreshed at 100Hz. Viewing distance was not strictly controlled but averaged about 50 cm. All participants completed a single, 1h session of 456 trials, 24 of which were initial practice trials and not included in any analysis. The instruction sheet stressed accuracy on all dependent variables, but at the same time discouraged a slow or elaborative response mode.

Trials were started by the participants by pressing the space bar on the keyboard. After a short pause of 300 ms the STM items were presented for 1000 ms. Then, a fixation cross (“+”) appeared for 250 ms, followed by an RSVP stream of 20 stimuli. Each of them appeared for 60 ms and was followed by a blank of 30 ms, amounting to a stimulus onset asynchrony of 90 ms. A 200 ms pause ensued, after which a single STM probe was presented for 1000 ms. In the dual-task group, a response screen appeared after a 250-ms blank pause. Participants in this group were asked whether the STM probe had been part of the STM set or not. Two additional response screens were presented in both single- and dual-task groups. The first screen prompted participants to identify T1 by pressing the corresponding digit on the keyboard, and the second screen did the same for T2.

All stimuli were randomly selected within the bounds of the experimental design. STM items were groups of 2, 4 or 6 digits and a single probe, selected from the complete digit set. The STM probe item had a probability of 50% of having been part of the STM set. RSVP targets were drawn independently in a similar fashion from the full digit set. STM items and RSVP targets were never repeated within their respective tasks. T1 was presented
at position 7, 8 or 9 in the 20-item stream, randomly chosen but equally distributed. T2 followed T1 with a lag of 1, 3, 5 or 8 items. Lag 8 is a time interval long enough (660 ms) to be considered out of range for potential attentional blink effects, and was thus taken to represent a suitable performance baseline for a two-target RSVP task. RSVP distractors were capital letters drawn from the complete alphabet, without repetition. All stimuli were presented in 16 point Times New Roman font in black (RGB 0, 0, 0) on a gray background (RGB 128, 128, 128).

**Results and discussion**

We used standard analysis of variance for repeated measures designs and substituted Greenhouse-Geisser adjusted values (rounded to one decimal) in case of a significant test of sphericity. The full factorial ANOVA for STM performance (in the dual-task group) showed a main effect of load, $F(2,36) = 36.04, p < .001$, and an interaction effect of load by lag, $F(6,108) = 2.19, p < .05$. The former was due to a continuous decrease of performance with increasing load (90.8%, 83.2%, and 73.7% for set sizes of 2, 4, and 6 items, respectively), providing clear evidence that the STM task was not trivial. The interaction effect was less clear-cut. The differences between accuracy on each set size on the four lags were modest at best and involved a limited effect size; see Table 1. In any event, the fact that the set size effect was numerically largest at the longest lag does not point to a particular processing problem related to the AB.
Table 1. *Mean STM performance in the dual-task group of Experiment 1 by lag and STM load (number of items) in percent.*

<table>
<thead>
<tr>
<th>Load</th>
<th>Lag 1</th>
<th>Lag 3</th>
<th>Lag 5</th>
<th>Lag 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>89.8</td>
<td>90.1</td>
<td>91.8</td>
<td>91.7</td>
</tr>
<tr>
<td>4</td>
<td>83.8</td>
<td>82.9</td>
<td>84.9</td>
<td>81.0</td>
</tr>
<tr>
<td>6</td>
<td>76.6</td>
<td>74.6</td>
<td>72.5</td>
<td>71.1</td>
</tr>
</tbody>
</table>

Accuracy on T1 was influenced by main effects of lag, $F(3,108) = 7.64, p < .001$, and task group, $F(1,36) = 5.93, p < .05$. The interactions of load by group, $F(2,72) = 5.70, p < .005$, and load by lag were also significant, $F(6,216) = 2.27, p < .05$. Figure 1 (black symbols) shows T1 performance as a function of lag. Clearly, performance dropped a bit when T2 was presented rapidly after T1. This effect is common to task versions in which T1 and T2 are defined as targets by the same features and presumably reflects competition for selection between T1 and T2 codes (Hommel & Akyürek, in press; also see Botella, Barriopedro & Suero, 2001, and Potter, Staub & O’Connor, 2002). The task-group main effect is obvious from Figure 1 as well; adding the STM task resulted in overall lower T1 identification performance. As expected, STM load primarily affected the dual-task group. While performance in the single-task group remained virtually unchanged for the presentation of 2, 4 and 6 items (89.2%, 89.0%, and 90.3%, respectively), performance in the dual-task group dropped from 84.6% for 2 items to 82.2% (4 items) and finally to 79.5% (6 items). Consequently, the difference between groups was much more pronounced with STM loads of four or six than with a load of two items, suggesting that task difficulty as such was determined more strongly by load than by the number of tasks. The last interaction of load and lag was difficult to interpret, as no meaningful trend was apparent in the data. There was a hint of slightly increased performance at Lag 3 and 5 in the most difficult 6-item STM condition, compared to performance at the other lags. The other load conditions seemed to
result in higher T1 accuracy for longer lags. This pattern had no mirror in STM performance that might indicate a trade-off between tasks.

T2|T1 performance produced a main effect of lag, $F(2.0,71.4) = 40.78, p < .001$. The task group variable was also marginally significant, $F(1,36) = 3.49, p < .07$. Figure 1 (white symbols) shows a pronounced AB effect with performance on T2 dropping clearly on Lag 3. Also visible is the Lag 1 sparing phenomenon (Chun & Potter, 1995), which satisfies the criteria of Visser, Bischof & Di Lollo (1999). The task group trend showed that if adding the STM task had an effect it would just decrease overall performance and not increase the AB.
To summarize, Experiment 1 shows that the presence of a STM task interferes with the overall performance in concurrent RSVP and it does more so with higher STM load at least when T1 is concerned. At the same time, however, the STM task does not increase the AB and thus impair the attentional processes underlying it. If the dual-task condition invoked additional executive processes for coordinating these tasks (Baddeley, 1986), its failure to boost the AB can be taken to imply that these executive processes are unrelated to those responsible for the AB.

**Experiment 2A: Competition bias towards distractors**

The outcome of Experiment 1 suggests that loading STM impairs performance on a concurrent RSVP task to a degree but does not specifically affect the processing bottleneck reflected by the AB. However, this test was purely in terms of capacity without consideration of *what* is loaded into STM. If we assume that, first, targets and distractors compete for selection (or some other crucial processing step) to the degree that the distractors match the target descriptions held in STM and that, second, targets and distractors are always similar to some degree (that varies as a function of the concrete stimulus sets chosen), it is possible that the impact of STM on the AB depends more on the particular content of STM than the rationale of Experiment 1 considered.

To investigate the impact of the specific content of STM on the AB we made use of the observation that items held in STM impact the selection of incoming stimulus events even if the reason for why they are held in STM is unrelated to these events. In particular, Downing (2000) and Pratt and Hommel (2003) demonstrated that maintaining items in STM for later use biases spatial attention towards locations where objects sharing features with these items are presented. For instance, holding in mind a face for later comparison automatically attracts attention to locations in which that face appears in between (Downing, 2000). This suggests that incoming information is continuously matched against information
STM currently contains and top-down supported to the degree that it matches (Bundesen, 1990; Duncan & Humphreys, 1989).

According to this logic interactions between the content of STM and a concurrent RSVP task would only or at least mainly be expected if some relation existed between the particular stimuli held in STM (be that a target template, as in the standard RSVP task, or an item stored for another reason) and the stimuli processed in the RSVP task. Experiment 2A was designed to manipulate the relationship between STM items and particular distractors in the RSVP stream. Various authors have argued and provided evidence that selecting a target is particularly affected by competition from temporally close nontargets, especially the one immediately following the target (Bottella et al., 2001; Chun, 1997; Dell’Acqua, Pascali, Jolicœur & Sessa, 2003; Hommel & Akyürek, in press; Potter et al., 2002). If so, and if this competition can be top-down biased by STM content, we should be able to influence its outcome, that is, performance on T1 and T2, by providing top-down support for distractors that follow T1 or T2. This is what we attempted to do in Experiment 2A. In particular, we had participants to maintain items in STM that were either (a) all unrelated to the stimuli in the RSVP stream, or a set including one item that matched the distractor presented (b) immediately following T1, (c) immediately following T2, or (d) at a position close to the end of the stream. If a match would provide top-down support for the respective distractor, condition (b) should specifically impair performance on T1 and condition (c) performance on T2.

**Method**

The design was very similar to Experiment 1, but we dropped two of the STM load conditions (2 and 6) and hence used a load of four items exclusively. Letters were used as items for the STM task, and a new factor was added, which concerned the position of the STM-related RSVP item in the stream. Apart from the control condition where no STM item
matched the items of the stream, one item of the STM set matched the distractor following T1, or T2, or a distractor at position 19 (position 20 being the last item in the stream). The probability of each of these four conditions was 25%. In order to be able to present a matching STM item at Lag 1, T2 was not presented at that position, but rather at Lag 2 instead (and at Lag 3, 5 and 8 as previously). Another 30 students (27 female, 3 male) participated in this experiment for course credit or a small fee. Mean age was 20.7 years.

**Results and discussion**

STM performance was unaffected by any factor, as was to be expected in the absence of a load manipulation. Performance was very good but not at ceiling (90% correct). T1 performance was also not sensitive to lag or the match with STM items (see Figure 2, left panel).

T2|T1 accuracy depended on lag only, $F(1.9,56.2) = 15.07, p < .001$. Figure 2 (right panel) shows that T2 accuracy followed a rather typical AB curve with performance slightly above 70% at the lowest point and approaching 90% at its peak. There was no evidence whatsoever that the repetition of an STM item at any position in the stream had any effect, $p > .27$. 
The boundaries of attention

![Figure 2: T1 accuracy (left panel) and T2 accuracy given T1 correct (right panel) as a function of lag in Experiment 2A. Separate lines show performance for each match condition.](image)

The outcome of Experiment 2A does not provide any support for the hypothesis that STM content can directly bias competitors of T1 or T2 and, thus, modulate performance on T1 or the size of the AB. Given the high level of STM performance, this failure to find an interaction between the two tasks was unlikely due to a neglect of the STM task. However, before jumping to conclusions we need to consider that our rationale depended on a number of intermediate assumptions that may or may not hold. In particular, even though previous findings are consistent with our crucial assumption that T1 and T2 codes compete with codes from succeeding nontarget stimuli for selection, so that strengthening the competitor codes should impair performance on T1 and T2, some element in this chain of arguments may be incorrect. To rule out that this was the reason for our failure to find an interaction we went for a more direct test in Experiment 2B. The rationale was very similar to that of Experiment 2A.
but instead of trying to strengthen potential competitors of T1 and T2 we this time attempted to provide top-down support for T1 and T2 themselves. That is, in some trials one item of the STM set matched either T1 or T2, with the expectation that this would facilitate the selection and/or further consolidation of the respective target and thus increase the likelihood that it will be correctly reported.

**Experiment 2B: Competition bias towards targets**

**Method**

The design was as in Experiment 2A, with only minor changes concerning the STM set and repetition variable. The STM set consisted of four digits instead of letters. One random digit of this set could match T1 (25% probability) or T2 (25%). In the remaining 50% of the trials no STM item matched any RSVP target – so to work against possible anticipatory strategies. Lags of T2 were 1, 3, 5 and 8, as in Experiment 1. The total number of trials was 600, 24 of which were practice trials and not considered in analyses. The experiment lasted for slightly more than 1.5hrs and participants were encouraged to pause when halfway through. Twenty new students (16 female, 4 male) participated for course credit or a small fee. Mean age was 21.7 years.

**Results and discussion**

STM accuracy was affected by the interaction between lag and match, $F(6,114) = 2.43, p < .05$, which possibly reflected a small benefit of item overlap: Performance was unaffected by lag in the no-match and match T2 conditions ($p > .69$, and $p > .14$, respectively), but slightly increased for Lags 3 and 5 with T1 matches, $F(2.2,41.7) = 4.08, p < .05$, as separate match condition analyses revealed. Table 2 shows the full set of STM performance means.
Table 2. Mean STM performance in Experiment 2B by lag and match in percent.

<table>
<thead>
<tr>
<th>Match</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>85.0</td>
<td>85.9</td>
<td>84.6</td>
<td>84.5</td>
</tr>
<tr>
<td>T1</td>
<td>83.6</td>
<td>88.6</td>
<td>87.9</td>
<td>85.4</td>
</tr>
<tr>
<td>T2</td>
<td>88.1</td>
<td>85.1</td>
<td>85.8</td>
<td>83.3</td>
</tr>
</tbody>
</table>

The analysis of T1 performance showed a significant main effect of lag, $F(3,57) = 3$, $p < .05$. This effect reflected a slight drop of performance when T2 follows T1 immediately, similar to what was seen in Experiment 1. Figure 3 (left panel) plots T1 performance as a function of lag.

Figure 3: T1 accuracy (left panel) and T2 accuracy given T1 correct (right panel) as a function of T2 Lag in Experiment 2B. Separate lines show performance for each match condition.
Most importantly, T2/T1 accuracy was affected by lag, $F(1.8,33.9) = 19.42$, $p < .001$, indicating a fairly sizeable AB (see the right panel of Figure 3), but there was no hint to an interaction with match, $p > .25$.

As evident from the complete absence of match-related effects, Experiment 2B fully supports the (negative) conclusions suggested by Experiment 2A. As we will point out in the General Discussion, these observations need not be taken to stand in conflict with previous findings of interactions between STM and visual attention (Downing, 2000; Pratt & Hommel, 2003). What seems clear, however, is that such interactions do not underlie and do not seem to play a role in the emergence of the AB.

**General discussion**

The aim of this study was to investigate possible interactions between cognitive operations related to STM on the one hand and performance on RSVP tasks and the AB in particular on the other. With respect to the first aspect of this aim our endeavor was successful: The empirical outcomes demonstrate interactions between STM and RSVP tasks that point to dependencies between the processes underlying these tasks. Performance on T1 and likely T2 was sensitive to presence of a secondary STM maintenance task and, more strongly so, to the number of items to be maintained (Experiment 1). Importantly with respect to the second aspect of our goal, however, none of these interactions varied reliably with lag. This suggests that STM maintenance is a process that impairs performance in a RSVP task but that it does so in a broad, temporally rather constant fashion. In other words, maintenance seems not to affect temporal attention.

Together with the findings of Akyürek and Hommel (in press), these observations are surprising from a theoretical point of view. If the AB would be due to interference within STM (Shapiro & Raymond, 1994), one would expect that, first, this interference should increase with STM load so that, second, the AB should increase with load as well. In view of
the pronounced impact of load on T1 and T2 performance, our findings provide evidence for
the first assumption and, yet, we found no support for the second. Accordingly, we conclude
that existing interference accounts of the AB are correct in predicting the general
performance level in a RSVP task but they do not provide a tenable explanation for the AB
(Akyürek & Hommel, in press).

How surprising our findings are from a consolidation point of view depends on the
(commonly not well defined) details of the particular view. Generally speaking, consolidation
theorists assume some sort of rate limitation in the consolidation of target-related information
into STM (e.g., Chun & Potter, 1995; Jolicœur, Tombu, Oriet & Stevanovski, 2002) but the
possible reason for this limitation, and the mechanism producing it, are not yet well
understood. The term "consolidation" is usually meant to refer to the transformation of a
transient and fragile perceptual code of a target stimulus into a more enduring format, which
in a RSVP task enables a participant to report the target a few seconds later. In view of the
available theoretical considerations, we can imagine at least four reasons for why this process
might lead to a performance deficit as represented by the AB.

First, consolidating into STM may take longer the more filled up it already is (which
is more problematic for T2 than T1) and the more recently the last element was entered (and
hence the more active it still is; which is more problematic for T2 if lag is short). This
possibility would have predicted considerable interactions between load and lag and, thus,
can be rejected based on the lack of such interactions both in the present study and in
Akyürek and Hommel's (in press).

Second, the consolidation process may be unable to operate on more than one event at
a time, so that T2 cannot be consolidated if it occurs while T1 is being operated on (note that
given the observation of T1-related performance drops at Lag 1 by Hommel & Akyürek, in
press, and Potter et al., 2002, this does not stand in conflict with Lag-1 sparing). According to
this approach we may have failed to find interactions between STM operations and the AB because the processes involved in the maintenance STM do not overlap with, or do not draw on the same source of capacity as, STM consolidation.

Third, consolidation may or may not be serial but it in any case may require operations that have side-effects producing the AB. Consolidating a particular event presupposes that it is somehow selected for consolidation so to avoid the storage of other, temporally close events that compete for selection. Targets are assumed to be selected by providing top-down support, i.e., additional activation for stimuli that match goal templates held or stored in memory (Bundesen, 1990; Duncan & Humphreys, 1989). In a competitive system, increasing the activation of one event must lead to relative inhibition, i.e., a decrease of activation of its competitors. Accordingly, to the degree that T1 receives top-down support T2 must be inhibited, at least if it appears before T1 selection is completed, which is consistent with the observation that T2 performance is better the less neural activation T1 produces (Shapiro et al., 2004). One may consider this to be the most elegant explanation because it does not require particular assumptions to account for the AB—instead, the AB emerges as a natural consequence of the fact that selection for (later) action is a competitive process. If so, our findings would be not surprising at all, because the operation that produces AB would not have any logical relation with maintenance. The only contribution of STM to selection would be the fact that some of its compartment would need to hold the target templates. This is likely to create main effects of load, as templates may be maintained less efficiently as STM load increases, and the more so the more related the STM items are to the targets—exactly as observed in the present study and by Akyürek and Hommel (in press). However, there would be no reason to expect any interaction with lag, because top-down support is an automatic consequence of having implemented the target templates (Downing,
The boundaries of attention 2000; Pratt & Hommel, 2003), and the inhibition it indirectly produces is an automatic consequence of competitive selection.

Fourth, selecting and consolidating a target may be controlled by a task set, which may be fragile and sensitive to interference while a target is processed. According to Di Lollo, Kawahara, Ghorashi, and Enns (in press), task sets need to be maintained by a "central processor" that for this purpose issues endogenous control signals. While processing a target no control signals can be issued, so that external stimuli can take over control and effect a task set change if they do not match the task-set specific target template. That is, if a distractor appears while T1 is processed a task-set change is induced so that T2 cannot be processed until the old set has been re-established, which again cannot happen before T1 processing is completed. Note that this account makes no reference to STM and hypothetical STM resource limitations, so that it remains unchallenged by our failure to find a systematic relationship between lag and load. That is, the observations of Akyürek and Hommel (in press) and those from the present study are consistent with a task-set account. More direct evidence in favor of this account comes from two recent findings. One is that stimuli can indeed become associated with the task sets they were processed under previously, so that presenting a stimulus again activates the corresponding task set automatically (Waszak, Hommel, & Allport, 2003). Even more interestingly, this association transfers to other, not-yet encountered stimuli of the same category (Waszak, Hommel, & Allport, in press). That is, repeatedly not processing and consolidating distractors in a RSVP task may indeed create an association of both the encountered distractors and the whole distractor category with a representation of the "don't process" set assumed during distractor presentations, which then can be triggered by any stimulus related to the previous distractors. Another supporting observation stems from Gross et al.'s (2004) MEG study of the AB. They found that successful processing of T1 and/or T2 is associated with a substantial increase of neural
synchronization between the brain areas that form the attentional network involved in handling RSVP tasks (for an overview, see Hommel et al., in press), whereas failures to process T2 were not accompanied by such an increase. Interestingly, distractors induced reliable decreases of synchronization, that is, their presence inhibited communication between the components of the attentional network, not unlike the scenario of Di Lollo et al. (in press) might be taken to suggest.

To summarize, our findings are consistent with accounts that attribute the AB to side effects of target selection, to a distractor-triggered change of the task set or, with some additional assumptions, to the serial nature of target consolidation. In contrast, they do not provide support for accounts that relate to capacity limitations of or interference in STM. In other words, it looks as if STM, the ‘forge of cognition’, does not have much to do with the AB phenomenon.

Lastly, we considered the implications of our failure to find matching effects in Experiments 2A and 2B. As pointed out in the introduction, previous observations revealed that holding event-related information in STM biases spatial attention towards locations where events sharing features with the remembered event appear (Downing, 2000; Pratt & Hommel, 2003). Given these findings we expected that holding an item related to T1 or T2 would somehow affect the processing of the respective target and, thus, facilitate reporting it. In the absence of further systematic research we can only speculate why we failed to find such an impact. One possible reason may have to do with the lack of spatial variability in stimulus presentation. Previous evidence of the impact of STM-stimulus matches relates to spatial attention: the focus of attention was attracted to the location where the matching stimulus appeared. However, our stimuli all appeared in the same location so that a possible effect on the control of spatial focusing had no way to express itself in the data. If so, one would expect measurable (negative) effects of a T1-related match on T2 if T1 and T2
The boundaries of attention appeared in different locations. Another possible reason for our null effects may have to do with the particular tasks used. The participants of Pratt and Hommel (2003) were using the information held in STM to detect and identify a target stimulus and to carry out a speeded response to it. This suggests that held information was integrated into the current task set in a format that enabled a direct match against incoming stimuli. Obviously, this was not necessary in Experiments 2A and 2B or any other experiment of the present study, where the STM comparison item was only presented long after the RSVP stream so that holding it "ready for matching" during the RSVP was neither necessary nor useful. The fly in the ointment here is the fact that Downing (2000) had a similar setup comprising of presentation of the STM item, an inserted dot detection task, and an unspeeded STM comparison—yet he did find a spatial effect of irrelevant primes matching the STM item on the dot detection task. A possible explanation may be that both tasks of Downing (holding one STM item and detecting a single dot) were much easier than ours (holding one STM item and selecting two targets from a RSVP stream), so that Downing's participants may have had more "resources" left and/or a greater motivation to hold the STM content in a ready-to-match format. However, in the absence of more research on this issue this remains a mere speculation.
Chapter 4: Lag-1 sparing in the attentional blink: Benefits and costs of integrating two events into a single episode

When people monitor a visual stream of rapidly presented stimuli for two targets (T1 and T2), they often miss T2 if it falls into a time window of about half a second after T1 onset—the Attentional Blink. However, if T2 immediately follows T1, performance is often reported being as good as at long lags, the so-called Lag-1 Sparing effect. Two experiments investigated the mechanisms underlying this effect. Experiment 1 showed that, at Lag 1, requiring subjects to correctly report both identity and temporal order of targets produces relatively good performance on T2 but relatively bad performance on T1. Experiment 2 confirmed that subjects often confuse target order at short lags, especially if the two targets are equally easy to discriminate. Results suggest that, if two targets appear in close succession, they compete for attentional resources. If the two competitors are of unequal strength the stronger one is more likely to win and be reported at the expense of the other. If the two are equally strong, however, they will often be integrated into the same attentional episode and thus get both access to attentional resources. But this comes with a cost, as it eliminates information about the targets’ temporal order.

Introduction

A major issue in the study of human visual attention concerns the number of elements that can be processed at a time. One aspect of this issue has to do with limitations in space, that is, with the question whether more than one location, or more than one event at a given location, can be concurrently attended. Another aspect that has been addressed more recently (see Shapiro, 2001), has to do with temporal limitations, that is, with the question of how quickly we can attend an event after just having attended another event. Research on these latter, temporal limitations has revealed a striking phenomenon: When people monitor a visual stream of rapidly presented stimuli for two targets (T1 and T2), the second target (T2) is often missed if it falls into a time window of about 100-600 ms after onset of T1 (e.g., Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). In analogy to an overt
blink of the eyes, Raymond et al. (1992) have called this temporal blindness to the second of two sequential targets the *Attentional Blink* (AB).

Several accounts of the AB have been suggested thus far (Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Enns & Di Lollo, 1997; Jolicœur, Dell'Acqua, & Crebolder, 2000; Shapiro, Raymond, & Arnell, 1994). However, as Shapiro, Arnell, and Raymond (1997) pointed out, ignoring differences in terminology allows one to extract three widely shared assumptions: (1) as T1 is masked by the item(s) following it, increased attention is required to create and consolidate its cognitive representation; (2) with increasing attentional demands of T1 processing less attentional capacity is left to consolidate T2, which makes its codes sensitive to inhibition, competition, and/or decay; and (3) this problem is enhanced with increasing response requirements, such as the need to perform a speeded response to T1.

One way to investigate the causes underlying these temporal attentional limitations in more detail is to study exceptional cases, that is, conditions under which the AB does not occur (e.g., Sheppard, Duncan, Shapiro, & Hillstrom, 2002). Arguably, the best-established exception of that sort is the so-called *Lag-1 Sparing* effect (Potter, Chun, Banks, & Muckenhoupt, 1998). It refers to the frequent observation that AB is more or less absent if T2 appears immediately after T1, hence, in the ordinal position Lag 1. In a comprehensive meta-analysis of studies in which Lag-1 Sparing was or was not obtained, Visser, Bischof, and Di Lollo (1999) were able to identify three conditions that need to be met to produce the sparing effect: Both targets need to appear at the same location in space; the interval between them must not exceed the effective temporal integration window; and the two targets, or the features defining them, must not differ to a degree that would require a switch of the attentional set (cf., Potter et al., 1998).

So far the mechanisms underlying Lag-1 sparing have not attracted a lot of attention, which led Visser et al. (1999, p. 464) to this, rather pessimistic sketch of the state of affairs:
"It is fair to say that Lag-1 Sparing has been treated with the theoretical equivalent of benign neglect. When mention is made of Lag-1 Sparing, it is usually to ascribe it to a sluggish attentional gate and to say no more about it". The sluggish-gate idea (see Chun & Potter, 1995; Shapiro & Raymond, 1994) assumes that an attentional gate is opened on presentation of T1. Processing T1 starts immediately but the gate is closed rather sluggishly, so that the next (i.e., Lag-1) item can "slip in" and access attentional resources as well. As a consequence, both items will be processed together and may become part of the same attentional episode (Sperling & Weichselgartner, 1995; Visser et al., 1999) or object file (Sheppard et al., 2002). Based on their meta-analysis, Visser et al. (1999) extended this hypothesis by assuming that Lag-1 items can slip in only if T1 and T2 are presented at the same location and if their identification does not require switching between different attentional sets.

Although attractive at first sight, the sluggish-gate idea is still largely underdeveloped and faces some empirical problems. Consider the situation that T2 appears immediately after T1 under conditions that according to Visser et al. (1999) allow Lag-1 Sparing to occur. The gate is opened to process T1 and, as it is sluggish, T2 slips in. A major question that arises is whether it slips in for free, that is, whether the fact that it does slip in and, therefore, gains access to attentional resources, has any consequences for T1. The very term of sparing suggests a positive answer, suggesting that T1 is processed and consolidated under (almost) all circumstances and, at least in most cases, T2 is processed and consolidated as well. Theoretically, this would imply that processing and consolidating T2 either needs no additional attentional capacity or that it needs no more than what is left by T1-related processing anyway. Hence, more performance for the same cognitive price. Empirically, this would imply that performance on T1 is independent of performance on T2. However, findings of Broadbent and Broadbent (1987) let one doubt whether this is the case. In their
Experiment 1, these authors presented participants with streams of words, target words presented in uppercase, nontargets in lowercase. Although T1 performance was not analyzed as a function of T2 performance, there are several indications that performance on the two targets was negatively correlated: While correct T1 report was much worse for Lag 1 than for Lag 2 (46% vs. 60%), T2 performance showed the opposite pattern (35% vs. 15%). Also, T2 performance was much better if T1 could not be reported than if it could (58% vs. 20%). A very similar error pattern was obtained by Chun and Potter (1995), who had participants identify two letters among digits. Chun (1997) investigated temporal binding errors in a Rapid Serial Visual Presentation (RSVP) paradigm, finding that these are influenced by the attentional blink and observing that T1 report suffers at Lag 1. Unfortunately, neither the specific type of errors nor the performance on T1 given that T2 was correct was reported. More recently, Potter, Staub, and O’Connor (2002) provided further evidence for a negative correlation between T1 and T2 performance in experiments using very short T1-T2 intervals: Gains in T2 report at intervals below 100 ms were accompanied by comparable losses in T1 report. Thus, all in all, there are a number of hints suggesting that T1 processing suffers from processing T2, especially at short lags. This also fits with the general observation that, in many single target tasks using RSVP, people often tend to report the item following the actual target (for an overview, see Botella, Barriopedro & Suero, 2001)—a tendency that also occurs in the standard AB task (Raymond et al., 1992).

Another reason to ask what is actually spared at Lag 1 has to do with the implications of being processed in the same integration window or of being integrated into a single episode. Assume that a sluggishly closing gate actually allowed T2 to slip in, and that this leads to the joint integration of T1 and T2 into a common cognitive episode. Even if it were possible to create a single episodic trace representing both a target and the item following it, it is not obvious in which way this might improve overall performance. Consider the version
of the AB task employed by Raymond et al. (1992), where T1 is a white letter among black
letter distractors and T2 is a black X. If T2 appears in Lag 1 one could imagine that both
targets are integrated into the same episodic trace and then, at report, retrieved together. If so,
some information would necessarily get lost: one being the order of the two items (after all,
they are treated as one event), another the fact that it was T1 that was white but not the X.
True, these losses do not create any problem because the participant knows that the X always
follows, but never precedes, T1 and that T1 is always white while the X is always black. But
what if any other item appears at Lag 1? In case of Raymond et al.'s (1992) design this would
be a black letter, which then would be integrated with T1 into the same episode. How does
the participant know which letter was white and which was first? Considering the number of
possible errors a participant could make in this situation it would be no trivial achievement to
still reach an accuracy level of 80% or more correctly reported T1 (e.g., Raymond et al.,
1992). Indeed, when Raymond et al. required participants to report a single target as well as
the three (distractor) letters following it, it became apparent that Lag 1 post-target intrusions
occurred fairly often (on 16% of trials).

The evidence for an exchange relation between T1 and T2 performance with short
intervals between them has led Potter et al. (2002) to challenge the sluggish-gate idea in its
original form. In particular, they doubt that it is only the actual moment in time when coding
takes place that decides about whether a target gets access to the attentional gate or not—one
of the major implications of the sluggish-gate metaphor. Instead, T1 and T2 are assumed to
compete for access. Clearly, T1 will often win the competition and get exclusive access.
However, at very short intervals T2 may sometimes prevail because it benefits from the
previous detection of T1: T1 triggers the mobilization of attentional resources but is
overwritten by T2 so quickly that the resources are eventually allocated to the second target
(an idea very similar to Müßeler & Neumann’s, 1992, account of the tandem effect).
This more dynamic, competitive scenario suggested by Potter et al. (2002) fits nicely with the discussed negative relationship between T1 and T2 performance at short lags. And yet, there are reasons to doubt whether the evidence Potter et al. provide is sufficient to justify their claims. One problem is that only one of their six experiments used the standard AB design with a single visual stream, that is, without spatial uncertainty, while the other experiments employed two streams. This means that most of their results may tell us more about limitations of spatial attention than about the purely temporal limitations reflected in the AB. A second problem, is that they only report unconditional accuracy on T1 and T2, so that it remains unclear whether and how often their subjects were able to report both targets. As most experiments yielded a mean accuracy of 50-60% it may even be that subjects mostly or always failed to report more than one target per trial. If so, one may doubt whether the findings can be compared to findings from standard AB experiments, where the rate of full reports at short lags is commonly substantial. Third, and even more worrisome, given that conditional accuracy for T2 (i.e., T2 given T1 correct) is not specified we do not know whether Potter et al. were able to demonstrate Lag-1 Sparing—which is commonly defined as better performance on T2 conditional accuracy than at subsequent lags—at all. This is the more problematic as the two-stream design they used in most of their experiments does not meet the criteria that Visser et al. (1999) considered to be necessary for Lag-1 Sparing to occur. Finally, it is far from obvious how a competitive approach accounts for full reports at Lag 1. If there is insufficient capacity for processing more than one target, how is it possible that both targets can be reported in a commonly substantial number of trials? One possibility is that competition between targets can have two outcomes: sometimes one target may win and exclude the other--the cases the competitive approach focuses at--and sometimes both may be integrated--the cases the sluggish gate metaphor aims at.
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In sum, then, the competitive approach of Lag-1 Sparing suggested by Potter et al. (2002) provides an attractive account of a number of observations that do not seem to fit naturally with the original sluggish-gate metaphor. At the same time, the additional evidence Potter et al. present does not yet seem to represent a sufficiently solid backbone of their own approach and does not seem to rule out the possibility of integration altogether. Accordingly, the aim of our study was to test some further implications of a competitive account, vis-à-vis the sluggish gate account, by using a standard AB task with a single visual stream, i.e., without spatial uncertainty, and by analyzing performance in terms of conditional accuracy. Given the emphasis a competitive account puts on T2-related effects on T1, we included analyses of conditional accuracy for both T1 (i.e., T1 given T2 correct) and T2 (T2 given T1 correct). Moreover, to tap into the possible common integration of T1 and T2, and the loss of order information this might imply, we also had an eye on order errors, that is, on cases where subjects correctly reported the identity of the two targets but confused their order.

Experiment 1

As a first step, we carried out an AB task fulfilling the following criteria: First, conditions should be optimal for Lag-1 Sparing to occur. Accordingly, we presented all stimuli at the same spatial location, used a reasonably short stimulus-onset asynchrony, and defined the two targets in such a way that a shift of task or attentional set was not necessary (Visser et al., 1999). Second, we wanted to compare performance on T1 and T2 under conditions in which confusion of target order matters and conditions in which it does not. Accordingly, we presented participants with two digit targets among letter distractors, and asked them to identify the two targets in the correct order. Obviously, we expected conditional T2 performance to be comparatively good at the shortest lag (Lag-1 Sparing), decrease then to show the standard AB, and get back to baseline at the longer lags. Along the lines of the competitive approach and its prediction of a negative relationship between T1 and T2
performance, we also expected T1 performance to be particularly bad at Lag 1. Finally, taking up the joint-integration idea, we would expected order errors to be particularly pronounced at Lag 1.

**Method**

**Participants**

Sixteen students from Leiden University volunteered to participate for pay in single sessions of about one hour.

**Apparatus and stimuli**

Display and timing was controlled to the nearest millisecond by a standard PC. A white asterisk served as fixation mark, appearing at the center of the black screen. Target stimuli were the digits 1, 2, 3, 4, 6, 7, 8, and 9, and distractors were the 26 letters of the alphabet, all appearing in white at screen center. All stimuli were presented in text mode; from a viewing distance of about 60 cm, each symbol measured about 0.3° in width and 0.4° in height. Participants were to identify the two targets and to type the corresponding numbers in the correct order in the computer keyboard.

**Procedure and design**

After an intertrial interval of 2,000 ms, each trial began with the presentation of the fixation mark for 1,000 ms, followed by a blank interval of 250 ms. Then a stream of 15 symbols appeared, each symbol being replaced by the next after 98 ms. Each stream consisted of two digits (T1 and T2) and 13 randomly drawn letters (without replacement). T1 could appear in stream position 2, 3, or 4 (randomly determined), and T2 in 1, 2, 3, 4, 5, 6, 7, or 8 positions later (Lags 1-8). T1 and T2 were always different. Participants were to identify T1 and T2 at leisure at the end of the trial. They were presented with the prompt "First digit:" (in Dutch), pressed the number key they considered correct, and then the procedure was repeated for the second digit. Feedback was provided by briefly (1,000 ms) presenting a pair of plus (correct)
and/or minus (incorrect) symbols, one for each response. Each participant worked through 10 randomly determined practice trials and 10 experimental blocks. Each block was composed of 32 randomly ordered trials, the possible combinations of 8 lags and four randomly determined pairs of (always different) targets per lag.

**Results and discussion**

A significance level of 5% was adopted for all analyses. Degrees of freedom were adjusted according to Greenhouse-Geisser, if applicable (i.e., in case of a significant test on sphericity). The data from one participant were excluded from analyses because of extraordinarily high overall error rates.

We first checked whether a standard AB with Lag-1 Sparing was obtained. To do that, we computed, for each participant, the conditional percentage of T2 report given that T1 was reported (T2|T1), separately for each lag. These data served as input into an ANOVA with lag (1-8) as within-participant factors. The lag effect was reliable, $F(3.5, 49.1) = 9.91$, $MSE = .02$, $p < .001$. As shown in Figure 1 (filled symbols), performance on T2 was very good at Lag 1, dropped then by more than 20% in absolute report accuracy, to recover around Lag 5, where an asymptotic level of about 70% was reached. Given this performance level at lags that clearly extend beyond the interval that entails the attentional blink, it is in our view reasonable to accept this as a baseline for two-target performance. A paired samples T-test confirmed that performance at Lag 3 differed significantly from Lag 8, $t = -3.40$, $p < .005$. That is, we were able to produce both an AB and a Lag-1 Sparing effect that satisfies the criteria suggested by Visser et al. (1999), namely performance at Lag 1 that exceeds the lowest level of performance by more than 5% in absolute terms.
Figure 1: Percentage correct conditional report of the second target given the first target (T2|T1), and of the first target given the second (T1|T2), as a function of lag in Experiment 1. Error bars represent standard error.

The next step was to see whether Lag 1 would really be spared or whether good T2 report at Lag 1 came at the expense of T1 performance. To do so, we reversed the logic underlying the previous analysis and computed the conditional percentage of T1 report given that T2 was reported (T1|T2), over all eight lags (see Figure 1, unfilled symbols). Interestingly, an ANOVA on these data did not reveal any lag effect, $F(3.9, 54.2) < 2$ (see unfilled symbols). Even if we consider the small numerical drop at the shortest lag, it seems clear that T2 sparing cannot be fully accounted for by a trade-off with T1—a finding that is at variance with the competition account of Potter et al. (2002). And yet, Lag-1 Sparing did not come for free either, as more detailed analyses revealed. Figure 2 provides an overview of the unconditional report accuracy for T1 (unfilled symbols) and T2 (filled symbols), as a function
The boundaries of attention of lag. Circles show percentages of trials in which a target was correctly reported in terms of both identity (which digit) and temporal position (e.g., T1 was reported as first target), a stricter criterion than applied to the data in the conditional analyses previously. Clearly, T1 report is dramatically impaired at Lag 1 but relatively stable across the remaining lags, $F(3.7, 51.2) = 26, MSE = .009, p < .001$, which fits with the observations of Potter et al. (2002). T2 performance, on the other hand, is relatively bad (though still way above chance) at the first three lags, increases from Lag 4 to Lag 5, where it reaches an asymptote, $F(7, 98) = 7.72, MSE = .008, p < .001$. Obviously, there is nothing special in T2 performance to Lag 1, nothing is spared here or at the two subsequent lags. But as computing the conditional T2 report rate relates the report of both targets to the report of T1 alone ($[T1&T2]/[T1&T2+T1]$), the large drop of T1 performance at Lag 1 increases the relative size of the additional contribution from T2 and, thus, makes conditional T2 performance look better.
Figure 2: Percentage correct unconditional report (+/- 1 SE) of the second target, where "p" denotes the position criterion and "i" the identity criterion (identity only: T2i; identity and temporal position: T2pi) and of the first target (identity only: T1i; identity and temporal position: T1pi) as a function of lag in Experiment 1.

And yet, something is spared, as the other two lines in Figure 2 reveal (see diamond-shaped symbols). They show again unconditional performance on T1 and T2 but with a laxer accuracy criterion. Here, we considered as correct all reports of the correct digit identities, irrespective of whether the order was correct or not. Not surprisingly, overall performance is somewhat better than according to the stricter criterion, which shows that the loss of item-order information is a general problem in an AB task. Moreover, the fact that performance is better across all lags suggest that this problem is not (only) due to the temporal proximity of the two targets; rather, it seems that order or temporal-position information is either difficult to code or to bind to stimuli belonging to the same stream of events. Similar to the strict unconditional analyses, both T1 and T2 performance showed a significant lag effect, $F(3.9,$
55.2) = 2.83, $MSE = .007, p < .05$, and $F(3.8, 52.5) = 10.24, MSE = .018, p < .001$, respectively.

Apart from the general difference in performance level the shapes of the curves with strict versus lenient accuracy criteria are relatively similar, but there are two interesting exceptions. First, T1 performance no longer drops at Lag 1. This suggests that the drop obtained with the strict criterion does not reflect that T1 was not encoded or stored. Indeed, the identity of T1 is maintained rather well, but it does not seem to be bound to the correct temporal position if the two targets appear in close succession. The second exception is that T2 performance shows a Lag-1-Sparing-type function with particularly good performance (here in absolute, unconditional terms) at the shortest lag. Thus, the loss of order information for T1 goes along with equally strong increase in reports of correct T2 identity. In fact, identity information for both targets is retained better at Lag 1 than at any other lag, which suggests that temporal proximity of to-be-processed stimuli does provide some extra benefit. But this benefit comes at the expense of order information.
Finally, we analyzed the different types of errors or, more precisely, partial reports. If we adopt the strict accuracy criterion, we can distinguish between six types of partial reports: trials in which no target was reported correctly (None), reports of correct T1 identity in incorrect position (and no correct T2 identity), reports of correct T1 identity and position, reports of correct T2 identity in incorrect position (and no correct T1 identity), reports of correct T2 identity and position, and reports of correct T1 and T2 identities in the wrong order. Figure 3 provides an overview of the distribution of these types of errors across lags. Reliable lag effects were obtained for T1 identity, $F(2.6, 36.1) = 11.71, MSE = .002, p < .001,$
T1 identity and position, $F(7, 98) = 8.55$, $MSE = .01$, $p < .001$, T2 identity, $F(7, 98) = 2.57$, $MSE = .002$, $p < .05$, and T1 and T2 identity, $F(2.3, 31.6) = 59.54$, $MSE = .004$, $p < .001$, but no effects were obtained for the categories none, $F(3.1, 44.6) < 1.93$, and T2 identity and position, $F(3.4, 47.5) < 1.09$.

Overall, the by far strongest contribution to partial reports comes from full T1 reports (i.e., of both identity and correct temporal position) accompanied by the absence of any T2 report. This is particularly true for Lags 3 to 8 where, apart from some T1-identity-only reports, other types of partial reports play a negligible role. Things change, however, at the two shortest lags. This is particularly true for Lag 1, where full reports of T1 show a pronounced decrease and even together with partial T1 reports do not reach the frequency of full T1 reports at longer lags. Thus, short lags lead to a loss of T1-related information, especially to the loss of position information. Interestingly, T2-only reports do not change much across lags: Full T2 reports are not reliably affected at all and identity-only reports show just a slight increase at Lag 1. That is, the most dramatic effect of lag concerns the reports of correct identities of both targets in the wrong order. This category is negligible across the longer lags but it provides the by far strongest contribution at Lag 1. This pattern has two implications: that Lag 1 facilitates the report of both target identities and that it does so at the expense of order information.

To summarize, Experiment 1 does not provide evidence in support of a competitive to account a la Potter et al. (2002), that is, good performance on T2 at Lag 1 cannot be (fully) explained by a trade-off against T1. In contrast, more than one identity can be processed at the shortest lag, the possibility that seems to be gone as soon as the first distractor arrives. But it is also true that this particularly good performance does not come for free: Processing two targets at the same time is accompanied by, or leads to the loss of information about the temporal order in which these targets appeared. Together with the similar observations in the
literature, we take that as converging evidence in favor of an integration account as implied by the sluggish gate metaphor.

**Experiment 2**

The first experiment provides some evidence for target integration at Lag 1, whereas hints towards a mere trade-off between T1 and T2 were lacking. One possible interpretation of the latter outcome is that for some reason competition between the two targets did not take place in our particular set up. However, it is also possible that competition did take place but to a degree that was insufficient to result in the exclusion of one target or the other from processing. Experiment 2 was designed to explore this possibility by manipulating the degree of conflict between the two targets by varying their (relative) visual discriminability. Reducing the discriminability of one target is likely to lengthen the time needed to complete its identification, which according to Potter et al. (2002) should reduce the odds of that target winning the competition for access to attentional resources. In other words, the less the discriminability of a target the more likely it will miss the open attentional gate. Accordingly, performance on T1 should increase with decreasing discriminability of T2, and performance on T2 should increase with decreasing discriminability of T1, particularly at Lag 1.

**Method**

**Participants**

Another 20 students (17 female, 3 male; mean age 19.1 years) from Leiden University volunteered to participate for pay or course credit in single sessions of about one hour.

**Apparatus and stimuli**

The experiment was controlled by the E-Prime© experimental software package. Each self-initiated RSVP stream was preceded by a black plus sign (“+”), presented for 200 ms on a gray background (RGB 128, 128, 128). Target digits were the same as above, but were varied
The boundaries of attention

in intensity, depending on the discriminability condition. On the basis of pilot testing, white (220, 220, 220) targets were considered to be easy to discriminate, black (0, 0, 0) targets as of medium difficulty, and gray (60, 60, 60) targets as difficult, based on the contrast with the gray background\(^1\). Distractors were as in Experiment 1, presented in black on a gray background at screen center.

**Procedure and design**

After the self-paced initiation of each trial a 800-ms pause was followed by the fixation mark, in turn followed by the first RSVP stimulus. The total stream consisted of 20 stimuli, presented for ~59 ms each and with an inter-stimulus interval of ~35 ms. Each RSVP contained two random target digits and 18 random letters. T1 was presented as either the 7\(^{th}\), 8\(^{th}\) or 9\(^{th}\) item in the stream. T2 followed at Lag 1, 3, 5 or 8. No letter nor digit was repeated within any trial. At the end of the RSVP a 200 ms pause ensued. Then the two targets were to be identified in the correct order as in Experiment 1. No feedback was provided. Each session entailed one practice block of 32 trials and three randomly mixed experimental blocks of 144 trials each.

**Results and discussion**

T2|T1 performance was analyzed by using a 3 x 3 x 4 repeated-measures design, with T1 discriminability (easy, medium, or difficult), T2 discriminability, and lag (1, 3, 5, or 8) as independent variables. Significant main effects were obtained for T1 discriminability, \(F(2, 38) = 9.7, \text{MSE} = .01, p < .001\), T2 discriminability, \(F(1.3, 24.2) = 36.11, \text{MSE} = .088, p < .001\), and lag, \(F(1.9, 36.1) = 39.06, \text{MSE} = .051, p < .001\). Reliable two-way interactions were obtained for T1 discriminability x lag, \(F(6, 114) = 3.28, \text{MSE} = .012, p < .005\), T2 discriminability x lag, \(F(6, 114) = 18.76, \text{MSE} = .01, p < .001\), and T1 discriminability x T1 discriminability, \(F(4, 76) = 4.48, \text{MSE} = .008, p < .005\). The three-way interaction of these variables was marginally significant, \(F(5.9, 112.5) = 2.17, \text{MSE} = .017, p < .052\). The main
effects indicated 1) that performance was much better with an easy-to-discriminate T2 (98%) as compared to medium (84%) and difficult (80%) T2s, 2) that a typical AB was obtained (which was also confirmed by a reliable difference between Lag 3 and Lag 8, our baseline, $t = -7.5, p < .001$), including Lag-1 Sparing (see Figure 4, filled symbols), and 3) that T1 discriminability was a mirror image of its T2 counterpart: Performance on T2 tended to be worse if T1 was easy to discriminate (85%) as compared to T1s of medium (88%) or high (88%) difficulty.

Figure 4: Percentage correct conditional report (+/- 1 SE) of the second target given the first target ($T2|T1$), and of the first target given the second ($T1|T2$), as a function of lag in Experiment 2.

The interaction effects reflected two relationships: First, in contrast to the other T2 conditions, performance on T2 was unaffected by T1 & T2 discriminability and lag if T2 was easy to discriminate; this interpretation was supported by the fact that dropping the easy-T2
conditions eliminated the three-way interaction, \( p > .4 \), as well as the other interactions with T2 discriminability, \( p \)'s > .5. We will see a similar pattern in T1 performance, where the easy-discrimination condition was also the least affected. These observations are direct reflections of the experimental manipulation and indicate little more than the fact that black letters are no particularly good masks for white targets. Second, and more importantly, in the medium and difficult T2 conditions, T1 discriminability had an effect on the two shortest lags but not on the longer lags (see Figure 5). This interaction was entirely due to the easy T1 condition, as dropping that condition eliminated the effect, \( p > .3 \). Such an outcome provides strong support for a competitive account of Lag-1 Sparing, according to which an easy-to-discriminate T1 is a particularly strong competitor that reduces the chances for T2 to get access to attentional resources.

![Figure 5](image)

*Figure 5: Percentage correct conditional report (+/- 1 SE) of the second target given the first target (T2|T1) as a function of T1 discriminability and lag in Experiment 2. Separate panels represent different T2 discriminability conditions.*
Chapter 4

An ANOVA on T1|T2 yielded main effects of T1 discriminability, $F(1.2, 23.5) = 9.9$, $MSE = .065$, $p < .005$, T2 discriminability, $F(2, 38) = 7.19$, $MSE = .01$, $p < .005$, and lag, $F(2.1, 40.8) = 17.63$, $MSE = .018$, $p < .001$. Lag interacted with both T1 discriminability, $F(3.4, 65.1) = 4.14$, $MSE = .013$, $p < .01$, and T2 discriminability, $F(3.1, 58.1) = 4.62$, $MSE = .015$, $p < .005$.

The overall effect of lag is shown in Figure 4: Performance on T1 was worse than on T2 at Lag 1 and then gradually improved until Lag 5, a pattern that is consistent with the Potter et al. (2002) study. As shown in Figure 6, T1 performance at short lags was the better the easier T1 discrimination and the more difficult T2 discrimination were. The fact that the ease of identifying T2 affects T1 performance at all is difficult to combine with, and certainly not predicted from the sluggish-gate account. In contrast, both interactions are exactly as predicted from a competitive account in showing that performance on T1 is a direct reflection of the relative competitiveness of both T1 and T2: better performance the stronger T1 and the weaker T2.
To compare these outcomes with those from Experiment 1 we also ran ANOVAs on unconditional T1 and T2 performance, separately for the two scoring criteria (lax = identity only, strict = identity & order). As Figure 7 shows, the results were comparable; for the sake of brevity, all significant effects are listed in the Appendix.
Figure 7: Percentage correct unconditional report (+/- 1 SE) of the second target, where "p" denotes the position criterion and "i" the identity criterion (identity only: T2i; identity and temporal position: T2pi) and of the first target (identity only: T1i; identity and temporal position: T1pi) as a function of lag in Experiment 2.

Partial reports were classified as in Experiment 1. Figure 8 provides an overview. The emerging pattern is very similar to that obtained in Experiment 1. First, the three longer lags and Lag 3 in particular are dominated by reports of correct T1 identity and position in the absence of T2—the sign of a standard AB. Second, the by far largest contribution to Lag 1 comes again from reports of correct T1 and T2 identities in the wrong order. Separate analyses of the error types yielded reliable lag effects for T1 identity, $F(1.8, 34.3) = 12.40, MSE = .009, p < .001$, T1 identity and position, $F(1.8, 34) = 37.92, MSE = .023, p < .001$, T2 identity, $F(1.4, 26.6) = 19.41, MSE = .004, p < .001$, T2 identity and position, $F(1.8, 34.3) = 10.14, MSE = .015, p < .001$, and T1 and T2 identity, $F(1.2, 23.6) = 181.56, MSE = .038, p < .001$, while no effect was obtained for category none.
Figure 8: Percentage partial reports as a function of lag in Experiment 2 (None correct: None; T1 identity only: T1i; T1 identity and temporal position: T1pi; T2 identity only: T2i; T2 identity and temporal position: T2pi; both targets in wrong order: T1i & T2i).

Figure 9 shows how error types are distributed at Lag 1. Even though the pattern looks complex it tells a rather coherent story. First consider the three conditions with an easy T1, hence, the three left-most bars. If T2 is easy as well—i.e., if the two targets are equally strong competitors—identity-related performance is excellent but subjects often commit order errors, accompanied by a smaller but still considerable tendency to report only T2. As T2 gets less discriminable, order errors and T2-only reports become less frequent and give way to an increasingly strong tendency to report T1 only. Next, consider the three medium-T1 conditions. The tendency to report T2 only is even stronger if T2 is easy to discriminate but is replaced by an increasing contribution from order confusions and T1-only reports as T2 discriminability decreases. Finally, consider the three difficult-T1 conditions, where we see the same trends as with medium T1s but on a higher overall level for almost all error types.
involved. These error patterns suggest at least two important conclusions. First, big differences in discriminability between the two targets strongly increase exclusive reports of one, namely, the better discriminable target. This observation is consistent with Potter et al.’s (2002) claim that targets compete for access to attentional resources and that the time needed to complete target identification is a crucial determinant of competitive strength. Second, small discriminability differences between the two targets seem to induce mainly order confusions, which is particularly obvious from the opposite effect of T2 discriminability on the error confusions (T1iT2i) with easy T1s (where easy T2s create the most confusions) and with difficult T1s (where difficult T2s create the most confusions). As subjects were able to correctly report both target identities both targets must have gained access to attentional resources. According to the sluggish-gate account this would mean that T1 and T2 became part of the same attentional episode, which necessarily eliminated information about the sequence of the two stimuli.
All in all, Experiment 2 shows that performance at Lag 1 of an AB task is systematically affected by the discriminability of the two targets. Assuming that absolute and, more important, relative discriminability of the targets determines their competitive strength when trying to get access to attentional resources our findings provide direct evidence that T1 and T2 do indeed compete for access to the next processing stage and that this competition is particularly pronounced at Lag 1. However, we also found strong evidence for integration, especially in cases where the two targets were likely to be competitors of equal strength. Thus, there are reasons to assume that competition and integration accounts do not provide alternative interpretations of the same phenomenon but, rather, refer to the different possible outcomes of concurrent target processing.
General discussion

Our study aimed at investigating the mechanisms underlying the so-called Lag-1 Sparing in the AB task. In particular, we asked two questions: One was whether T1 performance would be affected by lag, which would support Potter et al. (2002) suggestion that T1 and T2 compete for access to attentional resources. The second was whether Lag 1 would be associated with an increase of order errors in target reports, which would support the idea that the two targets may be processed in or integrated into a common attentional episode. Both questions can be answered affirmatively.

T1 report was strongly affected by lag, at least in Experiment 2. As in the study of Potter et al. (2002), the probability of correctly reporting T1 was reduced at Lag 1 to a degree that varied with the amount of "sparing" observed for T2. The fact that we were able to replicate this effect shows that Potter et al.’s observations are not restricted to the RSVP tasks with spatial uncertainty they used but generalize to standard AB tasks. Moreover, we were able to demonstrate the exchange relation between T1 and T2 in conditionalized accuracy data, vis-à-vis a standard AB and a Lag-1 Sparing effect that both satisfy the criteria of Visser et al. (1999). Thus, we can be sure that T1 performance is affected by the temporal distance between T1 and T2—which fits well with previous observations of Broadbent and Broadbent (1987) and Chun and Potter (1995)—and that at least part of the Lag-1 Sparing of T2 performance due a trade-off with T1—supporting the conclusions of Potter et al. (2002).

With regard to our second question about target-order errors the outcome is also clear. In Experiment 1 we saw that subjects often reported the right target identities in the wrong order when T1 and T2 were presented in direct succession. Experiment 2 confirmed this impression and showed that the frequency of order errors depends on the relative discriminability of the two targets, which we take to determine the targets’ competitive strength.
Taken together, our findings underscore Potter et al.’s (2002) point that some qualifications are in order of both the term "Lag-1 Sparing" and of assumptions about the mechanisms underlying it. Regarding the term it seems clear by now that whether one can consider...
something is spared or not strongly depends on one's performance criteria. This is obvious from Figure 10, where we present, for Experiments 1 and 2, the unconditional, lag-related performance on both targets (i.e., the percentage of trials in which both targets were reported correctly) as a function of two different criteria of what counts as "correct report". The filled symbols represent the rather lenient criterion that is commonly used in AB studies, namely, the requirement to report correct identities irrespective of order (e.g., Chun & Potter, 1995). Clearly, what we see here can be characterized as "sparing", inasmuch as Lag 1 shows better performance than any other lag. The unfilled symbols represent the stricter requirement to report both identity and order correctly. Here we see no evidence of any special role of Lag 1, which in fact produces the numerically worst performance.

In our view, the very fact that Lag-1 Sparing depends on whether target order is to be reported or not points to the mechanism underlying it. A strong interpretation of a competitive account along the lines of Potter et al.'s (2002) holds that targets compete for access to attentional resources and that only one target can win, hence, no more than one stimulus at a time can enter the first stage of processing in an AB task. (Potter et al. rightly point out that their findings do not require this conclusion but they do seem to have a strong preference for it.) However, we find it difficult to see how such an account may explain the pattern presented in Figure 10: Why, through competition between temporally close T1 and T2, would identity-related performance benefit but order information get lost? This does not mean that competition does not take place at all—in fact, we have seen several reasons to assume that it does—but competition as such does not seem to readily account for the patterns in our error data.

A better account for this particular pattern seems to us to be the suggested interpretation of the sluggish-gate metaphor discussed by Chun and Potter (1995), Shapiro and Raymond (1994), Visser et al. (1999) and others, that presenting two targets in close
temporal succession may lead to the joint integration of both events into a single episodic trace. If so, T2 codes can kind of parasitize T1 and enjoy the same prioritized attentional treatment as the first target. This comes with a cost, however: As both targets now belong to the same represented episode information about their temporal relation is lost, as witnessed by the excessive increase of order errors we observed in our two experiments. If these errors count, temporal proximity can be said to impair (or have no impact on) performance, but if they do not count temporal proximity has a positive effect—Lag-1 Sparing. The consideration that integrating both targets into a common episodic trace may benefit performance (as long as order is not an issue) is also consistent with recent demonstrations of Kellie & Shapiro (2004). By using a morphing technique they showed that the AB is eliminated if T2 is a visual continuation of T1 and, hence, is presumably perceived as a mere change of T1 but as not a new object. Moreover, the suggestion that identity information may often be retained while order information is lost fits well with observations of Kessler and colleagues in a recent MEG study of the AB (Kessler, Schmitz, Gross, Hommel, Shapiro, & Schnitzler, 2005a, 2005b). The activation patterns obtained in this study suggest that, in the AB task, a left-temporo-parietal network is coding the identity of the targets and their match with the maintained target template while a dissociable, slightly time-lagging right-temporo-parietal network is responsible for binding identities to temporal positions. That is, identifying the targets may well be independent from, and briefly precede assigning temporal order. If so, the identification network may (often) treat temporally close targets as one single stimulus which then receives a single time tag (or two distorted tags) from the temporal-binding network—thereby effectively eliminating or distorting order information. Indeed, Kessler et al. (2005b) found distinct M300 (the magnetoencephalographic equivalent of the P300) components for the two targets in prefrontal and right-temporo-parietal areas but only a single component in left-temporo-parietal areas.
The findings from Experiment 2 further suggest that, if two target stimuli are presented sufficiently close in time, they compete for attentional resources. One possible outcome of this competition is that one target wins at the expense of the other(s)—which will not be retained for later report. The easier a target can be discriminated relative to its competitor the better its chances to win and the less likely the competitor will be recalled. If two competitors are equally strong, however, they will often be treated as one single event and get both access to attentional resources. But this comes with a cost, as order information will be lost. While the joint integration of targets and its associated loss of order information can be better explained by the sluggish-gate metaphor, the trade-off of identification performance observed in Experiment 2 seems to be better accommodated by the competition account.
Footnotes

1. Note that we do not claim that our discriminability manipulation reflects variations on a single physical scale or dimension. On the contrary, the three types of targets differed in a number of respects: White targets were the most intense, the most unique, and the least well masked stimuli (the letter stream was black); black targets were the least intense, the least unique (same color as letter stream) and best masked stimuli, that however were easy to see on the gray background; whereas gray targets were of medium intensity, relatively unique, not well masked, but very similar to the background. However, the results will show that this mix of characteristics was successful in creating three conditions of sufficiently differing difficulty and “competitiveness” with respect to the hypothesized race for access to attentional resources. None of our conclusions will depend on how these differences were achieved.

2. Note that although Lag 1 is most strongly affected by our discriminability manipulation the AB-critical period still shows an effect. In other words, making the processing of the targets easier or more difficult as an impact on the size of the AB. This observation is consistent with a number of other studies (Chun & Potter, 1995; Grandison, Ghirardelli, & Egeth, 1997; Seiffert & Di Lollo, 1997, who also provide an overview) but inconsistent with McLaughlin, Shore, and Klein's (2001) failure to find a relation between target difficulty and the AB. This is somewhat paradoxical because McLaughlin et al.’s design can considered to be the most similar to ours in attempting to manipulate the perceptual quality of the targets and avoiding a task switch between them. However, in contrast to the present study, McLaughlin et al. manipulated the discriminability of T1 and of T2 in different experiments and by using the skeletal target-mask-target-mask task version introduced by Duncan, Ward, and Shapiro (1994). In the absence of more systematic research on this issue we are unable to offer an interpretation of how these procedural differences might explain the divergent outcomes.
What seems clear, however, is that McLaughlin and colleagues' conclusion that data-limiting difficulty manipulations do not affect the AB is too general.
### Appendix

#### T1 unconditional, strict

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#### T2 unconditional, strict

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#### T1 unconditional, lax

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#### T2 unconditional, lax

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Chapter 5: Top-down control of event integration

Selecting two targets from a quickly presented stream of visual symbols is much easier if the second target appears at Lag 1 (i.e. immediately after the first target) than when it appears later. This phenomenon may be due to both targets being able to get access to attentional resources if they appear within the same temporal integration window, which fits with the observation that targets are often reported in the wrong order at Lag 1. The present study investigated whether people have control over the size of their integration window. Control strategies were induced by raising different expectations: one group was led to expect a slow presentation rate of the visual stream and another group was led to expect a fast presentation rate. As predicted, target-order reversals for Lag 1 were more frequent for the group expecting slow presentation, suggesting that the expected presentation rate in that group motivated the choice of a longer integration window.

Introduction

Selecting one or more predefined target objects from a rapidly changing stream of visual information is a difficult task (Schneider & Shiffrin, 1977). Such rapid serial visual presentation (RSVP) tasks are known to produce the so-called Attentional Blink (AB): the second of two to be reported targets (T2) is often missed if it appears briefly after the first (T1; Raymond, Shapiro & Arnell, 1992). The AB has been attributed to competition between target codes for access to short-term memory (Chun & Potter, 1995), competition within short-term memory (Raymond et al., 1992), or to capacity limitations associated with consolidation into short-term memory (Jolicœur & Dell'Acqua, 1998). An interesting exception can be observed when T2 immediately follows T1, that is, at Lag 1: Performance on T2 can be much better than at the following lags and as good as, or even better than with very long lags; a phenomenon that has been called Lag-1 Sparing (Potter, Chun, Banks, & Muckenhoupt, 1998). Lag-1 Sparing and the AB are intertwined, since Lag-1 sparing is an escape from the dual task deficit evidenced by the AB. Yet, the sizes of the two effects are uncorrelated and can be dissociated by appropriate experimental manipulations, which
suggests that they have different origins (Visser, Bischof & Di Lollo, 1999). In the present study, we were focusing on mechanisms underlying Lag-1 Sparing but not (necessarily) the AB.

Sparing may be due to at least two different, not mutually exclusive processes. First, targets appearing close in time may compete for attentional resources, so that whatever is spared with respect to T2 is lost with respect to T1 (Potter, Staub & O’Connor, 2002). Indeed, a trade-off between the two targets at Lag 1 has been observed in several studies (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Hommel & Akyürek, in press; Potter, Staub & O’Connor, 2002), suggesting that competition does play a role. In particular, at Lag 1, the competition seems to be biased towards the identity of T2; whereas T1 is favored during the AB. However, the occurrence of biased competition cannot be the whole story. As found by Hommel and Akyürek (in press) and others (e.g. Shih, 2000), Lag-1 Sparing is accompanied by a substantial increase of order errors, that is, people are able to report both targets in a substantial number of trials but they do so in the wrong order. This suggests temporally close targets may, under particular circumstances, be integrated into the same episodic representation or object file in the sense of Kahneman, Treisman, and Gibbs (1992; cf., Raymond, 2003; Sheppard, Duncan, Shapiro & Hillstrom, 2002). Integration of two targets in a unique representation would, on the one hand, help to recall the identity of more than one target but, on the other, lead to the loss of information about their relative timing and temporal order (Hommel & Akyürek, in press). The increase of order errors and its associated improvement of identity report are typical of the Lag-1 condition and have no parallel in ‘blinked’ lags.

In the present study, we investigated whether people can exert control over this hypothetical integration process. Lupiañez, Milliken, and colleagues (Lupiañez & Milliken, 1999; Lupiañez, Milliken, Solano, Weaver & Tipper, 2001) provided evidence that people
can adjust the time window during which information about a given visual object is collected and thus when the object file holding this collection is closed. For instance, they have shown that the transition from priming by location repetition to inhibition of return occurs earlier in time when interfering distractors are present than when they are not (Lupíañez et al., 2001). That is, it seems possible that the mere expectation of the presence or absence of a distractor can affect the time taken to integrate information about a target. In other words, people may be able to control the size of the temporal integration window used to construct object files.

Consider how encouraging participants to use a short versus long integration window would affect the integration of the two targets at Lag 1. When encountering T1, the corresponding object file would be left open and information would be collected for a longer time, so that T2 would have greater chance to be included and integrated. The increased probability of joint integration should be accompanied by an increase in the frequency of order confusions. That is, people should be more likely to report both targets in the wrong order.

This is what we tested in the present study. We presented two groups of participants with standard RSVP trials, that we expected to produce Lag-1 Sparing, as defined by Visser et al. (1999; i.e., performance at Lag 1 exceeds the lowest level of performance at any other lag by more than 5%). In one group, we mixed a large proportion of typical RSVP trials in which stimuli had a fast presentation rate with a small portion of "slow" trials, where the presentation time of the visual stimuli was sufficiently long to render the task almost trivial. As there were only a few of these slow trials, we did not expect any major effect of this manipulation. In another group, we mixed a small proportion of fast trials with large proportion of slow trials. The high frequency of trials in which there was ample time to process the targets was expected to encourage participants to use a rather long integration window even in the few fast trials. As a consequence, the frequency of order errors in fast
trials at Lag 1 should be increased in this slow group as compared to the first, fast group. As a second independent variable, we manipulated the predictability of the point in time when T1 occurred: in one condition, T1 occurred always in the same position of the visual stream and, in another condition, T1 could occur in three different positions. If the size of the temporal integration window would be a general parameter that affects any integration process in a task, the predictability of T1 onset should affect the fast versus low manipulation. However, such a parameter may only refer to specific integration processes, scheduled for a particular point in time. If so, the fast-slow manipulation may only affect performance at Lag 1 when T1-related integration can be scheduled ahead of time, that is, only if the time point of T1 appearance can be predicted.

**Method**

**Participants**

Eighty Leiden University students (55 female, 25 male) volunteered to participate in the experiment in exchange for course credit or small fee. None of them was aware of the purpose of the experiment and all reported having normal or corrected vision. Mean age was 21.2 years.

**Apparatus and stimuli**

The experiment was designed using the E-Prime© software package and stimuli were presented on a standard PC using a 17” monitor refreshing at 100Hz. Participants were seated in a small, dimly lit cabin at a viewing distance of about 50 centimeter. A black plus sign (“+”) presented at the center of the gray screen served as fixation mark. Target digits were 1, 2, 3, 4, 6, 7, 8 and 9 and distractors were chosen from the 26 letters of the alphabet. All characters were set in 16 point Times New Roman font and presented in black. Participants were to respond to successive prompts (1st, then 2nd target) after RSVP offset by pressing the corresponding numeric keys on the keyboard.
Procedure and design

Participants initiated each trial by pressing the spacebar, followed 200 ms later by the 200-ms fixation mark. The RSVP stream immediately followed, it consisted of 14 items with either 80 or 240 ms duration per stimulus and no blank in between. Finally, after another 200 ms delay, two identification prompts were presented for the unspeeded responses to T1 and T2. Target and distractor items were randomly drawn from their sets (see above), but were never repeated within a trial. Each participant completed 36 practice trials and 540 experimental trials. Depending on the speed condition, sessions lasted from 60 to 75 minutes.

The design comprised of one within-subjects factor, the lag between T1 and T2, which varied from one to nine. Between-subjects factors were expected speed and the predictability of T1 position. Expected speed was varied by manipulating the frequency of fast and slow presentation durations. In the fast group, the stimuli were presented for a short duration in 80% of the trials and for a long duration in 20% of the trials, whereas in the slow group these stimuli appeared for a short duration in 20% of the trials and for a long duration in 80% of the trials. T1 position predictability was manipulated by presenting T1 always as the third item (fixed position) versus presenting it randomly but evenly distributed in positions 2, 3, and 4 (of 14).

Results and discussion

Performance was analyzed for accuracy on T1 and T2 and, most importantly for our purposes, the frequency of target order reversals. Only the fast trials were examined, as the slow ones only served to induce different expectations regarding the possibility to integrate the two targets in a single event due to the temporal contiguity. The significance level was set to 5% and degrees of freedom were adjusted to Greenhouse-Geisser values (rounded to one decimal) whenever appropriate.
Figure 1: T2 performance given T1 correct for fast and slow speed expectations (top panel), and fixed and variable T1 (middle). Bottom panel shows target-order confusions for fast and slow speed expectations.
The boundaries of attention

Performance on T1 produced only a main effect of lag, $F(6.4, 490) = 8.77, p < .001$. Accuracy was poorest at Lag 1 (84.9%) and recovered rapidly at Lag 2 (90.6%), from which on it remained rather stable (91.7%, 92.2%, 92.1%, 91.7%, 92.0%, 91.4%, and 91.7%). Note that the slight drop at Lag 1 is accompanied by particularly good performance on T2 (see Figure 1), which indicates a trade-off and, thus, competition between the two targets.

Conditional performance on T2 (T2|T1 correct) also yielded a main effect of lag, $F(5.7, 434) = 20.62, p < .001$. As shown in Figure 1, a modest but reliable AB is apparent, as is the well preserved performance on Lag 1 (i.e., Lag-1 sparing). The main effect of speed expectation reached significance as well, $F(1, 76) = 3.98, p < .05$. Overall, performance was better in the slow than in the fast group (82.3% vs. 77.5%). Most importantly, lag and speed expectation interacted, $F(8, 608) = 1.99, p < .05$, as did lag and position predictability, $F(8, 608) = 1.99, p < .05$, whereas the triple interaction was far from significance, $F<1$. With regard to the interaction between lag and position predictability, our findings are consistent with those of Martens and Johnson (in press) in showing a smaller blink for fixed position of T1. However, the small size of the blink is not due to better performance for the critical lags 2-4 but, rather, to comparatively worse performance at longer lags. We are unable to offer an explanation for this finding. More interesting for purposes, lag also interacted with speed expectation, indicating generally increased performance and the absence of an AB (as measured by comparing the critical Lags 2-4 with the longest lag) in the slow group! A possible explanation for this surprising finding might be that rendering the lion's share of the task more or less trivial by frequently presenting the visual stream in slow motion induced a rather relaxed attitude towards the task, which has been shown to reduce or even eliminate the AB (Olivers & Nieuwenhuis, in press).

The final analysis concerned the number of target-order confusions. Main effects were produced by both lag, $F(3.1, 233.5) = 286.97, p < .001$, and speed expectation, $F(1, 76) =$
4.22, \( p < .05 \). Most interestingly, these two factors interacted, \( F(8, 608) = 3.72, p < .001 \). As shown in Figure 1, order confusions proliferated at Lag 1, but more so in the slow group—exactly as predicted from an integration view. A Tukey test confirmed that the only significant difference was found at Lag 1, \( p < .05, q = 3.734 \). To see whether this effect might be due to the differential amount of training the two groups received on the fast trials (fast trials were less practiced in the slow group), we compared all fast trials in the slow group with the first 20\% of the fast trials in the fast group, so that practice on fast trials was perfectly equated. However, the interaction remained reliable, \( F(8, 608) = 2.50, p < .02 \), which rules out a practice account. Again, the difference between groups was limited to Lag 1, \( p < .05, q = 3.075 \).

**General discussion**

We hypothesized that expecting a slow presentation rate of stimulus sequences might encourage our participants to use a rather broad temporal integration window for collecting information into a given object file. If so, these participants should be more likely to produce order confusions, that is, to report the two targets in the reversed order. This is indeed, what we found: participants expecting a slow presentation rate produced more order confusions at Lag 1 than participants expecting a fast presentation rate. This suggests that people have control over the size of their integration window, and that decisions about the size are affected by expectations about the time available for interference-free processing of the relevant information—as claimed by Lupiañez and Milliken (Lupiañez & Milliken, 1999; Lupiañez et al., 2001). Importantly, the impact of speed-related expectations was independent of the predictability of T1 onset. This provides evidence that the parameter that determines the size of the integration window is a general one, that is, a task-wide parameter that is not scheduled for a particular point in time.
Our findings should not be taken to mean that target integration is the only factor that plays a role in Lag-1 Sparing. Given the drop in T1 performance at Lag 1, it seems obvious that the two targets were not integrated but competed for selection in a number of trials (cf., Hommel & Akyürek, in press; Potter, Staub & O'Connor, 2002). It is furthermore likely that expectation is not the only endogenous factor that can affect the integration window. The AB has been observed to be reduced or even disappear if participants are encouraged to relax (Olivers & Nieuwenhuis, in press) and if they manage to reduce their level of cortical activation (Shapiro et al., 2005). Although this does not necessarily mean that these factors also affect Lag-1 Sparing, such an impact is at least possible and seems worthwhile to investigate.

Finding that endogenous factors, such as temporal expectation, can affect the time an object file stays open does not exclude possible contributions from exogenous factors. One promising candidate seems to be the perceptual relation between the targets and/or the elements of the whole RSVP stream. If these relations create a perceptual Gestalt, the AB has been found to be dramatically reduced or even eliminated (Raymond, 2003; Sheppard et al., 2002, Kellie & Shapiro, 2004), and it may well be that perceptual relations between the two targets affect the likelihood that they are integrated into the same object file. It may also be that the mere presence of a distractor, expected or not, triggers the closing of an object file automatically (cf., Akyürek & Hommel, in press; Di Lollo, Kawahara, Ghorashi & Enns, in press).
Footnotes

1. Stimulus presentation time was audited using the E-Prime logging function. An average variation in stimulus onset of less than 2 ms per stimulus in either direction was observed.
Chapter 6: Target integration and the attentional blink

If people monitor a visual stimulus stream for targets they often miss the second (T2) if it appears soon after the first (T1)—the Attentional Blink. There is one exception: T2 is often not missed if it appears right after T1, i.e., at lag 1. This lag-1 sparing is commonly attributed to the possibility that T1 processing opens an attentional gate, which may be so sluggish that an early T2 can slip in before it closes. We investigated why the gate may close and exclude further stimuli from processing. We compared a control approach, which assumes that gate closing is exogenously triggered by the appearance of nontargets, and an integration approach, which assumes that gate closing is under endogenous control. As predicted by the latter but not the former, T2 performance and target reversals were strongly affected by the temporal distance between T1 and T2, whereas the presence or absence of a nontarget intervening between T1 and T2 had little impact.

Introduction

Human attention is limited with regard to space and time. An impressive example for a temporal limitation is the so-called Attentional Blink (AB), which occurs if people monitor a stream of perceptual events for particular target events: If the second of two targets (T2) occurs in an interval of about half a second after the first (T1), it will often be missed (Broadbent & Broadbent, 1987; Raymond, Shapiro & Arnell, 1992). An interesting exception is observed at lag 1, that is, if T2 appears right after T1. In this condition performance on T2 is often as good as at very long lags: the so-called lag-1 sparing phenomenon (Visser, Bischof & Di Lollo, 1999). The present study aimed at investigating why lag-1 sparing occurs and which mechanisms are responsible for it.

A key characteristic of lag-1 sparing is that it comes with a cost: First, relative increases in lag-1 performance on T2 are sometimes accompanied by drops in performance on T1 (Hommel & Akyürek, in press; Potter, Staub & O’Connor, 2002), at least if the time interval between the two targets is short. Thus, not all benefits associated with T2 are due to true "sparing"; instead, short lags may simply increase the probability that the two targets
compete for attentional resources, a competition that T2 sometimes wins. Second, there is evidence that most if not all of the relative increase in performance on T2 stems from trials in which both targets are reported correctly but the wrong order (Hommel & Akyürek, in press). This suggests that, even in the trials in which report of T2 does not go at the expense of T1, "sparing" identity information leads to the loss of temporal order information.

A possible explanation for this trade-off between identity and order information is motivated by the idea that registering T1 leads to the opening of an attentional gate or integration window, which closes after sufficient information has been gathered to identify the first target. This gate may be sluggish, so that T2 will get the opportunity to "slip in" if it appears soon enough (cf., Raymond et al., 1992)--which is more likely the shorter the lag. Integrating the two targets into the same attentional episode would certainly be beneficial for T2, which then could enjoy the same privileged processing as T1. However, if the two targets are processed "as one event" or at least concurrently there would be no way to determine their temporal sequence. Accordingly, people can only guess which of the two remembered targets came first, which will produce numerous order errors. In support of this possibility, Kessler et al. (2005) observed clearly separable M300 (the magneto-encephalographic equivalent of the better-known P300) peaks for two successive targets in frontal cortical regions and right-parietal areas (which, among other things, may be involved in sequencing), while temporal sources (presumably related to identification) showed only a single, merged M300. This suggests that stimuli that appear while the attentional gate is open get parallel access to attentional resources and are identified in parallel, and even their temporal positions may be properly registered. However, the temporal overlap of the identification processes may make the binding of identities to relative positions difficult and error-prone.

Given the apparently very beneficial consequences of opening and leaving open an attentional gate, the question arises why people do not leave this gate open until T2 is
processed, irrespective of the lag. The answer to this question is likely to be related to the many nontargets a typical AB stream includes. The most important of these may be the one directly following T1. In a study by Seiffert & Di Lollo (1997), the presence of this nontarget (or mask), was directly investigated. The authors concluded that a clear negative relation between the occurrence of the mask (which in their view degraded the perception of T1) and the attentional blink existed. Yet, the existence of this relation was challenged by McLaughlin, Shore & Klein (2001), who (using a variable mask-target duration paradigm) observed no relation between T1 accuracy and the severity of the blink. At the same time, an additive effect was found for the same manipulation on T2 and its mask (but see Giesbrecht, Bischof & Kingstone, 2003). If it can at least be assumed that a nontarget following T1 can have an effect on T1 & T2 performance, then there are at least two ways of how the presence of such a nontarget may affect the opening and, more important for present purposes, the closing of integration windows.

First, the occurrence of a nontarget may automatically trigger the closing of the gate. As suggested by Di Lollo, Kawahara, Ghorashi, and Enns (in press), the first nontarget that appears after T1 may hamper the proper maintenance of the target-related task set and induce a temporal loss of control. If T2 appears before control is reestablished, it will be missed. If it appears before the first nontarget, however, as is the case for lag 1, T2 can escape that problem and will be reported as often as T1. Note that the size of the integration window, that is, the time the attentional gate is open, plays no role in this approach. What matters is only whether a nontarget is or is not inserted between T1 and T2--performance on T2 should be bad if it is but excellent if it is not, irrespective of the time between the two targets.

Second, people may be able to control the size of their integration windows. As a typical AB stream consists of numerous distracting stimuli presented in fast succession, it would make sense to tailor the integration window to the rhythm of the stimulus sequence,
that is, to choose integration windows that approximate the presentation time of the targets (cf., Lupiáñez et al., 2001). Consistent with this idea, Toffanin, Akyürek, and Hommel (2005) found more target reversals at lag 1 if subjects were led to expect a very slow presentation rate than if they expected a very fast presentation rate. According to this approach, time may be more important for order reversals than the presence of nontargets, at least with respect to a given trial. On the one hand, it is true that the presence and timing of nontargets will affect the size of the integration window chosen. On the other hand, however, once the experience with the relevant stimulus events has led to the implementation of a particular size, the likelihood that T2 falls into the integration window should only depend on how quickly T2 appears after T1 has been registered and the window opened.

To gain more insight into the processes underlying target integration, and the role of time and nontargets in particular, we varied the duration of T1 on the one hand and the presence or absence of a nontarget at lag 1 on the other. Figure 1 shows the relevant manipulations for the shortest and therefore theoretically most important lags. The first and the third row show the two most standard conditions: T2 appears at the second lag after T1 and lag 1 is either filled with a nontarget (3rd row) or unfilled (1st row). To manipulate the temporal distance between T1 and T2, we could have increased the unfilled interval in the condition without an intervening nontarget and increased the interval between either T1 and the nontarget or between the nontarget and T2 in the condition with an intervening nontarget. Unfortunately, however, this would have introduced a couple of confounding factors, such as breaking the rhythm of the whole stimulus stream if the empty gap becomes too large (Sheppard, Duncan, Shapiro & Hillstrom, 2002) and changing the amount of backward or forward masking provided by the intervening nontarget. To avoid these kinds of effects, we decided to keep the interval between T1 offset and T2 onset constant but manipulate the interval between T1 onset and T2 onset by varying the duration of T1 (see 2nd and 4th row).
Given that some combinations of our experimental factors create rather trivial demands on target processing proper (e.g., performance is likely to be excellent if T1 and T2 are widely spaced and not separated by a nontarget), we focused on the apparently most sensitive measure of T1-T2 integration, namely, target-order reversals. In particular, we looked into whether order reversals at the shortest lag (lag 2 in our case) would be more likely if the two targets appear in close succession (irrespective of whether or not a nontarget appears in between) or whether order reversals would only occur in the absence of a nontarget stimulus in between (irrespective of the temporal distance between the two targets).

**Method**

**Participants**

Twenty Leiden University students (18 female, 2 male) participated in the experiment in exchange for monetary compensation or course credit. They were unaware of the purpose of the experiment and reported normal vision and concentration span. Mean age was 20.6 years.

**Apparatus and stimuli**

The experiment was run by the E-Prime© 1.1 SP3 runtime component on a standard Pentium© III class PC. A 17” flat-screen CRT running at 800 by 600 pixels resolution in 16 bit color and refreshing at 100 Hz was used for all presentations. Viewing distance was approximately 50 cm, but not strictly controlled. The fixation point at the start of each trial was a black plus sign (“+”) presented in the center of the display on a uniform gray background (RGB 128, 128, 128). The target digits were randomly picked (without repetition) from the digits 1-9, with the exception of 5. The nontargets were selected in the same way from the complete alphabet. All visual stimuli were set in 16 pt. Times New Roman font in black on the aforementioned gray background. Participants responded at leisure by pressing the appropriate digit keys on a standard USB keyboard.
Procedure and design

The completely within-subjects design had three independent variables: lag, the temporal position of T2 with respect to T1, which varied between lags 2, 3, and 8; the duration of T1, which was either short (70 ms) or long (210 ms); and the presence or absence of a nontarget at lag 1. Participants initiated each trial by pressing the spacebar, which triggered the presentation of the 200-ms fixation mark after a delay of 800 ms. Then the 20-item stream started. It was presented centrally to exclude spatial factors such as location switching costs. Each item lasted for 70 ms, with a pause of 30 ms in between items, except in the T1 long condition where T1 lasted for 210 ms (see Figure 1). Two hundred ms after the offset of the last item two successive unspeeded response screens for T1 and T2 identity ensued. A complete session consisted of two blocks of 288 experimental trials and 16 practice trials. All experimental variables were presented intermixed, so that participants would not be able to adapt to specific conditions. The total of 592 trials took about 60 minutes to work through, depending on individual response speed.
Results and discussion

Analyses were run on accuracy (percentage correct) on T1 (absolute) and on T2 (conditional, i.e., T2 given T1 correct), and on the percentage of T1-T2 order reversals (i.e., the trials in which both targets were reported but in the wrong order), as a function of T1 duration, the presence or absence of a nontarget at lag 1, and the lag between T1 and T2. ANOVAs for dependent measures were used and degrees of freedom were Greenhouse-Geisser adjusted and rounded to one decimal whenever appropriate. Correct order of report was not required in the analyses of T1 and T2 performance.

T1 performance was affected by the three main effects of T1 duration, $F(1,19) = 25.56$, $MSE = .002$, $p < .001$, the presence of a mask, $F(1,19) = 26.54$, $MSE = .001$, $p < .001$, respectively.
and lag, $F(2,38) = 4.92$, $MSE = .001$, $p < .013$. The latter indicated that lag 2 was slightly more difficult than lags 3 and 8 (97.0% vs. 97.9 and 97.6%, respectively). Duration and nontarget were also involved in an interaction, $F(1,19) = 36.27$, $MSE = .001$, $p < .001$, that indicated that the combination of short T1 presentation and an intervening nontarget produced worse performance than the remaining conditions, which were all close to ceiling (see Figure 2, left panel).

Performance on T2 was similarly affected by main effects of duration, $F(1,19) = 69.17$, $MSE = .002$, $p < .001$, intervening nontarget, $F(1,19) = 25.84$, $MSE = .004$, $p < .001$, and lag, $F(2,38) = 12.36$, $MSE = .004$, $p < .001$. In addition, the interaction of nontarget and lag was significant, $F(2,38) = 5.86$, $MSE = .003$, $p < .006$. The duration and nontarget effects were rather straightforward: performance was worse if T1 was short than if it was long, and worse if a nontarget stimulus appeared in between the two targets. The lag effect showed lower performance on lags 2 and 3 than on lag 8, that is, we obtained an AB. The size of this AB may seem fairly modest, but this is largely due to the inclusion of the not commonly used gap and long-T1 conditions. Without the trials from these conditions the difference between lags 2 (79%) and 3 (78.1%) on one side and lag 8 (88.5%) on the other is about twice as big, indicating a healthy 10%-AB. As shown in the center panel of Figure 2, the interaction is due to the gap conditions being virtually unaffected by lag, whereas performance on trials with a nontarget at lag 1 drops at lags 2 and 3. Given previous reports that the AB is absent if T1 is not masked (Raymond et al., 1992), this observation does not come as a big surprise.
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Figure 2: Performance on T1 (left panel, percent correct), conditional performance on T2 (center panel, percent correct), and T1-T2 order reversals (right panel, percent of the total number of trials) as a function of lag between T1 and T2, T1 duration, and the presence or absence of a nontarget between T1 offset and T2 onset.

The most interesting analysis referred to the frequency of T1-T2 order reversals (see Figure 2, right panel). These decreased with increasing duration (3.4% and 1.0%, respectively), $F(1,19) = 67.25, \text{MSE} = .001, p < .001$, were more likely in the presence than the absence of a nontarget (2.6% vs. 1.8%), $F(1,19) = 9.18, \text{MSE} = .001, p < .007$, and steadily decreased as lag increased (4.0%, 1.8%, and 0.9%, respectively), $F(1,4,32.7) = 24.37, \text{MSE} = .001, p < .001$. The interactions of duration and lag, $F(2,38) = 18.86, \text{MSE} = .001, p < .001$, and of duration and nontarget, $F(1,19) = 13.34, \text{MSE} = .001, p < .001$, were also significant. The former indicated that the increase of reversals at the shortest lag was more pronounced for brief T1 presentations. The latter showed that an intervening nontarget impaired order recall if T1 was brief but had no impact if T1 was long. Interestingly, there was no interaction relating the presence of an intervening nontarget and lag, $p > .27$. 

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Comparison of the middle and right panel of Figure 2 showed that while there was virtually no difference between the short T1 without intervening nontarget and the long T1 with nontarget conditions in the analysis of T2 accuracy, there was a remarkable difference between them in the reversals analysis. Separate ANOVA’s on these conditions confirmed this interpretation. On the accuracy analysis, T2 lag affected both conditions, \( F(1.4,27.1) = 8.21, \text{MSE} = .003, p < .004 \), but no other difference existed between them, \( p > .26 \). On the reversals analysis, a pronounced difference between conditions did exist, \( F(1,19) = 19.29, \text{MSE} = .001, p < .001 \). T2 lag also affected both conditions, \( F(1.3,24.3) = 16.84, \text{MSE} = .001, p < .001 \). Finally, the interaction was significant, \( F(1.5,28) = 15.13, \text{MSE} = .006, p < .001 \), indicating that the difference was largest at lag 2.

**General discussion**

The purpose of the present study was to compare the impact of the temporal distance between T1 and T2 on performance in an AB task with the impact of a nontarget intervening between the two targets. Performance on T2 is partly consistent with the findings of Di Lollo and colleagues (in press): T2 is reported more often if it is not separated from T1 by a nontarget. According to Di Lollo et al., this may indicate that the stimulus not matching the current input filter or search template creates an exogenously triggered attentional control problem, e.g., by activating a task set that is incompatible with what is needed for the current task. Accordingly, T2 appears at a point in time when the system is not optimally prepared and, thus, is more often missed. However, two observations do not seem to fit with the control approach of Di Lollo and colleagues.

First, an intervening nontarget impaired performance equally at lags 2 and 3. If T2 appeared at lag 3, it was always preceded by at least one nontarget (at lag 2), irrespective of the presence or absence of another nontarget at lag 1. Shouldn't this nontarget at lag 2 have triggered a control problem even in the conditions without an intervening nontarget at lag 1?
If so, shouldn't the effect of the lag-1 nontarget be restricted to T2s appearing at lag 2? Not necessarily. The control approach assumes that nontargets can exert their damaging effects only while the system is occupied with T1 processing, so that the necessary control signals to input filters cannot be issued. This would suggest that nontarget-induced costs are only to be expected if the triggering stimulus appears soon after T1 is presented, that is, if the nontarget appears at lag 1. More problematic for the control approach is the finding that an intervening nontarget impaired performance even when T1 appeared for 210 ms. In view of the excellent performance on T1 it seems unreasonable to assume that (at least) the visual perception of the first target required longer than 210 ms, which means that in this condition a nontarget at lag 1 would not meet a system that is too busy to issue control signals. Accordingly, this nontarget should have been as unable to trigger a competing task set as nontargets appearing at lag 2.

An alternative account for the obtained pattern in T2 performance in terms of temporal integration windows is viable. Consider that the integration windows used in a particular situation are tailored to match the expected length of the respective target stimuli (Toffanin et al., 2005). As T1 was often very long in our experiment, the respective integration window was likely to be somewhat larger than normal, that is, larger as one would expect if T1 is always very brief. This would have opened the possibility that distractor information fell into the T1-related window and enjoyed prioritized processing to some degree, which again would make it a strong competitor in short-term memory. This should have been more likely the shorter T1 was presented (as that implied sooner appearance of a nontarget) and the earlier the respective nontarget appeared, that is, if one appeared at lag 1. Accordingly, one would expect main effects of T1 duration and the presence of an intervening nontarget at lag 1, just as observed. To account for the (rather mild) decrease of the nontarget effect at lag 8, one may either assume that this is a ceiling effect or speculate
that the impact of the stored distractor can be counteracted in some way while waiting for the late T2. For instance, distractors may be less strongly consolidated, so that their codes decay more quickly and a later arriving T2 meets less resistance.

Our main interest was whether and how target-order reversals would be affected by our experimental variables. As expected, reversals were most likely at the shortest lag, which replicates the observations of Hommel and Akyürek (in press) and others. However, the lag effect only occurred for short T1 presentation. This provides strong evidence in favor of an integration approach: If we assume that the sizes of integration windows are not changed from trial to trial and, even more important, within a trial, an integration window opened upon the registration of T1 was more likely to allow for parallel processing of T2 the sooner T2 appeared. As processing the two targets in parallel made the binding between computed target identities and their temporal positions difficult and error-prone, order reversals increased as the temporal distance between T1 onset and T2 onset decreased, hence, if T1 was brief and lag was short. The consequences for T2 to fall into a still open integration window (i.e., the T1-duration effect) would not depend on the presence or absence of a nontarget, which explains why the impact of an intervening nontarget does not modulate the interaction between duration and lag. Some caution has to be taken with this account as there was some indication in the reversals analysis that the difference between the effect of the nontarget for T1 short and long durations was largest at lag 3. An explanation for this phenomenon could be that the attentional gate is not always shut perfectly and that additional intervening items increasingly contribute to the shutting down process, which would promote reversals at lag 3 when an extra (i.e. at lag 1) nontarget is presented.

Nontargets at lag 1 do have an impact on performance, but only if T1 is short. The fact that this impact is independent of lag suggests that it is unrelated to attentional selection and target integration. Along the lines of our account of the T2 performance pattern, we
assume that a short T1 increases the likelihood that a distractor at lag 1 falls into the open integration window and thus gains access to attentional resources. Once processed and consolidated to some degree, this nontarget will compete with the other items stored in short-term memory. This competition may further hamper the maintenance of order information, which then gets lost until target report. Consequently, subjects have to guess, which leads to order reversals.

To summarize, our findings do not support the control account of Di Lollo et al. (in press). Given the many differences between the design these authors used and the one we employed in the present study, we hesitate to draw strong conclusions from the failure of the control approach to account for our findings. It may well be that nontargets do challenge the current attentional set if the system is busy, but that the conditions under which they do are less general than Di Lollo et al. assumed. What seems clear, however, is that our present findings are not predicted by and do not require such an account.

Instead, an integration approach seems to have some promise in capturing the main observations with respect to T2 performance and order reversals. The assumption that processing target-related information is associated with establishing an integration window of a particular temporal extension has also been successfully applied to the interpretation of varying patterns of inhibition of return (IOR) effects. These effects are obtained if spatially varying target stimuli are preceded by noninformative spatial cues. If the interval between cue and target is short, the spatial correspondence between them facilitates performance on the target. With longer intervals, however, correspondence yields a disadvantage: IOR. Interestingly, the point in time (i.e., the interval) when facilitation turns into interference changes from study to study. Lupiáñez et al. (2001) have pointed out that this variability may not be accidental but reflect different sizes of integration windows suggested by the task and the difficulty to identify the target. Making a target more difficult to identify may induce
longer integration windows, because more information needs to be gathered before a decision about target identity can be made. This may increase chances that a temporally close cue falls into the integration window, which in the case of cue-target correspondence produces a benefit. In support of their account, Lupiáñez et al. were able to show that, indeed, increasing identification difficulty extends the cue-target interval during which facilitation is observed, while the presence of distractors reduces this interval. Given Toffanin et al.’s (2005) observation that order-reversals in an AB task are affected by the expectation of a slow versus fast stimulus presentation rate, it makes sense to assume that a very similar integration mechanism is at work in processing more extended streams of visual information, such as in the present experiment. The indications that the size of this integration window seems to be variable and sensitive to task constraints open new, interesting venues for further research.
Chapter 7: Response priming in rapid serial visual presentation

One aspect of temporal attention that is presently not well understood is the nature of cognitive codes that are active during the ongoing process of distributing attention. Three experiments are reported that investigated the impact and timeframe of perceptually activated response codes. By using a three-target, partially speeded RSVP design, compatibility on the response as well as the stimulus level was investigated and contrasted by examining its priming effect. Priming was strongest with stimulus-based target compatibility. Evidence was found that response codes are quickly and automatically accessed when a stimulus is perceived and that this activation also primes subsequent compatible identification responses to a degree. While the response-based effect was relatively small and limited to the accuracy domain, it seemed immune to processing bottlenecks such as the attentional blink, whereas the opposite was true for the stimulus-based effect. The results have some implications for potential models of temporal (visual) processing.

Introduction

One of the most robust demonstrations of the limitations underlying human attention is the so-called attentional blink (AB). The AB occurs if people monitor a stream of stimuli for multiple targets in a rapid serial visual presentation (RSVP) task. Whereas one target (T1) can often be reported with high accuracy, a second target (T2) is often missed if it occurs too soon after the presentation of the first (Broadbent & Broadbent, 1987; Raymond, Shapiro & Arnell, 1992; Schneider & Shiffrin, 1977). This suggests that processing a target for later report creates a transient attentional bottleneck that prevents the complete processing of other targets. However, this does not mean that they are not processed at all. On the contrary, analyses of side- and after-effects of unreported targets strongly suggest that their identity and meaning is successfully registered by the cognitive system.

One piece of evidence comes from the electrophysiological study of Luck, Vogel, and Shapiro (1996), who found a reliable T2-induced N400 for trials in which T2 could not be
reported. Given that the N400 component is commonly taken to indicate semantic processing, this suggests that T2 was fully identified at some level. Further evidence comes from Shapiro, Driver, Ward & Sorensen (1997), who investigated whether a missed T2 would be able to prime a subsequent T3. In their first experiment, which employed a similar design as used in our present experiments, they found substantial repetition priming or, more precisely, repetition blindness (RB). In their second experiment they used words that could be semantically related. Related words facilitated performance, even if the priming word was missed. This latter effect was replicated in a similar task by Martens, Wolters, and van Raamsdonk (2002).

These findings demonstrate that a great deal of processing takes place in the absence of conscious awareness, such as the identification of a stimulus and the activation of stimulus-related episodic traces and meaning. In the present study, we asked whether processing goes even further and, in particular, whether it extends to the actions related to a missed stimulus. There are reasons to assume that this might be the case. In several single-task studies it was found that unnoticed and unreportable stimuli can activate responses assigned to them (Eimer & Schlaghecken, 1998; Leuthold & Kopp, 1998; Neumann & Klotz, 1994). Dual-task studies have shown that stimulus-response translation is not prevented in the presence of an attentional bottleneck: Responses of a secondary task get activated before primary-task processing is completed (Hommel, 1998; Hommel & Eglau, 2002; Logan & Schulkind, 2000). Taken together, these findings raise the question whether unreportable stimuli can activate their assigned responses even when facing an attentional bottleneck. Hence, will a missed T2 in an AB task activate its response?

In the following experiments, we investigated this issue by applying the logic of Shapiro et al. (1997) to response priming. That is, we presented participants with a RSVP stream that contained two, later reported targets, T1 and T2, and then presented a third target
(T3) requiring a speeded binary-choice response at the end of the stream. The relation between the identity of T2 and T3, and between the responses these two targets required, was systematically varied. Of special interest was, first, whether performance on T3 would be better if the responses to T2 and to T3 match and, second, whether this response priming effect would depend on successful report of T2.

**Experiment 1**

The first experiment used a basic RSVP design, as employed to demonstrate the AB, added by a third target at the end of the RSVP stream. The stream consisted of letters and T1 was a digit. T2 and T3 were arrows pointing to the left or right, thus signaling a left and right key press, respectively. T1 and T2 were reported at leisure at the end of the trial, as usual, but T3 required an immediate, speeded response. Of primary interest was the compatibility between T2 and T3 (i.e. whether both arrows pointed in the same direction). Note that this manipulation confounds stimulus compatibility and response compatibility, so that a possible priming effect would not yet tell us whether response compatibility really mattered. However, we considered it important to first demonstrate that the paradigm works, that is, that T2-T3 priming can be found.

**Method**

**Participants**

Twenty-four students participated in the experiment, in exchange for course credit or monetary compensation. All of them reported having normal (or corrected) vision and concentration span.

**Apparatus and stimuli**

All stimuli were presented in a resolution of 800 by 600 pixels in 16 bit color on a 17” CRT refreshing at 100Hz. The experimental program ran on a Pentium® III PC and was
programmed in E-Prime® 1.1 SP3. Participants were seated individually in small dimly lit cabins at a viewing distance of about 50 cm. The fixation mark (“+”) as well as all RSVP items were presented centrally in black on a gray background (RGB 128, 128, 128), with the exception of the first and the third target, which were presented in soft white (RGB 220, 220, 220) and bright red (RGB 255, 0, 0), respectively. Each item was set in 16 point Times New Roman font. Digits were drawn randomly without replacement from 1-9 with the exclusion of 5. Distractors were drawn from the full alphabet. Responses were logged on a standard 125 Hz USB keyboard. The third target (T3) required a speeded identification response and reaction time (RT) was recorded accordingly.

**Procedure and design**

Participants initiated each trial by pressing the spacebar. Trials started with a delay of 800 ms followed by the presentation of the fixation mark for 200 ms. The RSVP ensued, consisting of 20 items with a duration of 70 ms each and an inter-stimulus interval of 30 ms. Another 1000 ms pause followed the RSVP offset, after which two response input screens were presented for the first two targets (T1 and T2). As the response to T3 was speeded, no input screen was presented for this target. Instead, participants were instructed to just respond as soon as they detected T3. T1 was identified by pressing the corresponding digit key. T2 and T3 were identified by pressing spatially corresponding re-labeled keys on the keyboard (keys W and O for T2 and Q and P for T3, respectively). A full experimental session lasted for approximately one hour and contained two identical blocks of 240 randomly ordered trials as well as 20 practice trials. The design consisted of two within-subjects variables: T2 lag and T2-T3 compatibility. Lags 2 and 8 were chosen in order to get an indication of performance within as well as after of the commonly assumed 600 ms temporal interval of the AB. Lag was determined by the number of items between T1 and T2. T1 position was randomly varied between stream positions 7 and 8 to reduce the predictability of target onsets. T3 always
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followed T2 two lags later, that is, T2-T3 lag was constant. The compatibility variable consisted of 2 levels, defined by the left/right congruency between the identity and responses to T2 and T3.

**Results and discussion**

The standard 5% significance level was used for all analyses. Repeated measures ANOVA’s were done for accuracy on T1, accuracy on T2 given that the response to T1 was correct, and accuracy as well as reaction time on T3 given that T2 was correct. An additional requirement for all analyses was that a valid response to T3 had to be given within the interval of 100 to 1300 ms after T3 onset, to safeguard against spurious key presses.

No variable reached significance on T1, which was not completely unexpected as any confusability between T1 and T2 was absent in this experiment—eliminating the probable cause behind lag effects on T1 previously found (Hommel & Akyürek, in press). Conditional T2 performance on the other hand was affected by both T2 lag as well as compatibility. The T2 lag effect was straightforward and represented a typical attentional blink curve; performance at lag 2 was 66.4%, compared to 80.5% at lag 8, $F(1,23) = 17.21, MSE = .028, p < .001$. Compatibility produced a sizeable effect as well in the present analysis. When T2 and T3 were compatible identification accuracy averaged 81.2%, compared to 65.7% when they were not—a difference of 15.5%, $F(1,23) = 16.09, MSE = .036, p < .001$. Although this facilitation of T2 might look like a backwards priming effect, some caution with its interpretation is justified. Since the response to T2 was not speeded it was actually entered after the response to T3, opening up the possibility of a memory-based effect. Figure 1 shows T1 and conditional T2 accuracy over all conditions of the experiment.
T3 accuracy was affected by compatibility; performance averaged 94% when T2 and T3 were compatible, while reaching only 74.8% when they were not, $F(1,23) = 20.58$, $MSE = .043$, $p < .001$. This large difference pointed at a strong priming effect. In contrast, T2 lag produced no reliable difference. The left panel of Figure 2 shows T3 accuracy as a function of lag. The immunity to T2 lag on the T3 accuracy analysis was also deviant from the results of T3 reaction time, on which both T2 lag and compatibility had effects. At lag 2, T3 reaction time was 507 ms on average, 49 ms slower than the 458 ms at lag 8, $F(1,23) = 16.22$, $MSE = 3605.86$, $p < .001$. Equally strong was the difference between T2-T3 compatibility conditions; reaction time was 511 ms when incompatible and 454 ms when compatible.
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\( F(1,23) = 24.57, MSE = 3202.24, p < .001 \). The right panel of Figure 2 displays T3 reaction time for both of these conditions.

![Figure 2: Left panel: T3 identification accuracy (percent correct) in Experiment 1, given T2 correct; plotted for each compatibility relationship over T2 lag. Right panel: same for T3 reaction time (milliseconds).](image)

**Experiment 2**

The second experiment was identical to the first with the exception of one adaptation. The second RSVP target was changed to a digit similar to T1 from the first experiment, but maintained the black color of the original T2. The response to this target remained unspeeded. The difference between the experiments was thus limited to the identity of T2 and the type of compatibility between targets. Whereas compatibility in the first experiment was based on (full) featural stimulus codes, compatibility in the second experiment was limited to
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the response-level. This response compatibility was realized using the finding that lower digits (1-4) are unconsciously associated with left-oriented responses and higher digits (6-9) with right-oriented responses, a phenomenon known as the SNARC effect (Dehaene, Bossini & Giraux, 1993). As before, the compatibility of the second target with the third was manipulated. It was assumed here that a representation of number magnitude shares neural codes related to response processing with representations of directionality (Caessens, Hommel, Reynvoet & van der Goten, 2004; Fias, Lauwereyns & Lammertyn, 2001). Since there was no actual stimulus based overlap between the digits and the arrow, any effect of (spatial) compatibility should be attributed to response coding alone. The speeded nature of the third target ensured that (short-term) memory factors were effectively irrelevant to the issue at hand and this should have maximized the opportunity for response selection processes to show up (Arnell & Duncan, 2002).

Method

Participants

Twenty new students were recruited for this experiment, who again participated for course credit or monetary compensation and answered to the same criteria as before.

Apparatus, stimuli and procedure

The experiment was constructed and run exactly like Experiment 1, with the noted exception of T2 identity, which was changed to a digit. Response keys to T2 were changed accordingly.

Results and discussion

T1 and (conditional) T2 identification accuracy showed effects solely related to the T2 lag variable. T1 accuracy dropped a modest 2.4% from the 97.3% average at lag 8 when T2 followed closely at lag 2, \( F(1,19) = 7.21, \text{MSE} = .002, \ p < .015 \). To exclude a potential confound between target confusability introduced by the deviant third target, performance was calculated according to the stringent requirement of having both target identity and
temporal position correct. This calculation revealed that T1 performance is not uncompromised when type-identical targets follow each other rapidly, which is an effect that has been observed before (Hommel & Akyürek, in press; Potter, Staub & O’Connor, 2002). Continuing with T2, this target’s accuracy dropped more substantially from 85.7% at lag 8 to 74% at lag 2, $F(1,19) = 14.88$, $MSE = .018$, $p < .001$, a pattern that indicated the presence of an attentional blink. Figure 3 shows performance on T1 and T2|T1 over all conditions.

![Figure 3: T1 (white symbols) and conditional T2 (black symbols) identification accuracy (percent correct) in Experiment 2, plotted separately for each compatibility relationship over T2 lag.](image)

The analysis of T3 accuracy produced notably different results. Instead of a lag effect, the compatibility variable proved to have an influence. Accuracy on T3 was 91.6% when T2 and T3 were compatible, compared to 87.5% when they were not, $F(1,19) = 8.36$, $MSE = .004$, $p < .009$. Figure 4 (left panel) shows T3 accuracy over T2 lag for both compatibility conditions.
The T2 lag variable was at least still marginally significant, showing slightly higher performance on the shorter lag, $F(1,19) = 3.97$, $MSE = .004$, $p < .061$. Interestingly, the picture was reversed again in the T3 reaction time analysis, in which T2 lag sorted the only effect. Reaction time to T3 was increased by 75 ms when T2 followed T1 with short lag, $F(1,19) = 47.32$, $MSE = 2372.74$, $p < .001$. While responses took 449 ms on average in the lag 8 condition, this changed to 524 ms when lag was reduced to 2 (see Figure 4, right panel). This difference is intriguing given that it had no reflection in the accuracy domain (also see Arnell, Helion, Hurdelbrink & Pasieka, 2004).

Figure 4: Left panel: T3 identification accuracy (percent correct) in Experiment 2, given T2 correct; plotted for each compatibility relationship over T2 lag. Right panel: same for T3 reaction time (milliseconds).

Summarizing, the experiment’s most important result was the priming effect of T2-T3 response compatibility on T3 accuracy. It’s worthwhile to note that this effect existed despite
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and independent of the presence of an attentional blink, as witnessed by the absence of lag-related interactions. A somewhat similar immunity of response congruency was found by Jiang & Chun (2001), for the case of distractor-target compatibility. The presence and signature of the response compatibility effect also indicates that separable compatibility effects are detectable even when no repetition blindness was found on the stimulus level as in Shapiro et al. (1997).

**Difference analysis**

Since the main focus of this study was the (primed) performance on T3, additional analyses were performed on both T3 accuracy and reaction time. An additional variable was added with regard to T2 performance; T3 measures were compared for cases in which T2 was correct and those in which it was not—indicative of an attentional blink. Furthermore, the data of Experiments 1 and 2 were merged and inspected for between-subjects group interactions.

On the T3 accuracy analysis, the between-subjects group variable was significant, $F(1,42) = 21.92$, $MSE = .06$, $p < .001$. This effect pointed out that overall performance in Experiment 1 was lower than in Experiment 2—79% and 91.3%, respectively. The main effect of compatibility was also significant, $F(1,42) = 32.72$, $MSE = .042$, $p < .001$. Performance in compatible conditions was higher (91.4%) than in incompatible conditions (78.8%). Furthermore, interaction effects of group with T2 blink, $F(1,42) = 12.47$, $MSE = .036$, $p < .001$, and group with compatibility, $F(1,42) = 23.04$, $MSE = .042$, $p < .001$, were significant. In the absence of a reliable main effect of T2 blink, the first interaction term pointed to an isolated difference due to T2 being blinked in Experiment 1. The difference between T2 conditions in Experiment 1 was 10.9%, where T2 correct performance was highest at 84.4%. The second interaction term indicated that the compatibility effect was stronger in Experiment 1 than in Experiment 2; a familiar pattern. Lastly, the three-way
interaction between lag, T2 blink and group was significant, $F(1,42) = 5.03$, $MSE = .036$, $p < .008$. Though somewhat mysterious, this effect seems to be due to deviant performance at Lag 8, specifically in Experiment 2 where the average T2 blinked performance is relatively high. Figure 5 shows performance for blink and compatibility conditions as a function of lag, in Experiment 1 (left panel) and 2 (right panel).

![Figure 5: Left panel: T3 identification accuracy (percent correct) for Experiment 1 as a function of T2 lag. Separate line styles represent compatibility and T2 blink conditions. Right panel: same for Experiment 2.](image)

The analysis of T3 reaction time showed no main effects of T2 being blinked or not and neither of experimental group. Effects that did reach significance were lag, $F(1,42) = 54.48$, $MSE = 6842.8$, $p < .001$, and compatibility, $F(1,42) = 8.25$, $MSE = 6893.68$, $p < .006$. Both of these were observed before—short lags and incompatible conditions increased RT. A single
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two-way interaction of group with compatibility was significant, $F(1,42) = 13.47, \text{MSE} = 6893.7, p < .001$. Compatibility sorted a large positive effect in Experiment 1, while it showed a slightly negative trend in Experiment 2. Another three-way interaction of lag, blink and group was significant as well, $F(1,42) = 4.6, \text{MSE} = 5452.1, p < .038$. It seemed to point at a reversal of the effect of missing T2 over lag; while missing T2 at Lag 2 resulted in longer reaction times, it actually decreased RT at Lag 8. Whether this reversal has significance or not is difficult to estimate, as it must be taken into account that missing T2 at Lag 8 is much rarer than it is at lag 2 (1171 and 2080 cases, respectively). Figure 6 shows the full set of RT means in both experiments.

![Figure 6](image)

*Figure 6: Left panel: T3 reaction time (milliseconds) for Experiment 1 as a function of T2 lag. Separate line styles represent compatibility and T2 blink conditions. Right panel: same for Experiment 2.*
It is obvious from the comparison of both experiments that there existed a marked difference between them that involved the strength of the T2-T3 congruency priming. In line with expectations, stimulus-related compatibility produced stronger priming than response-related compatibility did. Even though the source of priming was similar (e.g. T2-T3 congruency), the response-related effect in the accuracy domain seemed more resilient to the loss of T2 identification accuracy caused by the attentional blink.

**Experiment 3**

The comparison of results from the first two experiments still relied on between-group differences that were obtained with different stimuli and as such were still somewhat indirect. Experiment 3 addressed this issue by combining stimulus- and response-level compatibility in one variable, using a slightly modified design. T2 and T3 consisted of symbol characters that were associated by instruction with left or right responses. This implementation carried two further advantages; 1) it did not rely on assumptions about the SNARC effect in the response-compatible condition, and 2) it did not require a direct identity link between stimulus and directionality as used previously in the stimulus-compatible group, which also provided some control over the automaticity of response activation.

**Method**

**Participants**

A new group of 36 participants was recruited for this experiment, all of whom participated for money or course credit.

**Apparatus, stimuli and procedure**

The experiment was identical to Experiment 2, with the exception of the identity and response keys of T2 and T3. Each of these targets was one of the symbols “#”, “%”, “&”, and “@”. Participants were instructed that two of these symbols required a left response and that
the other two required a right response. Left and right responses for both targets were given
with the Q and P keys on the keyboard, which were relabeled with the arrow symbols as used
before. Participants were divided in two counterbalanced groups; the first was instructed that
“#” and “%” required a left response, while “&” and “@” required a right response. The
second group received the reverse instruction as a precaution against spurious effects of
stimulus-response couplings.

Compatibility between T2 and T3 was set up as follows; on 50% of trials T2 and T3
were incompatible, on 25% of trials T2 and T3 were response compatible (dissimilar
symbols, but requiring the same response), and on the last 25% of trials they were fully
compatible (identical symbols). As a result of these design changes the twin experimental
blocks now had 256 trials each.

Results and discussion

The analysis of T1 performance yielded no reliable effects, as was the case in Experiment 2.
Conditional T2 performance did show main effects of both the lag and compatibility
variables. Performance was worse at Lag 2 than at Lag 8, with 82.3% and 87.9%,
respectively; $F(1,35) = 34.43, \text{MSE} = .005, p < .001$. In the full compatibility condition T2
performance was best at 87.4%, compared with 85.1% in the incompatible conditions and
82.9% in the response compatible conditions, $F(2,70) = 12.59, \text{MSE} = .003, p < .001$. Post
hoc tests using the Tukey procedure for pairwise comparisons ( $p < .05, q = 4.163$) revealed
that 1) performance at Lag 2 in the incompatible condition was significantly lower than
performance at Lag 8 (all compatibility conditions), 2) performance at Lag 2 in the response
compatible condition was lower than performance in the stimulus compatible condition at the
same lag, and 3) performance at Lag 2 in the response compatible condition was lower than
in any condition at Lag 8.
Figure 7: T1 (white symbols) and conditional T2 (black symbols) identification accuracy (percent correct) in Experiment 3, plotted separately for each compatibility relationship over T2 lag.

On conditional T3 accuracy, the only main effect reaching significance was compatibility. Performance was worst in the incompatible condition at 80.6%; improved in the response compatible condition to 84.2%, and peaked when T2 and T3 were fully compatible at 87.5%, $F(1.7,59.2) = 20.51, MSE = .005, p < .001$. The interaction of lag and compatibility was also significant, $F(2,70) = 20.75, MSE = .004, p < .001$. The left panel of Figure 8 shows the relevant means. It seems that performance improved when T2 lag was long, but only when T2 and T3 were incompatible. Neither the response nor the fully compatible conditions showed this pattern.
T3 reaction time was influenced by both main effects of lag and compatibility. A short lag between T1 and T2 resulted in a higher reaction time to T3, averaging 746 ms, while a long lag yielded a quicker response of 672 ms, $F(1,35) = 37.43, MSE = 7864.7, p < .001$. The compatibility effect indicated that responses were faster in the fully compatible condition, compared to the incompatible and response compatible conditions, $F(1.7,59.6) = 55.42, MSE = 860.4, p < .001$. The right panel of Figure 8 plots average reaction time in these conditions. Tukey’s pairwise tests on the compatibility means ($p < .05, q = 3.399$) confirmed that only the difference between incompatible and response compatible was not significant. This result is reminiscent of those of Experiment 1 and 2; the stimulus-level information has a reflection in the time domain, whereas the response-level information has not. In addition to the main effects, the interaction term of lag and compatibility was also significant, $F(2,70) = 21.54,$

Figure 8: Left panel: T3 identification accuracy (percent correct) in Experiment 3, given T2 correct; plotted for each compatibility relationship over T2 lag. Right panel: same for T3 reaction time (milliseconds).
$MSE = 458.2, p < .001.$ As can be seen from Figure 8 (right panel), the performance in both compatible conditions behaved similarly; no change was apparent except for a linear drop in reaction time from Lag 2 to 8. The incompatible condition was deviant by resulting in additively faster responses at Lag 8. Given the relatively small effect size, its theoretical relevance remains somewhat doubtful.

Given the specific effects of missed T2 targets due to the attentional blink on T3 performance in stimulus-level and response-level groups in Experiments 1 and 2 (e.g. the absence of an effect in the latter), a similar analysis was done on the present data. A T2 blink variable was added to the design, and performance on T3 accuracy and reaction time was examined.

The first main effect on T3 accuracy was that of T2 blink, $F(1,35) = 37.23, MSE = .022, p < .001.$ Performance on T3 suffered from the attentional blink; missing T2 reduced accuracy from 84.1% to 75.4%. The second main effect was compatibility, $F(1.6,56.6) = 6.68, MSE = .025, p < .004.$ The interaction of T2 blink and compatibility presented an interesting difference between response and stimulus levels, $F(1.7,58.2) = 6.15, MSE = .024, p < .006.$ The initial results suggest that performance in the response compatible condition was relatively stable over blinked and non-blinded trials, compared to the others. Further analysis revealed several differences ($p < .05, q = 4.197$). First, when T2 was not blinked and the targets were stimulus compatible, performance was better than in the same blink condition when targets were either incompatible or response compatible. Second, when T2 was blinked and the targets were incompatible, performance was below any of the non-blinded conditions. Third, when T2 was blinked in the response compatible condition, performance was better than in the blinked incompatible condition, but worse than in the non-blinded stimulus compatible condition. This was taken as an indication that the response compatible conditions were relatively unaffected by the attentional blink, supporting the
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results of Experiment 1 and 2. Fourth, performance in the stimulus compatible T2 blinked condition was worse than performance in the non-blinked condition for both response and stimulus compatibility. The last effect in the ANOVA on T3 accuracy was the interaction of lag and compatibility, $F(1.7,59.7) = 10.58, \text{MSE} = .025, p < .001$. While a short lag caused lower performance in the incompatible condition, this effect was reversed in the compatible conditions, in which a short lag resulted in the highest performance. The left panel of Figure 9 plots T3 accuracy over lag, given that T2 was missed.

![Figure 9](image_url)

*Figure 9: Left panel: T3 identification accuracy (percent correct) for Experiment 3 as a function of T2 lag, given T2 blinked. Right panel: same for T3 reaction time. Separate line styles represent compatibility and T2 blink conditions.*

The analysis of T3 reaction time showed two main effects; the first one of T2 lag, $F(1,35) = 26.52, \text{MSE} = 21117.5, p < .001$, and the second one of compatibility, $F(1.4,47.4) = 4.17,$
MSE = 8348.2, \( p < .035 \). The response to T3 was slower when lag was short (750 ms) than when it was long (678 ms). The compatibility effect was mostly due to the difference between the stimulus-compatible condition at 699 ms and the incompatible and response-compatible conditions at 723 and 720 ms, respectively. A single interaction term reached significance; T2 blink with compatibility, \( F(1.5,53.6) = 3.8, \) MSE = 6741.8, \( p < .039 \). Again, the effect seemed to be due to the deviance of the stimulus-compatible condition, which showed a faster response when T2 was identified correctly, whereas the others did not seem to be affected by the blink much at all. It should be noted that at Lag 8, especially in the compatible conditions, performance on T2 was quite high, which limited the number of observations in the present analysis. The number of observations at Lag 8 when T2 was missed was 1114 compared to 1553 at Lag 2. Although these numbers were not catastrophic, we hesitated to draw strong conclusions about the interaction effect. Figure 9 (right panel) shows the relevant response times.

Taken together, the results of Experiment 3 supported those of Experiment 1 and 2 and provided an extension by demonstrating the separable priming effects of stimulus- and response-level compatibility independent of numerical left/right association and stimulus-bound directionality.

**General discussion**

Although the overall picture was one that showed a distinct pattern of priming for response- and stimulus-related priming, there were a number of subtle effects that deserve separate mention as well. Comparison of Experiment 1 and 2 showed that the response conditions differed from the stimulus conditions in several ways. Stimulus-level compatibility resulted in strongly enhanced T2 and T3 recognition and markedly faster reaction time to T3. Response-level congruency enhanced only T3 identification. By itself, the presence of a facilitating effect could be considered surprising, given the opposite pattern of repetition...
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blindness observed by Shapiro et al. (1997). The reason why the present results do not match those of Shapiro et al. might be that the present paradigm requires only a target-matching response, whereas the targets of Shapiro et al. required full identification. It could also be suspected that the temporal interval between targets was involved in some way. The present study employed varying target intervals and onsets and this might have made it harder to strategically predict target onset. Lastly, the targets used by Shapiro et al. did not differ from each other nor from the distractors, which might have increased identity confusion. The combination of a predictable onset and confusable targets might have led to a different mode of detection.

Missing the prime (T2) in the stimulus compatible condition decreased T3 identification success and increased reaction time at Lag 2, but that effect seemed to reverse at Lag 8. This reversal might simply point to a very light attentional load that allows rapid T3 processing. The response compatible conditions did not show a clear impact of missing T2 on T3 accuracy. T3 reaction time was similarly unaffected, showing a trend in the opposite direction instead (faster reaction when T2 was missed). Despite the fact that the response effect was much more limited than its stimulus-based counterpart, it seemed much less sensitive to the attentional blink. Apparently, response codes are somehow independently active and not bound to specific target representations. It is possible that response codes are a type of implicit knowledge and that this is why they behave differently. Previous studies such as those of Shapiro et al. and Martens et al. seem to indicate that the distinction between implicit and explicit knowledge could be relevant.

The results of Experiment 3 repeated the presence of stimulus-level priming on T3 reaction time and accuracy and the absence of the latter in response-level conditions. In this experiment the priming effect seemed to be more sensitive to the Lag between T1 and T2; the facilitation disappeared at Lag 8. Since the stimuli used in Experiment 3 were of an abstract
nature, it could be speculated that their representation was somehow more fleeting and more sensitive to the passage of time. In that vein, one could argue that the priming effect found in the stimulus-based group from Experiment 1 represents facilitation due to codes that carry over directly to uniformly (or inherently) mapped stimulus-response combinations (as with arrow symbols), while the effect in the response-based group from Experiment 2 indicates the ‘residual’ indirectly mapped level. Experiment 3 provided evidence against such an account, however. In the stimulus compatible condition of Experiment 3 a performance pattern similar to the one found in Experiment 1 was obtained. This condition was independent of direct or uniform stimulus-response mappings, since only abstract symbols were used. Therefore, despite the divergent performance at Lag 8, the central mechanisms underlying both types of priming are likely similar.

Missing T2 had a muddled impact on T3 reaction times, but T3 accuracy did show some interesting effects. Response-level compatibility turned out to facilitate T3 identification the most at any lag. Stimulus-level compatibility was also better than no compatibility at Lag 2, but resulted in the poorest performance at Lag 8. While response compatibility had a fairly constant facilitating effect, the stimulus-related effect was much more sensitive to the lag between T1 and T2. This could be taken to mean that the abstract symbols used in this experiment had implications for the representation of featural codes, but not for response codes.

The present findings have implications for potential models of the attentional blink. An account for the resilient activation of response codes and the observation that these codes can produce priming on subsequent identification tasks is needed. At some level at least, response codes seem to be independent of the temporal attentional bottleneck. How this independency is lost for stimulus (perceptual) codes is not yet clear, though the distinction between codes is an indication that separate code types are being used on some level. One
possibility could be that stimulus features are more strongly bound to the representation of a target than its associated response is. Existing models of temporal attention do not seem to offer a full understanding of this phenomenon. One promising suggestion made by Shapiro et al. (1997) is that processing can proceed up to semantic levels before the attentional blink bottleneck arises. If a response code is considered to be a type of semantic and perhaps implicit information, then a two-stage model along these lines could offer a parsimonious account of the present results.
Chapter 8: Synopsis

In the preceding chapters the primary objective has been to improve our understanding of the attentional process. Two themes have been used in this study to approach this objective. The first was the role of (items in) short-term memory in the guidance of attention. The second was the level of control over attention due to other sources, such as stimulus-based events and meta-knowledge (or task set). Taken together, the results of this study have some implications for existing unitary models of temporal attention. In the following, the main empirical results will be briefly summarized and discussed with a focus on theoretical options that are compatible with the present findings.

Short-term memory and the attentional blink

Chapter 2 described three experiments that investigated dependencies between tasks that tax short-term memory and temporal attention. A major conclusion that can be drawn from the results is that attention is indeed linked to STM; either because attention requires resources from STM, or because some type of code-based crosstalk occurs between the two. Evidence from Experiment 1 suggested that one basis of this dependency could lie in the semantic overlap between codes in STM. Since the load (number of items) on STM proved to decrease attentional performance, support for a capacity-sharing account was obtained as well. Both effects remained limited in scope, however, which indicates that while attention was affected by memory-induced difficulties, it cannot be heavily dependent on STM. Some inter-task dependency was observed, yet it also became apparent that no particular moment in time rendered the system particularly sensitive to interference. Even under the most taxing conditions, in which participants were asked to memorize six digits while repeating a word
out loud and to detect two digits amidst distractors appearing eleven times per second, there seemed to be no particular moment when an absolute limit was reached.

One interesting possibility to match these findings with existing theory presents itself. Attention might be guided by control processes that rely only indirectly on the actual contents of STM. This assumption is particularly attractive as it maintains compatibility with most theories that suppose a major role for STM in the control of attention. According to the theory of visual selection proposed by Duncan & Humphreys (1989), a stimulus receives attention after successfully matching its sensory information with templates in memory. This filter procedure does not need to actively compare the contents of STM with sensory information; its parameters could be set by STM, after which it can function independently without suffering from massive interference of irrelevant information in STM. An STM-based model of visual attention that features a configurable gate to memory is compatible with the present data. The configurable gate hypothesis can account for limited dependency between STM and attention. Regardless of the load on STM, the gate would never lose selection efficiency, as it will remain configured. If items in STM are close competitors to those that configure the gate, the set-up of the gate has to be more specific, which presumably decreases the likelihood of rapid selection. Finally, if STM is loaded, items that are selected still have to enter STM. In this model, a delay caused by limits on STM capacity can occur without it affecting selection. Figure 1 shows the memory-related structure of the configurable gate model. Task meta-knowledge is not directly represented in this figure, although its effects similarly concern the gate.
Perceiving a stimulus might proceed as follows: the stimulus causes sensory activation, for example the sensations of “strong white”, “rectangular” and “distributed green”. Not all of these sensations automatically transfer to short-term memory. Perhaps the first sensation of “strong white” does get quick access, as it is highly salient and as such able to pass through the attentional gate. Suppose ‘task knowledge’ is available to the perceiver, which specifies a rectangular object. Configured with this information, the attentional gate allows the second sensation to pass. Finally, consider the relevance of information in STM. The perceiver might recall writing with a green marker on the object. This last bit of information also configures the gate and allows the third sensation to pass. Presumably, the configuration of the gate becomes more complex if multiple detailed specifications are required. The sensations
themselves that are entering STM may compete with the information that was used to configure the gate, yet the gate’s parameters remain set and would treat subsequent incoming information the same way, regardless of the fate of items in memory. The attention-insensitive interference observed in Experiment 1 could be explained by competition restricted to STM. It is assumed here that STM deals with integrated events, so that the outcome of this scenario would eventually be the perception of a scribbled whiteboard.

Experiments 2 and 3 specifically tested for short-term memory subsystems in an attempt to prevent differential coding between tasks. If the model proposed by Baddeley (2000) holds true, the capacity of STM can be extended by using dedicated storage in specialized compartments—the visuospatial sketchpad and the phonological loop (see Chapter 1, Figure 2). An extension by these means could directly alleviate capacity shortages in STM, or act indirectly by increasing the mutual differentiation between items (and hence decreasing competition). In Experiment 2, a purely visual rendition of the dual-task STM & RSVP paradigm, designed to reduce the incentive to encode information in a phonological format, a sizeable increase in task difficulty was observed—to the extent that the original STM loads of up to six items proved to reduce performance to chance level. Despite the large impact on task difficulty, the overall pattern of limited interference between (visual) STM and attention remained similar to the one observed in Experiment 1, with limited effects that were not time-dependent. The addition of articulatory suppression, implemented in Experiment 3 to completely block the use of the phonological loop, resulted in a virtual replication. Performance was altogether fairly robust considering the difficulty of these experiments. Participants were generally able to distribute attention almost as if no additional task was imposed. Certainly, this is an impressive feat.

If the contents of STM were to play an active role in the guidance of attention, the absence of interactions of STM load and performance in the RSVP task is hard to explain.
Complete independence of STM and attention is not likely either, since evidence for task-related difficulty was obtained. The results are however compatible with the configurable gate model. Subsystems of STM could be drawn in Figure 1 without affecting the central interplay of elements. Whether or not information in STM subsystems can act in the same way on the configuration of the gate or is subject to the same access procedure as other kinds of information (e.g. task knowledge) is beyond the scope of the present model, but may provide be an interesting avenue for future research. The configurable gate model is also compatible with studies in the literature that pointed to a strong link between working memory and attention. For example, the experiments by Downing (2000) showed that attention was guided by the contents of visual STM (also see Chapter 1). A parsimonious account of the results was given, which is that there was an automatic shift of attention to the probed location due to the contents of STM. Since a direct link between STM and attention seems less likely given the results of the present study, a slight modification seems necessary. Without a direct link, such as proposed by the configurable gate model, an account for Downing’s results can still be given. According to the gate model, the contents of STM had an effect on the settings of the attentional filter, in turn resulting in the observed attentional shift. Both in Downing’s study as in the one by Pratt & Hommel (2003), strong evidence was found for a considerable automatic component to attentional selection. Although the configurable gate model can account for this component by assuming that the configuration of the gate may be automatically adjusted under certain circumstances by items in STM, that does present a departure from ‘classic’ attentional filter models such as proposed by Folk, Remington & Johnston (1992).

Not all models of visual attention treat short-term memory similarly. Some authors have proposed that memory operations such as storage and retrieval are what limits the distribution of attention (e.g. Vogel & Luck, 2002). The experiments in Chapter 3 were
designed to engage STM operations rather than merely loading content. The first experiment formed a baseline, comparing ‘overhead’ costs associated of an STM task added to an attentional task with the latter task alone. The difference concerns maintenance operations to STM. In accordance with expectations, the dual task posed more difficulty to participants than the single task did. Similar to the experiments in Chapter 1, the impact of the second task was limited in magnitude and again did not show any sign that it was somehow linked to critical moments in the attention task. This outcome matched those found previously and extended them by isolating dual-task costs.

The second experiment tested top-down support of encoding and maintenance in STM. Items relevant to the STM task were repeated during RSVP; either as distractors or as targets. Supposedly, repetition would enhance maintenance of information; a benefit if it matches a target, a possible drawback otherwise. The repetition proved to be completely futile. No sign of any impact of this manipulation was obtained, not for distractor nor target repetitions. As a post-hoc explanation in the case of repeated distractor items, one might argue that these are filtered out during some early attentional stage while the task is performed, and hence cannot be effectively modulated by secondary items as taken from the STM task. Yet this would imply that repetition of target items should then differ fundamentally from the distractor situation, which was not the case.

**Controlling attention**

There is little doubt that attention is at its limits when circumstances require dividing it over multiple rapidly incoming perceptual events, as witnessed by the attentional blink phenomenon. From the results so far, it seems that this problem does not occur due to capacity constraints on STM. An alternative account that would explain the deficit is that the operation of the attentional gate could have temporal characteristics that are not well suited to RSVP conditions. In particular, it may be relatively slow to select incoming sensations. An
early account involving a ‘sluggish’ attentional gate was proposed by Raymond, Shapiro & Arnell (1992). According to the slow gate hypothesis, one would then expect that the shortest time interval between two target stimuli in an RSVP would result in the worst performance. Curiously enough, this is not always the case. In many experiments reported in the literature, performance (on T2 identification) in the so-called Lag 1 condition is very good, even up to single-target level performance. This counterintuitive finding was the motivation for the investigation of Lag 1 sparing in Chapter 4. The first experiment successfully obtained the sparing phenomenon using a standard non-spatial RSVP and additional analyses were done to further specify it. The crucial step was the separation of identity and order information. While identity information was maintained well in the Lag 1 condition, order information tended to be lost. This could be due to a process in which the two targets are jointly integrated in a single attended event (by virtue of their quick succession). In this joint integration, their identities are preserved, but their separation (in time) is no longer well perceived and their order is lost. An event like this can occur if stimuli enter the system at such a rapid rate that items are floating in sensory storage. If attentional selection then occurs, the floating stimuli are gobbled up by chunks that are not defined by timestamps.

In a second experiment, the conditions under which joint integration is possible were investigated. From previous work, it was already known that both targets have to be of the same general type if joint integration is to occur (Visser, Bischof & Di Lollo, 1999). For example, if the first target is a color patch and the second is a line pattern, no joint integration will occur—and no sparing will be observed. In the present experiment however, the type of target remained the same (digits in a letter distractor stream), yet their perceptual contrast was varied. Either target could be difficult, normal or easy to perceive by varying the intensity of the stimuli. The results showed that a competitive relation existed between the two targets when they were of unequal perceptual strength. When T1 was easy to perceive and
accordingly often identified correctly, performance on T2 suffered and vice versa. Apparently, a clear featural distinction between items provides a sufficient boundary so that joint integration is less likely. It also seems to introduce an element of salience to the detection process. The item that stands out the most is more likely to be selected and reported, at the expense of the chance to report the other.

These results indicate that it is unlikely that the cause of the AB is simply a lack of processing speed of the attentional gate. Given the conditional integration of features into merged percepts, it seems more likely that the gate does not select information in a strictly defined way, especially when items are similar and only individually separable by timestamp. As observed, a clear distinction based on featural information between items renders selection more stringent. The selection process remains subject to a certain rate limitation—without it, neither joint integration nor mutual competition would occur.

The ‘fuzzy’ selection properties of the attentional gate prompt the question what kind of information can be used to configure it, and how. It is possible that predominantly featural information is commonly used, although it is also clear that task knowledge and integrated events from STM have an effect too. In Chapter 5 the level of control over the attentional gate was investigated by testing the hypothesis that the gate is under endogenous control. This type of control should be firmly in the task set domain, and is less likely to be a derivate of information in STM. If the gate is indeed under endogenous control, then knowledge about average target duration should exert an effect on task performance as it relates to the amount of time that is optimal for the selection of the target item. If the gate is not so easily controlled, then the temporal integration window should be triggered by stimulus-level events only, such as the appearance of a distractor item that signals the need to stop integration and to close the gate. The results showed that attentional performance was indeed affected by target duration, as were order errors. The presence of a distractor between targets did not
The boundaries of attention seem to matter much. In other words, support for top-down control over attention was found. These findings seem to suggest that the attentional gate is highly configurable, allowing selection of items on featural, semantic and even temporal characteristics. This amount of control need not be a problem for STM-based models of attention, yet it does provide a strong extension of their architecture. A link to task set (meta-knowledge) that is not directly related to STM is probably needed to account for the effects on attentional selection. The configurable gate model of attention could incorporate this extension with relative ease by linking it directly to the filter.

A subsequent experiment on high-level control over selection was reported in Chapter 6. In the paradigm used throughout the experiments so far, the difference between a target and a distractor must have been defined in some way to allow successful selection. This difference cannot be determined in the basis of visual appearance alone; knowledge of global ‘semantic’ differences (e.g. between letters and digits) must have been used. The present experiment featured conditions with a predominance of fast and slow RSVP durations, without manipulating the specific identity of target and distractor items. The manipulation was hypothesized to create an expectancy of average speed that might affect the behavior of participants. Evidence that this was the case was indeed obtained. Participants in the predominantly slow condition were found to make more Lag 1 order errors. As they were expecting a slower presentation, they apparently expanded their integration window in time. Having the broader integration window caused these participants to jointly integrate the targets more often, and in turn to lose order information. The reverse was true for the fast-expectancy group; order errors were less frequent here. In other words, the expectancy of speed caused participants to execute a structural change in selection, independent of identity information about individual stimuli. The results support the notion that the attentional gate can be adjusted globally, on a level above individual features and events.
Chapter 8

The last aspect of attentional control that was studied is the issue of response selection. In Chapter 1, the response selection theory of Pashler (1989) was discussed. Whether or not his idea that the selection of a response poses a major bottleneck in dual-task situations transpires to the RSVP paradigm, response information does seem to be a likely candidate for some form of control. A series of experiments in Chapter 7 tested the importance of response codes for attentional performance. In order to do so, target compatibility in terms of visual appearance and associated response was manipulated. The stimulus-driven factor of appearance had a large effect on performance. Identification of a target that was preceded by an identical twin showed strongly facilitated performance. If a target was missed due to the attentional blink, the priming effect suffered. Perhaps less predictable, response compatibility had an effect as well. Although the effect was limited in scope, it was particularly resilient. Even when a target could not be reported, its response code facilitated performance on a subsequent response-compatible target. This result has the implication that once the response information in STM is used to configure the attentional gate, relatively little further interference results. Compared to stimulus-based (bottom-up) configuration of the gate that has a big effect, yet is more vulnerable to interference or decay, that is a remarkable property.

In closing

The experiments reported in this thesis fit well within the framework of the STM-based configurable gate model of attention. This framework is not proposed to be the ultimate explanation of the full range of attentional phenomena, however. Much remains unclear and so far only a few psychological mechanisms are well defined. Even if the framework is only a modest beginning, it provides a point of departure to inspire further research.
The boundaries of attention

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Samenvatting

Dit proefschrift gaat over visuele aandacht, of specifieker, over de grenzen aan het vermogen om aandacht te verdelen over meerdere snel opeenvolgende dingen. In de voorafgaande hoofdstukken is een poging gedaan om meer inzicht te verkrijgen in het aandachtsproces en te verklaren waarom het soms niet mogelijk is om de aandacht te verdelen tussen verschillende stimuli. Globaal waren hierin twee thema’s te onderscheiden. Het eerste thema was de interactie tussen elementen in het korte-termijn geheugen en de sturing van aandacht. Het tweede thema was de mate van controle over aandacht die kan worden uitgeoefend door metakennis over de experimentele taak aan de ene kant en stimulusgebaseerde gebeurtenissen aan de andere. De gerapporteerde bevindingen geven enkele nieuwe inzichten in het aandachtsproces en kunnen worden verklaard door een globaal model dat compatibel is met reeds bestaande theorieën.

De experimenten in dit proefschrift zijn gebaseerd op het zogenaamde “Rapid Serial Visual Presentation” of RSVP paradigma. Hierbij worden in snelle opeenvolging stimuli getoond, met een frequentie van circa 100 milliseconden per stuk. De waarnemer moet uit deze stroom van stimuli enkele vooraf aangegeven doelstimuli (targets) detecteren en rapporteren. Het is bekend dat als deze targets in de stroom elkaar snel opvolgen, het moeilijker wordt om beide targets correct te rapporteren; meestal wordt de tweede target gemist. Dit gebeurt in het bijzonder wanneer het tijdsinterval tussen targets kleiner is dan 500 milliseconden. Dit fenomeen heet de “Attentional Blink” of kortweg AB, een term die refereert aan de parallel met het knipperen van de ogen. Sommige auteurs hebben de AB wel toegeschreven aan het ontstaan van een gebrek aan geheugencapaciteit of de onmogelijkheid om informatie snel genoeg vast te leggen. Vanuit dit oogpunt is het van belang om de precieze relatie tussen geheugen (-functies) en selectieve aandacht te onderzoeken.
In Hoofdstuk 2 werden drie experimenten beschreven die aantonden dat er ingerdaad een relatie bestaat tussen de inhoud van het korte-termijn geheugen en selectieve aandacht. Om dit samenspel te testen werd de RSVP ingebed in een geheugentaak, waarbij enkele stimuli (zoals letters of cijfers) onthouden moesten worden tot nadat de RSVP afgelopen was. De relatie tussen het geheugen en de aandacht kwam onder andere tot uitdrukking in een steeds verdere verslechtering van het vermogen om de aandacht te verdelen wanneer tegelijkertijd ook steeds meer elementen onthouden moesten worden. Ook wanneer een semantische relatie bestond tussen de elementen in het geheugen en de doelstimuli in de aandachtstaak, vermindere de prestatie in die taak. Hoewel dit erop wijst dat aandacht en het (korte-termijn) geheugen dus met elkaar te maken hebben, bleek ook dat deze relatie slechts beperkt was. Met name de afwezigheid van een interactie tussen de belasting van het geheugen en het tijdsverloop van de aandachtstaak was opmerkelijk. Dat wil zeggen dat de prestatie in de aandachtstaak over de hele linie verzwakte, en niet alleen wanneer de targets elkaar snel opvolgden. Zelfs in de zwaarste testcondities, waarbij moeilijk definieerbare visuele symbolen werden gebruikt als stimulusmateriaal, werd de voornoemde interactie niet waargenomen.

De interactie tussen het korte-termijn geheugen en selectieve aandacht werd verder bestudeerd in Hoofdstuk 3. De experimenten in dit hoofdstuk waren gericht op het ontrafelen van factoren die van invloed zouden kunnen zijn op het opslaan en vasthouden van informatie in het geheugen gedurende de aandachtstaak. In het eerste experiment werd de toevoeging van een geheugentaak aan de RSVP an zich bestudeerd. In het tweede experiment werd geprobeerd de opslag van relevante informatie te versterken door belangrijke stimuli heimelijk te herhalen gedurende de RSVP. Er werden in geen van beide experimenten echter aanwijzingen gevonden dat deze manipulaties een meer directe relatie van geheugen met aandacht aan het licht brachten dan de al geobserveerde algemene en relatief indirecte relatie.
De resultaten uit het tweede en derde hoofdstuk werden in Hoofdstuk 8 samengevat en geplaatst in het kader van een globaal model van selectieve aandacht (zie Figuur 1 in Hoofdstuk 8). Kenmerkend voor dit model is dat selectieve aandacht wordt weergegeven als een relatief onafhankelijke selectieprocedure. Deze procedure is een proces dat ten dele wordt aangestuurd door snel detecteerbare eigenschappen van stimuli zoals kleur of grootte, en ten dele door meer cognitieve factoren. In dit laatste geval gaat het ten eerste over metakennis over de huidige situatie; het kan bijvoorbeeld zo zijn dat de targets altijd cijfers zijn en in dit geval is de informatie over deze categorische eigenschap een vorm van kennis die de selectie kan beïnvloeden. Ten tweede spelen ook elementen in het geheugen een (weliswaar beperkte en indirecte) rol, zoals hiervoor al werd besproken. In dit model wordt aangenomen dat de selectieprocedure op verschillende manieren kan worden geconfigureerd, maar dat deze dan relatief onafhankelijk kan opereren en dat de specifieke configuratie niet zwaar leunt op de functies van het geheugen. Dit laatste is op zijn minst een belangrijke aanvulling op bestaande geheugengebaseerde modellen van de AB.

In een RSVP wordt behalve de AB onder bepaalde omstandigheden nog een ander fenomeen geobserveerd. Het gaat hier om het zogenaamde “Lag 1 sparing”. Lag 1 sparing treedt op wanneer twee targets (beiden van dezelfde categorie; bijvoorbeeld cijfers) elkaar direct opvolgen, zonder andere afleidende stimuli (bijvoorbeeld letters) ertussen. In dit geval is de rapportage van de targets heel goed, wat in schril contrast staat met de AB. Lag 1 sparing wordt wel toegeschreven aan een trage selectieprocedure. Wanneer de selectieprocedure de eerste target doorlaat, blijft de deur als het ware nog net iets langer openstaan, en de tweede target kan zo ook nog doorgelaten worden. Hoewel deze verklaring intuïtief aantrekkelijk lijkt, blijft het enigszins vreemd dat twee targets voor de prijs van één kunnen worden verwerkt doordat de selectie eigenlijk te traag is.
Summary in Dutch

In Hoofdstuk 4 werden twee experimenten beschreven die het Lag 1 sparing fenomeen nader onderzochten. Het eerste wat bleek was dat hoewel de rapportage van de identiteit van beide targets goed was, hun volgorde juist vaak werd vergeten. Met andere woorden, men wist niet meer welk cijfer het eerste was en welke het tweede, maar wel wat de cijfers waren. Dit verlies aan informatie kan worden verklaard door aan te nemen dat wanneer twee targets in één keer worden doorgelaten, zij samen als één geïntegreerde gebeurtenis in het geheugen belanden. Binnen deze gebeurtenis wordt dus geen onderscheid meer gemaakt naar tijd. De tweede bevinding was dat er bovendien competitie tussen targets gaande was, waarbij identificatie van de ene target ten koste ging van de ander. Dit laatste bleek uit het effect van perceptuele moeilijkheid van de targets. Wanneer de eerste target moeilijk waarneembaar was (maar toch werd waargenomen), werd de tweede target vaker juist gerapporteerd. Als de tweede target moeilijker was, werd juist de eerste vaker correct geïdentificeerd. Kennelijk krijgt de sterker waargenomen target ook meer aandacht en dit verschil tussen de waarneembaarheid van targets doet het effect van Lag 1 sparing deels teniet. Mogelijkerwijs geeft het verschil tussen targets voldoende contrast om gezamenlijke integratie tegen te gaan.

De resultaten uit Hoofdstuk 4 vormden een aanwijzing dat selectieve aandacht een proces is dat werkt op basis van verschillende elementen. Selectie van informatie is gevoelig voor verschillende factoren, zoals de semantische categorie van stimuli en hun visuele verschijning. De vraag in Hoofdstuk 5 was in hoeverre de selectie van informatie wordt gestuurd door stimulusgebaseerde eigenschappen. In een experiment werd gekeken of de tussenkomst van een niet-relevante stimulus vlak na de eerste target een effect had op het integratieproces bij Lag 1. Dit bleek slechts ten dele het geval, wat het belang van endogene controle over selectie onderstreepte. Ter vergelijking had de duur van de eerste target wel een duidelijk effect op de integratie; een kortere aanbiedingsduur resulteerde in meer
volgordefouten. Dit was in lijn met de verwachting, omdat bij een korte duratie vaker gezamenlijke integratie van targets zal optreden.

In Hoofdstuk 6 werd getest of de selectieprocedure ook aangestuurd kan worden door de verwachtingen die een persoon heeft omtrent de huidige taak. Proefpersonen werden verschillende RSVP taken aangeboden. In de ene groep waren de RSVP stimuli overwegend snel (80 ms per stuk), in de andere overwegend langzaam (240 ms), maar beide snelheden kwamen in beide groepen random voor. Deze verschillende condities leidden ertoe dat proefpersonen in de eerste groep meestal een snelle aanbieding verwachtten, en in de tweede groep juist een langzame. Gebaseerd op deze verwachting zou de snelheid van de selectieprocedure (onbewust) kunnen worden aangepast om zo de selectie te optimaliseren. In de snelle groep zou een korte selectie beter zijn om irrelevantie stimuli buiten te sluiten, terwijl in de langzame groep een langere selectie beter zou zijn om de beschikbare tijd goed te benutten voor optimale waarneming van de targets. Het bleek uit het patroon van volgordefouten dat de snelheid van selectie inderdaad op deze manier werd aangepast. De groep die een trage aanbieding verwachtte maakte meer volgordefouten, omdat zij als het ware de deur te lang open lieten staan en zo de tweede target relatief vaak met de eerste mee naar binnen lieten. De selectieprocedure lijkt dus in dit opzicht onder cognitieve controle te staan.

De resultaten uit de hoofdstukken 5 en 6 passen in het model van selectieve aandacht dat hiervoor werd beschreven. De verschillende vormen van configuratie van de selectieprocedure vormen hierbij de stimulus- en cognitie-gedreven aspecten van visuele selectie. Een verdere toevoeging aan de diversiteit aan configurerende elementen werd ontdekt in Hoofdstuk 7. De experimenten in dit hoofdstuk vergeleken de werking van puur stimulusgebaseerde eigenschappen met die van geassocieerde responsen. De resultaten wezen erop dat stimulusgebaseerde eigenschappen een sterke factor zijn voor selectieve aandacht,
maar ook dat met bepaalde stimuli geassocieerde responsen een rol spelen. Opmerkelijk hierbij was dat dit laatste type informatie een effect had op taakprestatie, zelfs als de bijbehorende stimulus niet correct gerapporteerd kon worden. Dit wijst erop dat responsinformatie ten minste hierin verschilt van elementen in het korte-termijn geheugen. Ook deze informatie speelt echter een rol in visuele aandacht, en het is waarschijnlijk dat de attentionele selectieprocedure ook hiermee geconfigureerd kan worden.
Curriculum Vitae

Elkan Akyürek was born on June 7th, 1978 in Groningen, the Netherlands. From 1990 to 1993 he attended the Praedinius Gymnasium, after which he and his family moved to The Hague. He continued to complete his secondary education in 1996 at the Gymnasium Haganum. Elkan chose to study cognitive psychology at Leiden University that year, and graduated Cum Laude, in 2000. Further pursuing his interests in this area of science, he became a Ph. D. student in Leiden and member of an international research project investigating the dynamics of feature integration funded by the Volkswagen Foundation. He has recently accepted a postdoctoral research fellowship at the University of Reading.