The dynamics of attention in serial visual processing

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If the brain were so simple we could understand it, we would be so simple we couldn't.

Lyall Watson

Table of Contents

1 Synopsis……………………………………………………………….…….6

Footnotes……………..……………….……………………………….88

2 Experiments…………………………………………………………......94

T2+1 Blank…………..…………………………………………………....94

Explicit Order………..……………………………………………….……98

Task-Set……………..…………………………………………………...100

SD-ISI Variation…………………......……………………………102

RSVP-Speed………………………..……………………………….104

Target-Colors………………………..……………………………….108

Single vs. Dual Stream……………..………………………………..110

Cueing SOAs on a finer Scale………………..………………....114

Monoptic / Dichoptic Blink………..…………………………....119

3 References……………..………………………...……..…………...126

4 Summary in German…………………………………..……......150

The dynamics of attention in serial visual processing

Gathering, selecting and weighing information from our adjacencies are fundamental parts of human perception and a necessary precondition to successfully interact with our environment. And even though the end-result of these processes, our everyday perception, seems unambiguous and effortless to achieve (we just open our eyes and there it is), a great deal of our cortical areas and cognitive mechanisms are dedicated to produce this perception. One essential aspect in this procedure is to prioritize relevant over irrelevant information, a process commonly known as selective attention. William James wrote: “my experience is what I agree to attend to” (1890, p. 402). It becomes immediately clear from that quote that attention is, at least to some degree, under voluntary control. This means that we can choose whether we attend to a certain stimulus or not. However, this is not the whole story. If we perceive a sudden and unexpected movement in our peripheral visual field, this will most likely interrupt our current task and will automatically turn our head to see what is happening there. This means that the attentional orienting process cannot only be elicited voluntarily in a goal-driven manner, but also automatically by salient stimuli in our environment. To what extent attention is elicited by bottom up stimulus saliency and by the voluntarily top down task set, respectively, is still a matter of debate (e.g. prominent: Folk, Remington, & Johnston, 1992; Theeuwes, 1992, 1994, also see Belopolsky, Schreij, & Theeuwes, 2010; and Ansorge, Horstmann, & Scharlau, 2010, for more recent studies). There is empirical evidence that suggests that the bottom-up influence is initially strong, but vanishes over time (e.g. Donk & van Zoest, 2008).

This orienting implies that attention has a limited spatial extent, much like the fovea on the retina. In order to attend to another location, attention must first disengage from the current location, then move, and finally engage at the new location. The idea of such a "spotlight of attention" dates at least back to Helmholtz (1867, p. 741, also see James, 1890, p. 438) and is, as we will see below, still very popular among psychologist (see e.g. Posner & Petersen, 1990).[1]

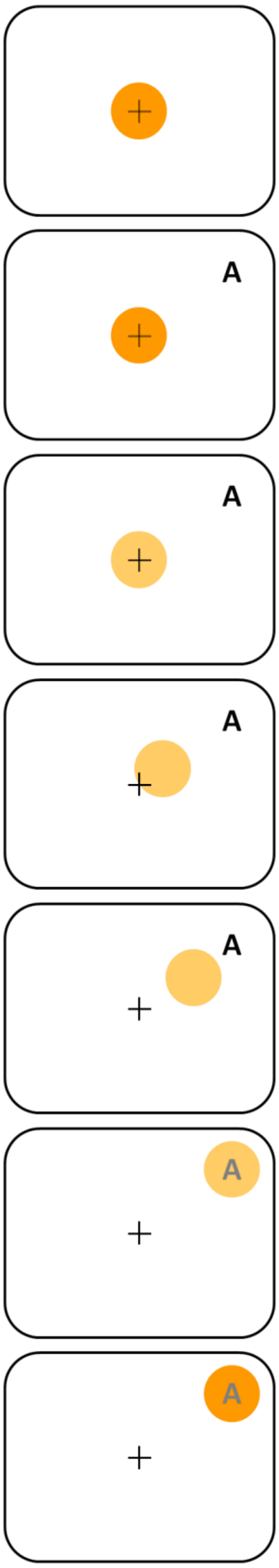


Figure I: spotlight of attention

According to Ward (2008), orienting is one of the three main aspects of attention, the other two being searching and filtering. Unlike in orienting, in which we (automatically or voluntarily) react to the appearance of a new stimulus, in search we are actively looking for a certain stimulus. This search can be done very quickly and easily if the stimulus we search for differs from the surrounding stimuli in a single dimension like color, size, orientation or shape (for instance a blue paperback among green paperbacks on a bookshelf). In fact, this search can be completed in roughly the same time regardless of the number of surrounding non-targets. If, however, the stimulus we are looking for differs from the surrounding distractor-stimuli by a conjunction of features (for instance a particular combination of color and shape, like a green apple among red apples and green pears), the number of surrounding non-targets has a large effect on search

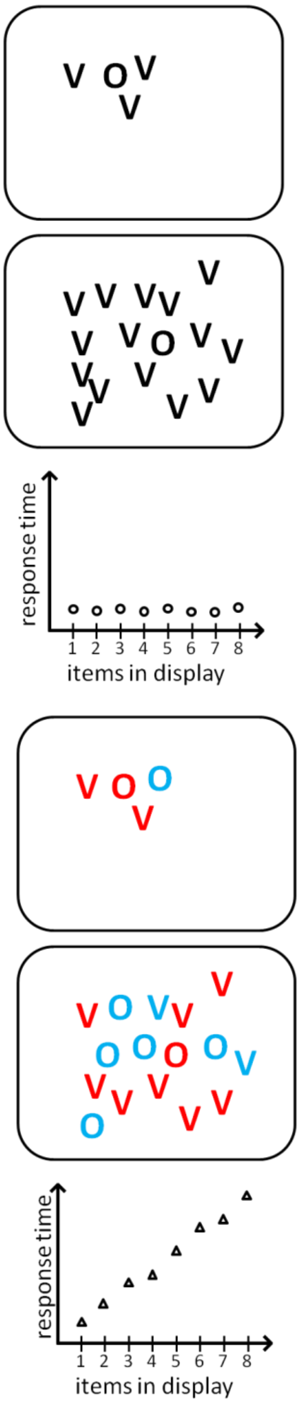


Figure II: Schematic representations and idealized search functions for single-feature and feature-conjuntion search

times (e.g. Treisman & Gelade, 1980). It is hypothesized that the simple, single feature search (the blue among green books; also known as pop-out or parallel search) can be done without focusing attention on each of the stimuli in turn (e.g. Woodman & Luck, 1999). The feature-conjunction search (the green apple among red apples and green pears; also known as serial search) on the other hand, requires that the simple features (in this example shape and color) are bound together into an integrated perceptual object (Treisman & Gelade, 1980; but see Wolfe, Cave, & Franzel, 1989). In this model, attention is the glue that pastes the different features together. This feature integration must be performed for each stimulus in turn until the target (the green apple) is found, explaining the higher search times for more crowded scenes.

As with most psychological theories, this interpretation of search times is not undisputed. Although it is widely accepted that attentional processing of targets defined by conjunctions of features is more demanding than processing of targets that are defined by a single feature (e.g. Bundesen, 1990; Duncan & Humphreys, 1989), it is still unclear whether this is due to integration or not. The observed differences may also appear due to the difference between bottom-up saliency and goal-driven attentional deployment in orienting as discussed above (see e.g. Posner, 1980): If the target differs in only one feature-dimension from the surrounding distractors (e.g. color), this target automatically elicits an attentional orienting process, because it is the most salient stimulus in the scene. If on the other hand the target is defined as a combination of certain features, it is not a priori the most bottom-up salient object. This means that attention has to be voluntarily oriented to each object in turn until the target is found. As Trick and Enns (1998, p. 371) point out, it is most likely that feature binding and spatial orienting are both required in any visual search task and should therefore be seen as complementary and not as competing.

The third aspect of attention described by Ward (2008) is filtering. Filtering means that we can quickly extract a great deal of information from attended stimuli and at the same time suppress information from unattended stimuli. The most impressive examples of filtering are inattentional blindness and the cocktail-party effect. Inattentional blindness can be characterized as the failure to detect an unexpected, yet fully visible object, as attention is occupied with a different task (for an overview, see e.g. Simons, 2007). In a highly prominent study by Simons and Chabris (1999), participants had to watch a short video-clip and count basketball passes by players wearing white shirts while ignoring passes made by players wearing black shirts. With this additional task, about half of the observers failed to notice "when a person in a gorilla suit entered the display, stopped and faced the camera, thumped its chest, and exited on the far side of the display" (Simons, 2007). Although the term "blindness" suggests that the missed stimulus (i.e. the gorilla) is not processed at all, the related cocktail-party effect indicates otherwise. Early studies by Cherry (1953), Treisman (1964), and Moray (1959) using a

**Figure III:
Invisible gorilla test**

dichotic-listening task showed that strong cues from the unattended audio-stream (like one's own name) are consciously perceived, and that information from the unattended stream can be recalled when task-demands on the attended stream are lowered, suggesting that the information in the non-attended stream is at least processed up to the semantic level.

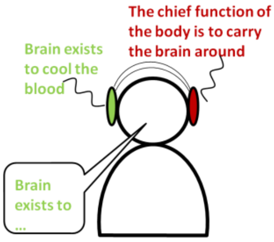


Figure IV: schematic representation of a dichotic-listening task

Later on, the dichotic-listening task was converted to the visual domain by Neisser and coworkers, using two distinct, but superimposed videos instead of auditory streams (e.g. Neisser & Becklen, 1975). Their results resemble the ones observed in the auditory domain quite closely (also see Wolford & Morrison, 1980). The dichotic-listening and inattentional-blindness experiments fueled the debate about when exactly attentional filtering takes place and to what degree unattended information are processed. This dispute between early- (e.g. Broadbent, 1958) and late- (e.g. Duncan, 1980) selection theories dominated the literature for quite a while. As Pashler (2004, p.5) concludes, more recent evidence suggests that perceptual selectivity is possible although it is often less than 100% successful (e.g. Kahneman & Treisman, 1984; Yantis & Johnston, 1990). This "compromise" fits well with Treisman's approach (1960), suggesting that filtering attenuates rather than abolishes processing of non-attended stimuli. This means that the filter in Treisman's model therefore allows unattended stimuli to pass trough, but only in an attenuated form. This mechanism ensures that highly relevant but unattended information can reach consciousness as well.

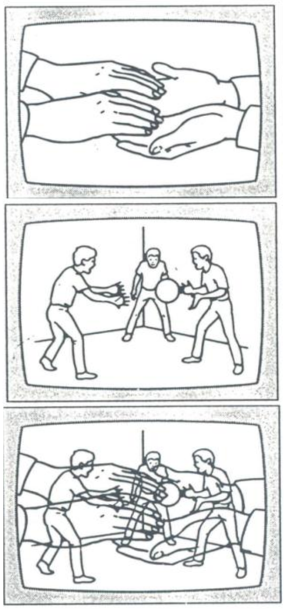


Figure V: Frames from the two films used by Neisser & Becklen, 1976

So what is attention? As yet, no exact definition has been agreed upon, but an elegant summary of what attention characterizes was given by James more than hundred years ago (1890, p. 403-404): "It is the taking possession in the mind, in clear and vivid form, of one out of several simultaneous possible objects or trains of thought. Focalization, concentration of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others". This quote illustrates that James especially emphasized the filtering aspect of attention. We will return to the question of attentional filtering later, when we discuss several theories of the attentional-blink phenomenon.

In the last several decades the empirical focus of attention research has shifted to the visual domain (see, e.g. Pashler, 2004, p.4). Since then, researchers have addressed many fundamental questions about the way in which visual information is selected. A number of studies support Helmholtz's claim of a spotlight of attention, most prominently the cueing experiments done by Posner and colleagues in the late 70s and early 80s (e.g. Posner, 1978, 1980, Posner, Snyder, & Davidson, 1980; also see Prinzmetal, McCool, & Park, 2005). In these experiments, participants were asked to detect a light appearing in one of several possible conditions around fixation. In the majority of the trials one of the locations was precued, indicating at what location the light most likely appeared. Posner's results were unambiguous: response times were fastest when the light actually appeared at the precued location and slowest when the light was

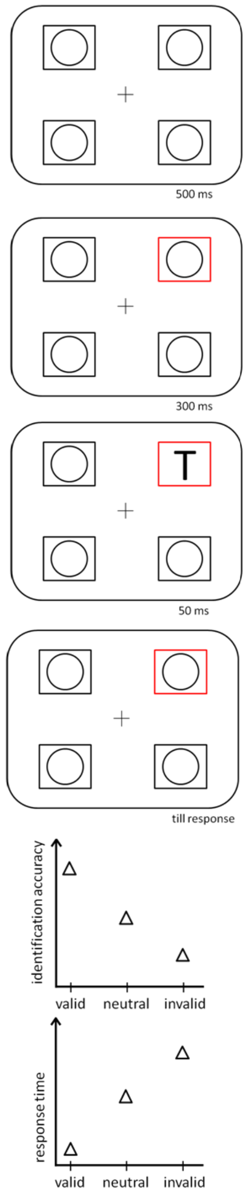


Figure VI: Spatial cueing paradigm in the style of Prinzmetal and colleagues

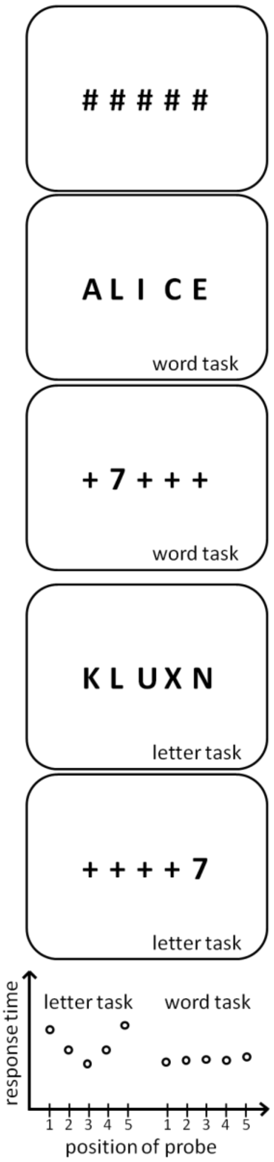


Figure VII: Prototypical shape of the attended region found by LaBerge

presented at a different location than the precue indicated. Reaction times of uncued trials lied almost exactly in between the valid- and invalid-cued trials. Further evidence that attention can be directed to a specific spatial location comes from LaBerge and coworkers (LaBerge, 1983; LaBerge & Brown, 1986). LaBerge was interested in the spatial extend of the spotlight. Therefore, he asked subjects to perform two successive tasks on each trial. The second task was always to detect a dot appearing at one of 5 possible positions. The first task was either to determine whether a string of five letters formed a word (the word task), or whether the middle letter in that five-letter string was a vowel (the letter task). LaBerge hypothesized and found that the word task required participants to attend to the five-letter string as a whole, resulting in a wide attentional spotlight. Therefore the reaction times in detecting the dot (the secondary task) did not differ as a function of dot position. In the letter task on the contrary, subjects focused their attention at the middle letter of the string, since this was the only task relevant. As a result, reaction times for the secondary task got slower and slower the larger the distance between the dot and the middle position became. These results furthermore indicate that the size of the focus of attention depends of the task at hand (cf. the zoom-lens model described in Footnote 1), and that the attentional spotlight does not have a distinct range, but is rather distributed in a gradient fashion.

This latter claim is further supported by the illusory line motion phenomenon (e.g. Hikosaka, Miyauchi, & Shimojo, 1993a, b, c). In this phenomenon participants have to fixate on a dot at the middle of the screen. Next, a stationary line is presented at one of the dot's ends. In the vast majority of participants this induces the impression of motion: it seems as if the line grows from the attended dot towards the unattended end. This perception can be explained as the result of an attentional gradient: the dot is the attended object, the parts of the line closest to the dot fall into the spotlight as well. With increasing distance to the dot, the gradient and thus the attentional facilitation get weaker, resulting in the impression of asynchrony in appearance of the line (see Scharlau & Horstmann, 2006, p. 88; also see Shimojo, Hikosaka, & Miyauchi, 1999; Bachmann, 1999).

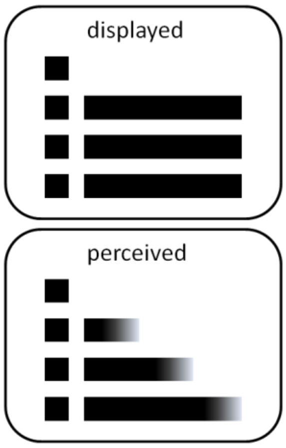


Figure VIII: Illusory Line Motion

One last aspect of the spotlight metaphor should be discussed here. If attention shifts from one location (for instance the fixation point) to another (e.g. the target-location), how does it move? Does it illuminate intervening locations? Does it move at a fixed speed so that locations farer away take longer to be reached? Whereas the answer to the first question remains uncertain, the second one can be negated (see Yantis, 2004, p. 236). Data from Remington and Pierce (1984), as well as Kwak, Dagenbach, and Egeth (1991) and Kröse and Julesz (1989) all indicate that spatial distance over which attention has to travel does not influence the time until it gets there. However, as Yantis (2004, p. 236) points out, these results do not falsify the spotlight metaphor, as it is still possible that attention moves at a variable velocity, for instance it could move faster the further it has to go.

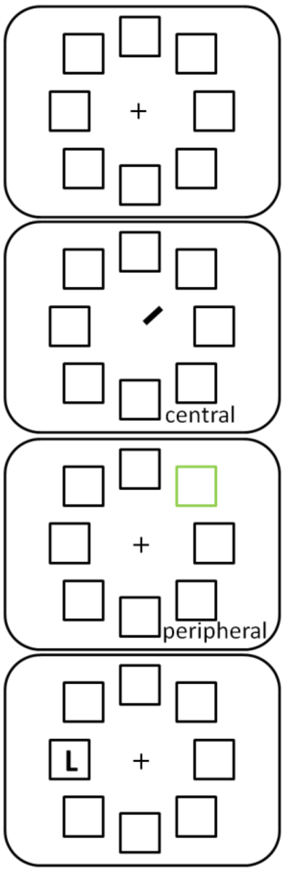


Figure IX: peripheral and central cueing

After looking at several spatial characteristics of attention, I will now come back to the question what triggers an attentional shift. As quoted at the beginning of this manuscript, James emphasized that we can voluntarily direct our attention to specific stimuli (in his words: active). He also noted that certain stimuli, “very intense, voluminous, or sudden” (James, 1890, p. 416) immediately and involuntary draw attention to themselves (i.e. passive). It wasn’t until a century later before Jonides (1981) empirically tested whether one could resist this automatic attentional capture. To this end, he employed two different kinds of cues: peripheral, i.e. at the target-location, and central, i.e. a cue at fixation that pointed at the target-location. Jonides found that while it was easy to disregard the central cues, it was nearly impossible to ignore the peripheral cue, even when it never appeared at the correct target location (Remington, Johnston, & Yantis, 1992). However, the attentional capture by irrelevant stimuli might not be as absolute as originally thought. For instance Bacon and Egeth (1994) demonstrated that a task-irrelevant singleton only captured attention when the target was defined as a singleton as well (albeit in a different dimension). When the target was defined in a more complex way, the irrelevant singleton had no negative effect on task performance. This led to the idea of an attentional control setting, stating that only stimuli which are compatible with an a priori determined feature set will tend to receive attention (e.g. Folk, Remington, & Wright, 1994; Folk, Remington, Johnston, 1992). In view of this theory, the incapability to ignore the non-predictive cue in

Jonides (1981) is a result of the fact that both the cue and the target had a sudden onset, therefore the feature-dimension “onset” was relevant, even though the cue itself was not. This hypothesis is not undisputed. Whether and to what extend singletons that do not fit the attentional set still capture attention is still the matter of a heated debate (e.g. Schreij, Owens, & Theeuwes, 2008; Folk, Remington, and Wu, 2009; Schreij, Theeuwes, & Olivers, 2010a, b).

Another difference between “active” and “passive” attentional deployment is much less equivocal: Müller and Rabbitt (1989) found that central and peripheral cues had distinctively different time courses. Whereas “passive”, automatically elicited attention is transient, i.e. is deployed rapidly and diminishes shortly afterwards, “active”, voluntary attention, is sustained, i.e. it takes longer until it is deployed, but it diminishes rather slowly. These results were later corroborated in several different paradigms (e.g. Nakayama & Mackeben, 1989; Cheal & Lyon, 1991; Carlson, Hogendoorn, & Verstraten, 2006). These rapid and transient characteristics of attention are not only relevant when attention is deployed in space, but also when it is deployed in time, to which I will turn next.[2]

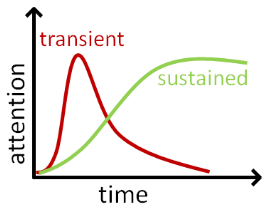


Figure X: schematic functions of transient and sustained attentional deployment

Much of the earlier work concentrated on understanding how humans process information distributed across space. In the remaining part of this manuscript, I will concentrate on the temporal aspects of attention. Interest in this line of research has only risen in roughly the last twenty five years. Since then researchers have addressed many fundamental questions about the way in which visual information is selected: How are items selected, when they compete for attention in time rather than in space? Has attention to “dwell” on one object, before it can turn to another? Does the processing of an earlier stimulus impair the chances of a later object to reach consciousness? Does it enhance them (e.g. Duncan, Ward, & Shapiro, 1994; Bonnel & Prinzmetal, 1998; Broadbent & Broadbent, 1987; Bachmann, 1984)?

In the past two decades the “rapid serial visual presentation” design has become a fruitful experimental paradigm for questions regarding the temporal nature of attention (RSVP; Lawrence, 1971; Potter & Levy, 1969). In RSVP visual stimuli, e.g. digits and letters, appear sequentially at the same spatial location, each presented for a tenth of a second or less and immediately replaced by the next one. Observers are usually instructed to either report all items they have seen (whole report), or to report pre-defined target items (for example digits) and ignore the remaining distractor stimuli (for instance letters; partial report; e.g. Nieuwenstein & Potter, 2006). By manipulating the presentation speed, changing the amount of information the observer has to report, and coupling the behavioral measure with EEG recordings, the RSVP paradigm has provided researchers with a versatile tool to study not only the time course of attention and memory consolidation, but also how brain processes contribute to conscious information processing (see Chun & Wolfe, 2001; Dux & Marois, 2009, p. 2).

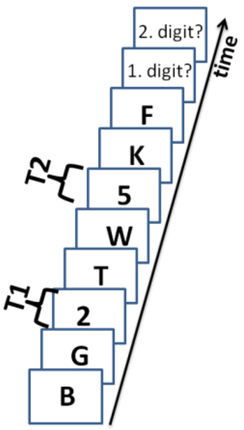


Figure XI:
Rapid Serial Visual Presentation

Especially the two-target version of the RSVP paradigm has become increasingly popular to investigate an apparent limitation in visual perception: Whereas observers have little to no difficulties in reporting the first target stimulus (T1) in a sequence of distractors, they often fail to identify the second target (T2) when it is presented up to 500 ms after the first (Broadbent & Broadbent, 1987). It is as if attention, analogous to the lid closure of an eye blink, briefly switches off before new information can be processed. Hence, this phenomenon was named the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992 p. 858). This second-target deficit is quite robust: over the years, it was found in hundreds of studies, it is reliable for a vast majority of subjects even after extensive training (e.g. Taatgen, Juvina, Schipper, Borst, Martens, 2009) and it can be found with a number of different types of stimuli like words (e.g. Broadbent & Broadbent, 1987; Luck, Vogel, Shapiro, 1996), alphanumerical stimuli (e.g. Hilkenmeier & Scharlau, 2010), symbols (e.g. Chun & Potter, 1995), or pictures (e.g. Evans & Treisman, 2005). Moreover, the attentional blink can also be found within different modalities, e.g. auditory (Duncan, Martens, & Ward, 1997) or tactile (Hillstrom, Shapiro, Spence, 2002). All of this suggests that the attentional blink reflects a fundamental mechanism of human attention; and thus can give us insight into the basic components of information selection and processing (see Martens & Wyble, 2010).

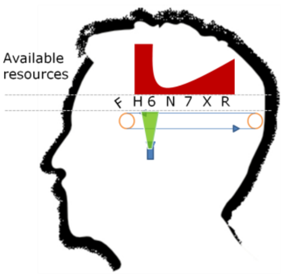


Figure XII: resource-depletion model: blink

The basic empirical finding that the second of two task-relevant stimuli in a stream of irrelevant distractors is often missed gave rise to theories stating that when the first target-stimulus (T1) in the stream is detected, a process is triggered to ensure T1's encoding and consolidation till it reaches consciousness. This processing not only takes time, but momentarily consumes most of the attentional resources available. As a result, when T2 is presented shortly afterwards, there are little attentional resources left. Therefore, T2 cannot be processed properly and eventually its representation is lost, i.e. the blink occurs (e.g. Ward, Duncan, & Shapiro, 1996; Duncan, Ward, & Shapiro, 1994). When the temporal distance between T1 and T2 increases, it is more likely that T1 has already finished processing. Thus, on average there are more and more attentional resources freed up; and successful encoding and consolidation of T2 becomes more and more likely.

Interestingly, when T1 and T2 are presented right after each other within 100 ms, T2 performance is virtually unimpaired, a finding known as lag-1 sparing (Potter, Chun, Muckenhoupt, 1998, Visser, Bischof, & Di Lollo, 1999).[3] The lag-1 sparing result is especially surprising for the afore mentioned theories of resource-depletion: When T2 is presented in such close proximity to T1, all resources should be devoted to T1. Hence, T2 performance at lag 1 should be worst, not unimpaired.

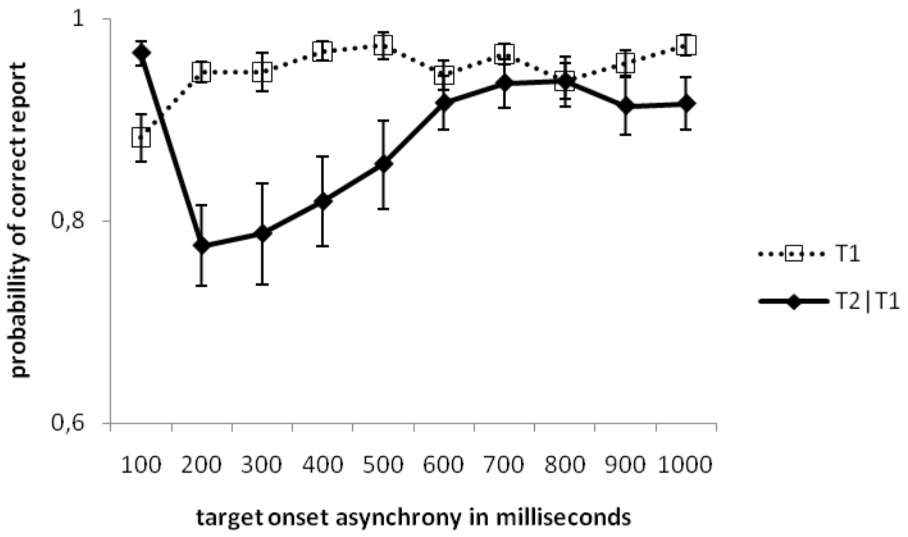


Figure 1: Typical time course of the attentional blink. Error bars represent standard errors of the mean. The data is taken from the 100 ms / item condition of the “RSVP-Speed” experiment described later in this manuscript.

To account for this intriguing result, many theories modified the basic resource-limitation account by introducing two different stages of processing and a sluggish attentional gate (most prominent: Chun & Potter, 1995). In the first, capacity-free stage, multiple stimuli are analyzed in parallel. If one of the stimuli shows task-relevant features, this stimulus opens an attentional gate (also known as “episode”, Chun & Potter, 1995; “batch”, Jolicœur, Tombu, Oriet, Stevanovski, 2002; “window”, Visser et al, 1999; or “event”, Akyürek, Riddell, Toffanin, & Hommel, 2007) and is transferred to the second stage of processing. In this second stage, the stimulus is further encoded and consolidated until it obtains a more durable representation and becomes consciously reportable. In contrast to stage 1, processing in the second stage is resource-heavy. This means that stage 2 can only work in a serial manner, i.e. it can only

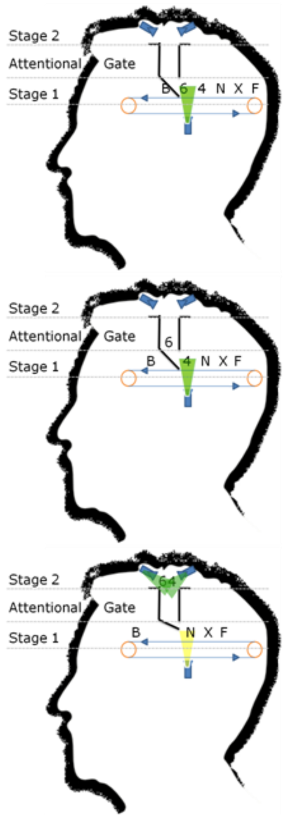


Figure XIII: 2-stage-model: lag-1 sparing

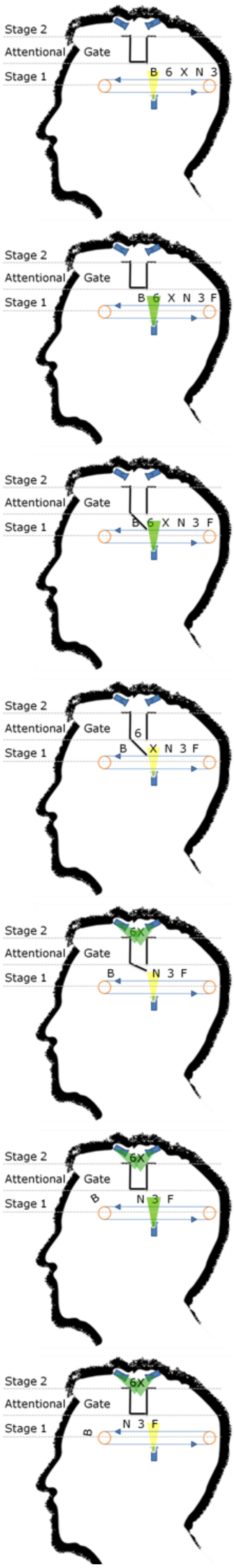


Figure XIV: 2-stage-model:blink

process one "chunk" of information per time. However, the attentional gate to the second stage does not close right after T1, but rather "sluggishly" (e.g. Potter, 2006; Potter, Staub, and O'Connor, 2002). The post-T1 item can slip through the gate as well and will most likely be processed together with T1 in stage 2. If the post-T1 item is a distractor, it will accidentally receive privileged processing. The system will eventually realize that this stimulus is not task-relevant and will discard it. In case of lag 1, the post-T1-item is T2, which explains the high performance for both targets within 100 ms. This joint processing of the two targets in stage 2 is commonly known as episodic integration. With the auxiliary assumption of episodic integration, resource-limitation theories can easily predict the time course of T2 performance in RSVP as depicted in Figure 1: when both targets are presented within 100 ms, they are processed in one episode, hence T2 accuracy is unimpaired. When T2 is presented about 200 ms after T1, the attentional gate to the second stage is already shut down and therefore T2 has to wait until processing of T1 in stage 2 is finished: "When T2 appears before the second stage is free, it will be detected by Stage 1 processing, but Stage 2 processing will be delayed. The longer the delay, the greater the probability that T2 will have been lost…" (Chun & Potter, 1995, p.122). This explains the steep decrease in T2 performance at lag 2. With increasing temporal distance between T1 and T2, it becomes more and more likely that T1 consolidation is complete and T2 can enter the second stage of processing, explaining the gently inclining performance for T2 between 300 ms and 500 ms. After about 500 ms, encoding of T1 should be completed and no longer interfere with processing of T2 and T2 performance should again be unimpaired. Theories that incorporate episodic integration and two stages of processing are still widely popular in the attentional blink literature (e.g. Bownman & Wyble, 2007; Jolicœur & Dell'Acqua, 1998; Dux & Harris, 2007a; see Dux & Marois, 2009 for a recent review). Besides the basic time course of the AB, episodic-integration theories can account for a number of related findings as well: The claim that the T2-deficit arises because T2 has to wait for T1 processing to be completed and is therefore prone to decay and overwriting by subsequent stimuli is well supported by data from Giesbrecht and Di Lollo (1998). Their data show that the blink is strongly attenuated when T2 is the last item in the stream and can therefore not be overwritten by trailing distractors (also see Vogel & Luck, 2002; and Sessa, Luria, Verleger, & Dell'Acqua, 2006).

experiment:
T2+1 blank

stream:
SD 100ms; ISI 0

lags: *1,2,3,6*

targets:
black digits

distractors:
black letters

conditions:
a) standard AB
b) T2+1 item replaced with blank

main result:
Blink deminishes when T2+1 item absent

Figure XV: summary of experiment „T2+1 blank“

In two of my own experiments, I could largely replicate this latter result. When the distractor trailing T2 (the T2+1 item) was replaced with a blank, the blink was nearly absent. However, when a later distractor was replaced instead (the T2+2, or T2+3 item), the time course of the attentional blink did not differ significantly. Interestingly, replacing the T2+1 item had the same effect as T2 being the last item in the stream (see Giesbrecht & Di Lollo, 1998). This means that the additional 100 ms were sufficient to shield T2 from getting overwritten by trailing distractors.

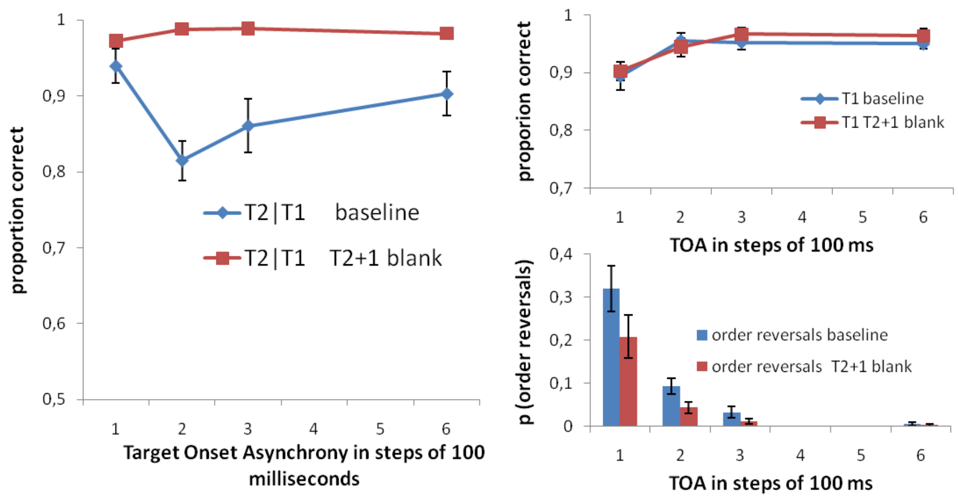


Figure 2: results of the “T2+1 blank” experiment as a function of lag and condition. Left: conditional T2 accuracy. Right (top): T1 accuracy, right (bottom): proportion of order reversals. Error bars represent standard errors of the mean.

Episodic integration theories can also explain the controversial finding that the blink gets stronger the more similar T1 and the T1+1 distractor are (Isaak, Shapiro, & Martin, 1999; Chun & Potter, 1995; but see e.g. Maki, Bussard, Lopez & Digby, 2003). According to episodic integration, T1 and the adjacent distractor are processed together in the second stage. When both items are quite similar, disentangling the target from the distractor takes longer. Therefore processing of T2 is even more delayed and the probability of T2 getting overwritten increases. Likewise, the attentional blink is strongly attenuated when the T1+1 distractor is replaced by a blank (Chun & Potter, 1995, Raymond et al., 1992).

One empirical finding in particular made Potter and colleagues rethink their original two-stage model (Potter, Staub and O'Connor, 2002): As can be seen in Figure 1, T1 performance at lag 1 is impaired compared to later lags. It seems as if the high T2 accuracy at lag 1 comes at the cost of decreased T1 performance. In fact, T2 often outperforms T1 if the two targets are presented in close succession. This reliable finding challenges the basic two-stage account. How can T2 performance be superior to T1 performance when T1 enters the second stage first and therefore gets privileged access to limited capacity processing resources in any case? Potter and colleagues enhanced the original two-stage model to a "two-stage competition model", which postulates that T1 does not automatically get access to the resources in stage 2, but that the targets compete in stage 1. Depending on the respective circumstances, the more salient target wins and will be processed. This results in a tradeoff between the targets: the attentional resources that one target wins (and which lead to that it is identified), the other target automatically loses (Potter, 2006). Whichever target wins this competition at stage 1 is transferred to the second stage first. This does not mean that the two-stage completion model cannot predict lag-1 sparing: When the temporal distance is short, and yet both targets get identified at stage 1, they can both enter stage 2 together and are still processed as one episode. In case T2 wins the competition at stage 1, it actually is T1 which is spared, not T2.

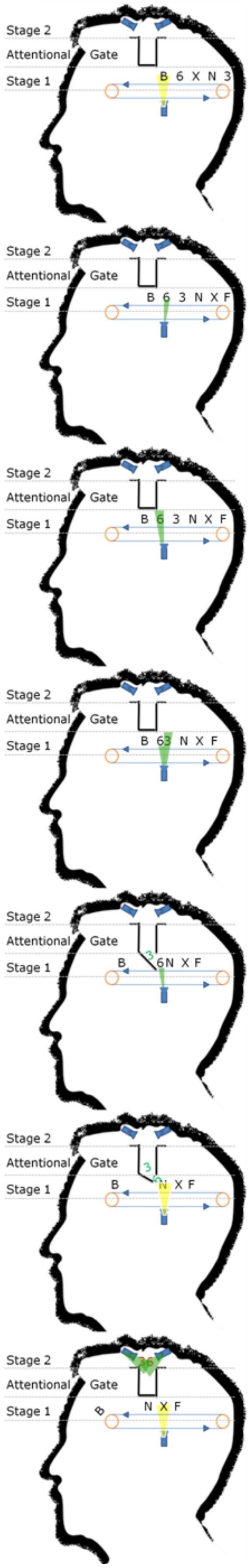


Figure XVI: 2-stage-competition model: T1/T2 tradeoff

To summarize: at very short temporal intervals, the mechanisms of the two-stage competition model differ from the mechanisms in the basic two-stage model. In the former, at intervals below 100 ms T2 steals all the identification resources elicited by T1. Therefore T2 will be identified easily and can enter stage 2. T1, however, has little resources left and will not become identified at stage 1. Thus it cannot join T2 in stage-2 processing and its representation is lost. At stimulus onset asynchronies (SOAs) around 100 ms, T2 enters the competition a little bit later, which gives T1 time to utilize some resources for its own. T2 often gets the remaining ones, both targets will be identified at stage 1 and therefore can both enter stage 2. When the temporal interval between T1 and T2 increases to about 200 ms, T2 comes too late to compete with T1: T1 already used its resources to become identified at stage 1 and is already in stage-2 processing. As in the original two-stage model, T2 will also be identified at stage 1, but as processing at stage 2 is serial, T2 has to wait at stage 1 and becomes prone to decay and overwriting (see Potter et al., 2002, Potter, 2006, Dux & Marois, 2009). Interestingly, the results of Potter et al. (2002) further suggest that competition is not bound to a specific location, but overlaps to neighboring ones. Moreover, by including direct competition between the two targets, Potter and coworkers also incorporated the approach of Shapiro et al.'s interference model (1994). Whereas Shapiro and colleagues assume competition at a relatively late stage of processing in the visual short term memory, Potter et al. (2002) state that the competition appears before the items even enter the second stage of processing.

Over the last years, several studies with three or more targets in a single RSVP stream have seriously challenged the capacity-limitation interpretation of the blink being a result of resource-heavy T1 processing: They showed that observers were able to identify several proximal targets as long as they were presented immediately after each other, a finding referred to as “spreading of the sparing” (e.g. Di Lollo et al., 2005; Nieuwenstein & Potter, 2006; Olivers, Van Der Stigchel & Hulleman 2007; Kawahara, Kumada & Di Lollo 2006). In fact, Kawahara, Enns, and Di Lollo (2006) demonstrated that performance for the third target in a stream of three consecutive targets was significantly higher than performance of the first target, which is clearly at odds with resource-depletion models. Of particular interest in this context is the study of Nieuwenstein and Potter (2006). In this study participants were able to report a string of up to six consecutive colored items without showing an attentional blink. When the task changed and participants were asked to report only two items of a particular color, the same stimulus string produced the standard blink pattern. This means that report- accuracy of the same items at the same temporal distance is higher when all stimuli have to be reported, in comparison to only two items having to be reported. Put differently, observers are able to encode three targets in a row in the same time as they otherwise fail to report the second of two targets.

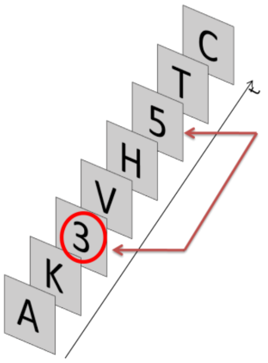


Figure XVII: temporal cue used by Hilkenmeier and colleagues

Another finding that does not sit easily with the limited-capacity idea is the fact that T2 performance can be increased when the second target is precued. Precueing T2 can be accomplished in several ways. In some of our own work we used a temporal cue that provided information about the temporal position of T2 (Hilkenmeier, Tünnermann, & Scharlau, 2009; Hilkenmeier & Scharlau, 2010; “we” is used when I am referring to work that was done with at least one coauthor). In these studies the participants’ task was to report two digits among distractor letters. In the cueing condition the identity of the T1-digit was a valid cue for the lag T2 would appear in. If T1 was a “1”, T2 would appear in lag 1, i.e. immediately after T1. If T1 was a “3”, T2 would appear in lag 3, i.e. T1 and T2 were delineated by two intermediate distractors. This temporal cue embedded in the identity of T1 significantly increased T2 accuracy, even for extremely short temporal distances between T1 and T2 of about 50 – 100 ms. This means that within this quite short time span the identity of a target is processed and the relevant information can rapidly be extracted and used to adjust the task and substantially increase performance. This finding goes against the notion that an extensive, time-consuming identification process causes the blink.

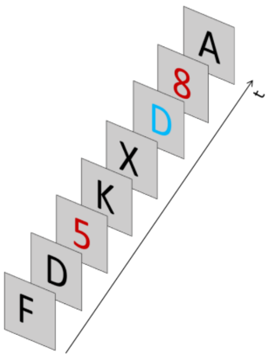


Figure XVIII: cue used by Nieuwenstein and colleagues

Another way to increase the identification accuracy of the second target is to insert an additional item with a task-relevant feature in the RSVP stream just prior to T2. This was for instance done by Nieuwenstein and colleagues (Nieuwenstein, 2006; Nieuwenstein, Chun, Hooge & Van der Lubbe, 2005). In their studies the task was to report two colored digits among black distractor-letters. Cueing T2 was achieved by coloring the distractor-letter preceding T2. Importantly, even distractors that were presented in a different color than the to-be-cued targets were highly effective cues, as long as their color matched one of the possible target colors. This indicates that cueing can occur in the absence of shared features between cues and targets, as long as they both match the same attentional set (also see Scharlau & Neumann, 2003; Folk, Remington, & Johnson, 1992; Folk, Remington, & Wright, 1994). The "rapid reversal" of the attentional blink found by Olivers et al. (2007; also see Kawahara, Kumada et al., 2006; Olivers & Meeter, 2008) goes in the same direction: Participants were confronted with a stream containing T2 at lag 2 and additionally a third target (T3) at lag 3 (basically, instead of a cue preceding T2, they used T2 to cue the immediately following T3). An attentional blink was found for T2 but not for T3 which was almost completely spared; even though it was presented in a temporal position relative to the first target which is normally strongly impaired (see Figure 1). These results evidence that the attentional blink is not, as Raymond et al. (1992, p. 858) suggested, ballistic: It can be postponed as long as task-relevant information is presented; it can be attenuated when the temporal position of T2 is cued; and it can rapidly recover when consecutive targets are shown during the blink-period.

Figure XIX:
TLC model: blink

All of this suggests that attention uses a more flexible mechanism for mediating attentional deployment than simply deplete all of its resources at once (Wyble et al., 2009).

To account for these more recent empirical findings, the theoretical landscape shifted. Instead of emphasizing on resource-depletion or a bottleneck as the source of the attentional blink, Di Lollo and colleagues (2005) suggested to focus on the afore mentioned filtering aspects of attention. In their “temporary loss of control” model (TLC) they do not see the blink as a result of resource-depletion, but as the temporary loss of an endogenously established task set. In the typical attentional blink paradigm, this task set would be something like “reject distractors and accept targets” (see, e.g. Kawahara et al., 2006, p. 406). Importantly, this filter is volatile rather than static. Following an earlier idea of William James (1890, p. 420), the endogenous filter needs a periodic maintenance signal to be sustained (see Di Lollo et al, 2005, p. 192). In the period leading to the first target, this signal can easily be maintained, meaning that the pre-T1 distractors can easily be inhibited. When T1 appears, the endogenous maintenance signal is discontinued, since the system is now busy with consolidating this first target (Olivers & Meeter, 2008, p.4; Di Lollo et al, 2005, p. 198). Thus, the filter is no longer under endogenous control, but becomes vulnerable to alteration by the T1+1 stimulus. If this next item also belongs to the target-category, the input filter remains unaltered and the T1+1 stimulus is processed efficiently, i.e. sparing occurs. On the other hand, if the T1+1 stimulus is a distractor, it will exogenously disrupt the input filter, prolonging any processing of trailing target stimuli, which eventually leads to the blink. As soon as consolidation of T1 finishes, the system gradually regains control over the input filter again, reinstates the correct task set and allows target processing to return to normal.

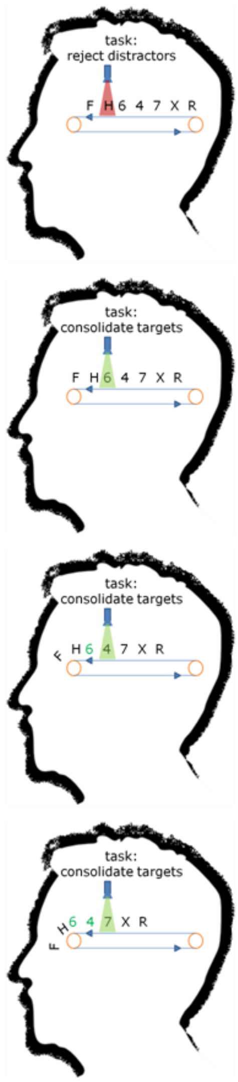


Figure XX: TLC model: spreading of the sparing

As Olivers and Meeter (2008, p. 4) point out, it is questionable “whether TLC indeed manages to avoid the limited-capacity resource depletion argument. Notably, it assumes that T1 occupies a central executive for some time, during the course of which the system is not ready for T2. It appears then that limited capacity resources have entered through the back door”. To be clear, unlike limited-capacity models, TLC states that the system can handle more than one or two items before its resources deplete. The capacity of the visual short term memory is the only limit here. In TLC the cognitive system is limited in the way that it can only execute one process at any given time, i.e. either maintaining the input filter or consolidating T1 (see e.g. Di Lollo et al, 2005, p. 193).

Taken together, the TLC deserves credit for being one of the first attentional-blink theories that “break the bottleneck” and shift the focus to attentional filter settings as source of the attentional blink. In subsequent years, more and more models followed this theoretical shift and emphasized the role of attentional control and attentional gating, for instance the “simultaneous type, serial token” model of Bowman and Wyble (STST, 2007), the “boost and bounce” theory of Olivers and Meeter (B&B, 2008), or the “episodic simultaneous type,

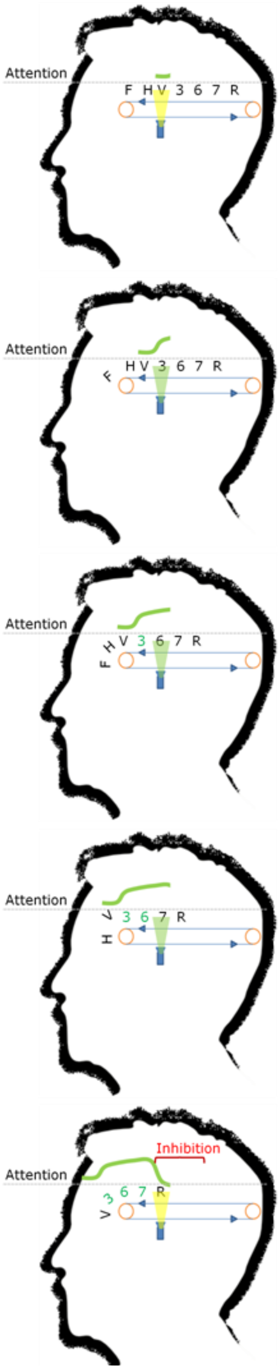


Figure XXI: eSTST: spreading of the sparing

serial token" model (eSTST, Wyble, Bowman, & Nieuwenstein, 2009). All of these theories share the idea that a spatiotemporally constrained window of attentional enhancement is deployed in response to detection of a potentially relevant stimulus (Wyble et al., 2009, p. 3). The attentional facilitation is hypothesized in a rapid and transient way: the enhancement should peak around 100 ms (or, more roughly between 50 ms and 150 ms) and quickly decrease afterwards (see Reeves & Sperling, 1986; Nakayama & Mackeben, 1989; also see the attentional cascade model, Shih, 2008, 2009). In all of these theories the attentional facilitation (the "blaster" in (e)STST, or the "boost" in boost & bounce) hits the T1+1 item as well, allowing for lag 1 sparing. However, the theories differ in the way they manage the transition from sparing to the attentional blink: The models of Wyble and colleagues (STST; eSTST) as well as the attentional cascade model (Shih, 2008) hold on to the idea of time-consuming consolidation of T1 (and the T1+1 item) suppressing further attention until T1 has been encoded. This means that eventually T1 causes the blink. In the Boost and Bounce theory on the other hand, time-consuming target processing plays no role in the rise of the blink. Instead, this model assumes that it is the first distractor after target information that shuts down further attentional deployment (Olivers & Meeter, 2008).

Whether the blink is caused by T1 itself, or by the first post-target distractor is still a matter of debate. The T2-cueing results of Nieuwenstein and coworkers (Nieuwenstein, 2006; Nieuwenstein et al., 2005) and the rapid recovery results of Olivers et al., 2007 indicate that the blink deficit is caused by the first post-target distractor, not by T1 itself: In these studies T2 performance increased in lags at which T2 is usually blinked, but this increment did not come at the cost of reduced T1 performance. If time consuming and resource-heavy T1 consolidation causes the blink, one should expect some effect on T1 performance since T2 identification interferes with T1 consolidation. On the other hand, studies that show decreased T1 performance when T2 is presented in lag 2, as for instance Potter et al. (2002; also see Figure 1) indicate that an early T2 indeed interferes with T1 processing. Furthermore there is evidence about the post-T1 distractor not being needed to induce the blink, as long as T2 is sufficiently masked (Nieuwenstein et al., 2009). This is clearly is at odds with the Boost and Bounce theory that emphasizes the role of the post-target distractor.

Figure XXII: eSTST: blink

The theoretical shift from limited capacity and resource depletion to attentional control is highly controversial. A number of recent studies report that the apparent spreading of the sparing with three targets in a row really is due to a tradeoff between T1 and T3 (Dux, Asplund, & Marois, 2008; 2009; but see Olivers, Spalek, Kawahara & Di Lollo, 2009), or that the apparent sparing of T3 really is caused by a methodological artifact (Dell'Acqua, Jolicoeur, Luria, & Pluchino, 2009). Dell'Acqua et al. report that when T3 accuracy is analyzed contingent on correct report of T1 and T2, T3 performance actually is impaired. They conclude that the blink is still best explained by a capacity-limited process in which T1 opens an attentional episode. T2 can slip into this episode as well when it is presented within 120 ms of T1 and both targets are processed together. Even if T3 is the next item in the row, there are little chances for it to enter the episode as well and it will eventually get blinked (2009; p. 28f).

After conducting a thorough review of the attentional blink literature, Dux and Marois (2009, p. 51) argue in a similar vein: they conclude that it is possible for a common capacity-limited attentional resource to underlie the deficit. According to this view “the process that is responsible for the trade-off between T1 and T3 performance in the serial target experiments of Dux et al. (2008; 2009) is the same which underlies the AB impairment in the distractor-less design of Nieuwenstein et al. (2009), or the attenuating effect of distraction in the experiments of Olivers and Nieuwenhuis (2005; 2006); namely, the deployment of selective attention. The more attention that is deployed for T1, either because it is more salient, more task relevant or requires more encoding into working memory, then the less that is available to process subsequent targets. Similarly drawing attention away from T1, either by cuing a distractor prior to T2 (e.g., Nieuwenstein, 2006) or by including distracting tasks (see above), may alleviate the T2 deficit. The neuroimaging evidence that AB manipulations recruit the frontal-parietal attentional networks of the brain (Hommel et al., 2006; Marois & Ivanoff, 2005) adds further weight to the view that, first and foremost, the attentional blink

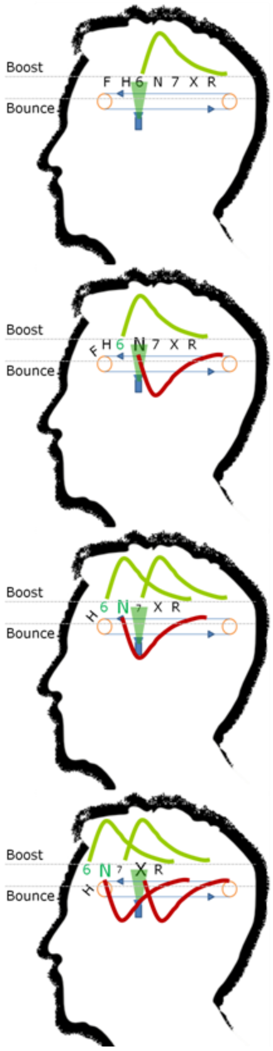


Figure XXIII: B&B: blink

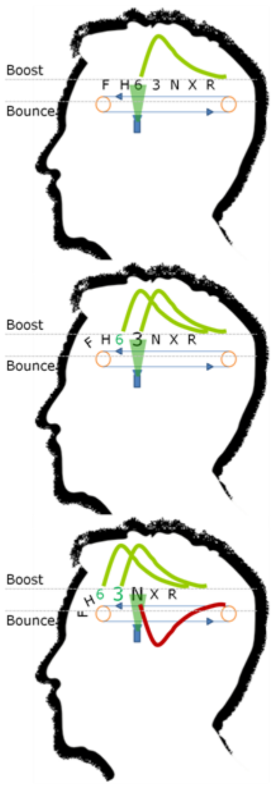


Figure XXIV: B&B: sparing

represents a deficit of selective attention." Similarly, Akyürek, Toffanin, and Hommel (2008, p.575) point out that "lag 1 sparing is presumably associated with two logically related but nevertheless different processes: integration into the same episodic file and competition within this file".

As can be seen by this overview of the literature, there still is a heated controversy on what underlying mechanisms cause the time-course of the attentional blink. However, it seems that one critical – and the most controversial – point is the explanation of lag-1 sparing. Is it due to a sluggishly closing gate and episodic integration? Or is it due to delayed attentional enhancement?

In the majority of our own research, we have created conditions for which these different theoretical approaches on lag-1 sparing make different predictions. To this end we did not concentrate on target-identification accuracy at lag 1, but instead investigated the accompanying phenomenon that the reported targets are often perceived in the wrong order (Olivers, Hilkenmeier & Scharlau, 2010; Hilkenmeier, Olivers, & Scharlau, 2011; Hilkenmeier, Scharlau, Weiß, & Olivers, 2011). As can be seen in Figure 3, lag-1 sparing is indeed accompanied by a substantial proportion of temporal order reversals (Chun & Potter, 1995; Bowman & Wyble, 2007; Hommel & Akyürek, 2005; Akyürek & Hommel, 2005). These order reversals were originally regarded as strong evidence in favor of episodic integration in a second stage of processing: when T1 and T2 are presented in close succession, they are processed as a single event – that is, they

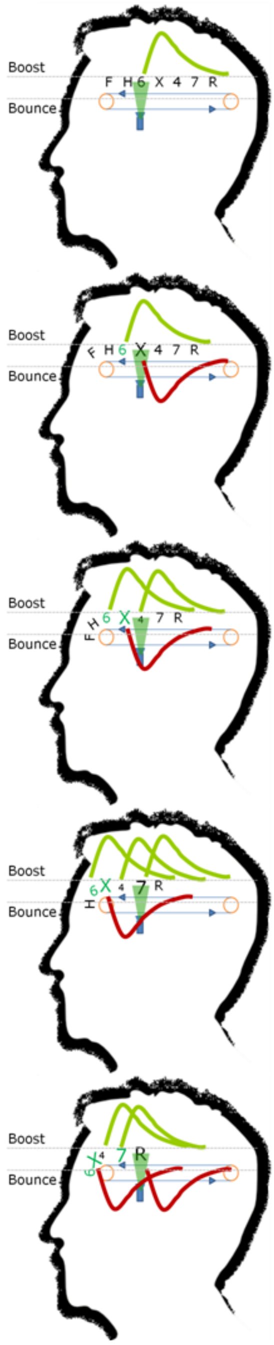


Figure XXV: B&B: rapid recovery

are merged into a single representation or receive a single memory trace, with a single time stamp (e.g. Bowman & Wyble, 2007; Akyürek, Riddell, Toffanin, & Hommel, 2007; Hommel & Akyürek, 2005; Akyürek, Toffanin, & Hommel, 2008). Therefore the actual temporal order between the targets is lost, leading to an increase in order errors (e.g. Bowman & Wyble, 2007; Chun & Potter, 1995).

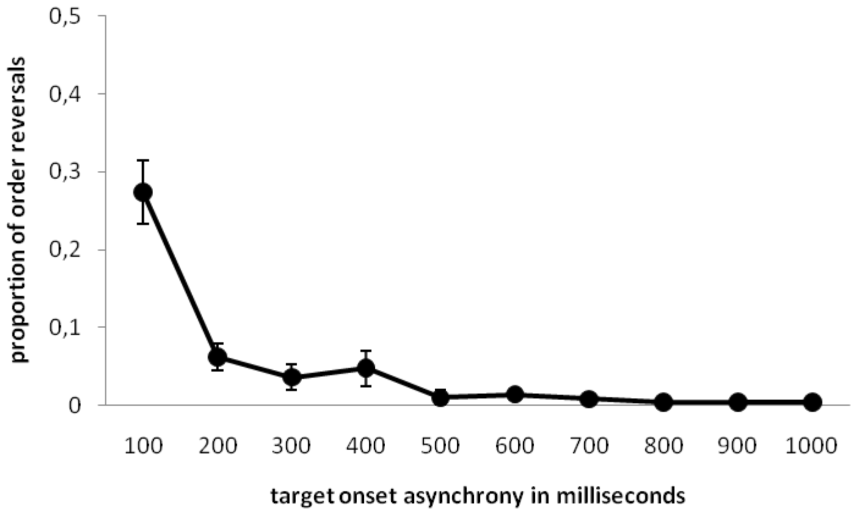


Figure 3: typical time course of order reversals found in RSVP. Error bars represent standard errors of the mean. The data are taken from the 100 ms / item condition of the "RSVP-Speed" experiment described later in this manuscript.

Temporal order errors are consistent with theories of attentional enhancement as well: one of the more intriguing effects of attentional enhancement is that it can alter the perceived order of the stimuli presented. That is, an attended stimulus can overtake a like, but unattended stimulus in the race to awareness, an effect commonly known as "prior entry" (Titchener, 1908). If lag-1 sparing in the attentional blink is due to a somewhat delayed attentional enhancement in a way that T2 benefits from attentional facilitation originally triggered by T1, this should not only lead to increased identification accuracy for T2, but, based on prior entry, to a substantial amount of target-order reversals.

In sum, the basic finding of order reversals with both targets being presented within about 100 ms is consistent both with an episodic integration account as well as with an attentional enhancement account. We have come up with a cueing design that can differentiate between these two theoretical approaches.

Before I get to the prior-entry account and the related cueing experiments in more detail, I will, in a classic psychophysical sense, test the phenomenon of order reversals under a wide variety of conditions, i.e., study “the effect on a subject's experience or behavior of systematically varying the properties of a stimulus along one or more physical dimensions” (Bruce, Green, & Georgeson, 1996, p.462). This means, I will discuss which factors do and do not influence the proportion of order reversals and offer a theoretical explanation for these results. Afterwards, I will explicate the prior entry account in more detail, speculate what might open and close an integration episode; and present empirical findings that strongly favor the attentional over the integration explanation.

To start, I will discuss one objection that is essential for most of the claims made in the rest of this manuscript: In the original AB paradigm and in the vast majority of all published AB studies since, the participants' only task is to identify the two targets. To reliably compute the proportion of order errors, it is necessary to modify this task and ask participants to report the two targets in the perceived order. One might object that this is a more demanding task or even that it is a dual task: first identify the targets and then make a judgment about their order of appearance. Therefore, it might be that the task utilized in the experiments reported here is not strictly equivalent to the standard attentional blink task and thus our results will not be transferable to the AB paradigm as such (see e.g. Visser, Bischof, & Di Lollo, 1999 for influences on the AB task). For two reasons I am confident about this objection being invalid and that the AB with explicit order task is equivalent to the AB without explicit order task. For one, in Chun and Potter (1995) participants were encouraged but not required to report the targets in the perceived order (p. 118f). Nevertheless the time course of order reversals reported by these authors looks strikingly similar to the time course when participants are asked to report the targets in the correct order (Compare Figure 8 in Chun & Potter, 1995 to Figure 1 in Hilkenmeier & Scharlau, 2010; Figure 3 in Akyürek & Hommel, 2005a; Figure 2 in Akyürek, Toffanin, & Hommel, 2008). This suggests that participants report the targets in the order they perceived them in any case, regardless of the fact whether they were explicitly asked to do so or not. Secondly if the explicit order task differs from the basic identification task, it must be more demanding, especially at short inter-target intervals. This would suggest that identification accuracies of the targets suffer in comparison to when the participants' only task is to identify the two targets. A visual comparison of the time course of T1 performance and the conditional T2 performance suggests that this is not the case (compare e.g. Figure 2 in Chun & Potter, 1995 to Figure 1 in Hilkenmeier & Scharlau, 2010; Figure 1 in Akyürek & Hommel, 2005; Figure 1 in Akyürek, Toffanin, & Hommel, 2008).

Nevertheless I explicitly designed one control-experiment to test the before raised objection. In two successive blocks participants were asked to identify the two targets. In one block the instruction emphasized that the targets had to be reported in the correct order. In the other block the instruction stated that they could give their report in any order they wanted. The order of the blocks was counterbalanced between subjects.

experiment: *explicit order*

stream: *SD 100ms; ISI 0*

lags: *1,2,3,6*

targets: *black digits*

distractors: *black letters*

conditions:
a) *report targets in correct order*
b) *report targets in any order*

main result: *asking participants to report targets in correct order does not change the AB*

Figure XXVI: summary of experiment "explicit order"

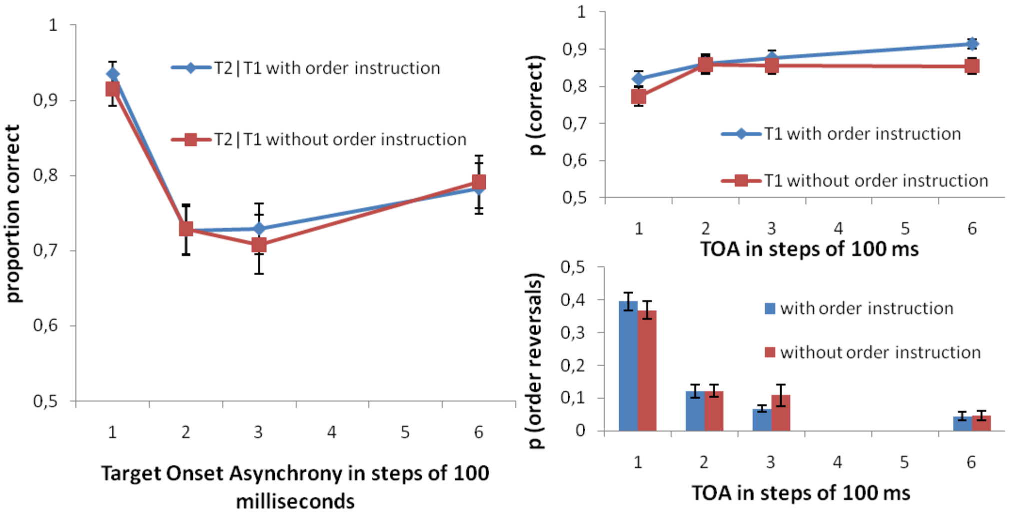


Figure 4: Results of the "explicit order" control experiment as a function of lag and condition. Left: conditional T2 accuracy. Right (top): T1 accuracy. Right (bottom): proportion of order reversals. Error bars represent standard errors of the mean.

As can be seen in Figure 4, there is no significant difference for the conditional T2 accuracy or the proportion of order reversals between the two conditions. Dealing with null-effects is not easy, especially when, as in this case, the null-result is the desired one. Whether a result reaches significance or not depends on a number of factors including the population effect size and the number of subjects tested ("Never use the unfortunate expression 'accept the null hypothesis'"; Wilkinson & the Task Force on Statistical Inference, 1999, p. 599). When the number of subjects is small, it is less likely to reject the null-hypothesis, even if there is a true difference in the underlying population. Luckily, power analyses can provide us with an estimate of the minimum sample-size required to detect an effect of an a priori determined size with certain likelihood. For this experiment the a priori determined likelihood to find an effect of at least medium size exceeded 90% (Faul, Erdfelder, Buchner, & Lang; 2009; for effect sizes see Cohen, 1988). Therefore, it is relatively safe to assume that the additional order judgment does not influence the attentional blink too much. A closer inspection of Figure 4 reveals that the identification accuracies are higher in the "dual task" condition: There is a significant main effect of condition for T1 accuracy, meaning that T1 identification is better when subjects were asked to report both targets in the correct order. It is hard to make perfect sense out of this result, but the import message here is that the AB task with additional order instruction is not more demanding than the AB task without this instruction. In the following, I will work under this premise.

After concluding that the additional order-judgment task has no major effect on the primary target-detection task and therewith the time-course of the attentional blink, I will look at that relationship the other way round: Before participants can judge the order of events, they first have to go through a demanding identification process. It is thus possible that they have little resources left for the actual order judgment. In other words, the high demands of the target-identification task might have inflated the number of order reversals. Participants might simply do not have the resources to deal with both tasks at the same time. This would explain the relatively high amount of order reversals after 100 ms. In other experimental paradigms as for instance the temporal order judgment (TOJ), a delay of 100 ms between the target stimuli is usually sufficient for a correct order judgment (e.g. Scharlau, 2002; Scharlau, Ansorge, & Horstmann, 2006; Stelmach & Herdman, 1991; Weiß & Scharlau, 2011). However, as pointed out in Hilkenmeier, Scharlau, Weiß, and Olivers (2011) one of the main differences between a typical TOJ task and a typical AB task are the higher task demands for the latter one. We conducted several experiments to investigate the influence of task demands on the proportion of order reversals, all with the same, unexpected result: When the task-set is smaller and the identification demands are therefore lessened, participants make more order reversals, not less.

When subjects were asked to either report two target digits in the correct order, out of all possible digits (2 out of 9), or to report whether a “5” or a “7” appeared first (1 out of 2), they made less order reversals in the former condition than in the latter.

experiment:
Task-Set

stream:
SD 50ms; ISI 20

lags: *1,2,3*

targets:
a) *black digits*
b) *black 5 and 7*

distractors:
black letters

conditions:
a) *standard AB*
b) *report whether the 5 or the 7 appeared first*

main result:
More order reversals when the task set was smaller and the task apparently easier

Figure XXVII: summary of experiment “task-set”

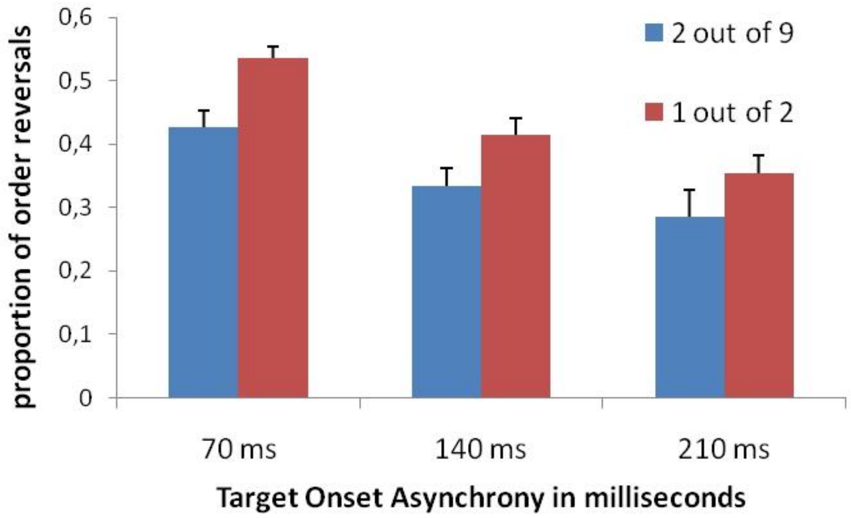


Figure 5: order reversals as a function of lag and task-set size. Error bars represent standard errors of the mean.

One could argue that this difference is due to guessing. In the standard AB task (i.e., 2 out of 9) guessing has a rather limited influence. Given a participant has only seen one target and has to guess the other one, chances of a correct guess are one out of eight. When the guess is wrong, this trial will not be taken into account for the computation of order reversals. Even when the guess is correct, there is still a “fifty-fifty chance” for the reported order being correct or not. When the participant has not seen any target, the chances of producing an order reversal are even lower. In the “1 out of 2” condition the influence of guesses are much higher, as can be seen in the following example:

Imagine that correct order and incorrect order are guessed equally often (which isn't even necessarily the case considering the small number of repetitions we use). Case 1: a subject is only certain about her order judgment in 20% off all cases. In the remaining trials she has either seen only one target or no target at all. Of these 20%, the order is perceived incorrectly in 35% (i.e. 7 percentage-points). In the remaining 80% of trials, she guesses the order (50% correct, 50 % incorrect). Since she can only choose between “5” and “7”, her guess will in any case be taken into account for the proportion of order reversals (either as a correct answer or as an order reversal). That leaves her with 47 percentage-points order reversals.

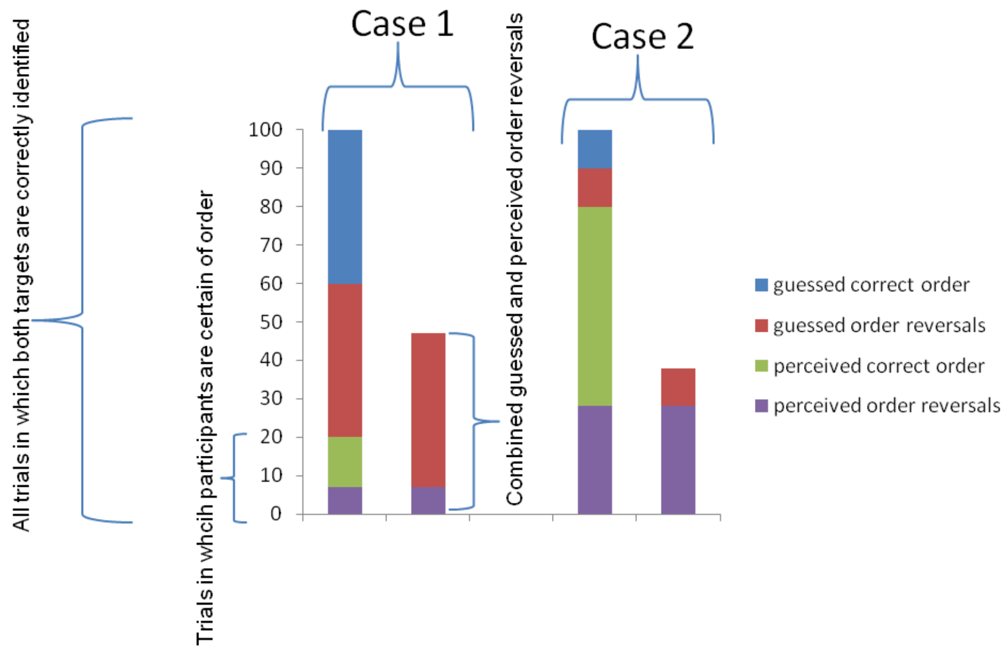


Figure 6: Distribution of perceived order and guesses for two hypothetical cases. Even though the proportion of perceived correct order and perceived incorrect order is identical in both cases, the measured proportion of order reversals is higher for the case with more guesses.

Case 2: a subject is certain about his order judgment in 80% of all cases. Of that 80%, the order is again incorrect in 35% (i.e. 28 percentage-points). In the remaining 20% of trials, he guesses the order (50% correct, 50% incorrect). All of his guesses will be taken into account as well. That leaves him with 38 percentage points order reversals. Despite the proportion of actual perceived order-reversals being equal (35%), the measured order reversals differ considerably (47% to 38%).

To conclude: the more a participant guesses in the “1 out of 2” condition, the higher the proportion of reported order reversals. Thus, the results presented here might be due to a methodological artifact. However, the results do not change even when we control for guessing by using a ternary TOJ task and giving participants the opportunity to refrain from their judgment (see Ulrich, 1987). Participants rarely use the third “uncertain” judgment category, but indicate that they perceive the targets in a distinct order. Interestingly, they still make more order reversals in the easier task with less target-alternatives (Hilkenmeier, Scharlau, Weiß, & Olivers, 2011, Experiment 1f). This leaves us with a very puzzling result, though the important message here is that order reversals do not increase when the task demands of the primary target-identification task increase.

A further control experiment showed that order reversals do not vary in respect of stimulus-duration / inter-stimulus-interval variations, given the overall stimulus onset asynchrony remains constant.[4]

Thus, presenting the items, especially the targets, without any ISI does not increase order reversals, even though one might assume that the temporal separation is less clear (and therefore integration is more likely to occur) when the targets are presented right next to each other compared to when they are separated by an inter-stimulus interval (Chua, personal communication).

Moreover, this result is well in line with Coltheart's finding regarding visible persistence (1980), showing that briefly presented stimuli are perceived up to 100 ms when they are not overwritten by subsequent masks (also see Sperling, 1960; Keysers & Perrett, 2002). According to Bloch's law, these "persistent" stimuli should have been perceived rather gray than pure black. Anyway, it seems as if this had not influenced identification accuracies either.

experiment:
SD_ISI Variaton

stream:
a) SD 17ms; ISI 51
b) SD 34ms; ISI 34
b) SD 51ms; ISI 17
d) SD 68ms; ISI 0

lags: *1*

targets:
black digits

distractors:
black letters

conditions:
4 different SD / ISI variations, mixed into a single blokc

main results:
SD / ISI variation has no influence on order reversals, as long as the TOA remains constant

Figure XXVIII: summary of experiment "SD_ISI variation"

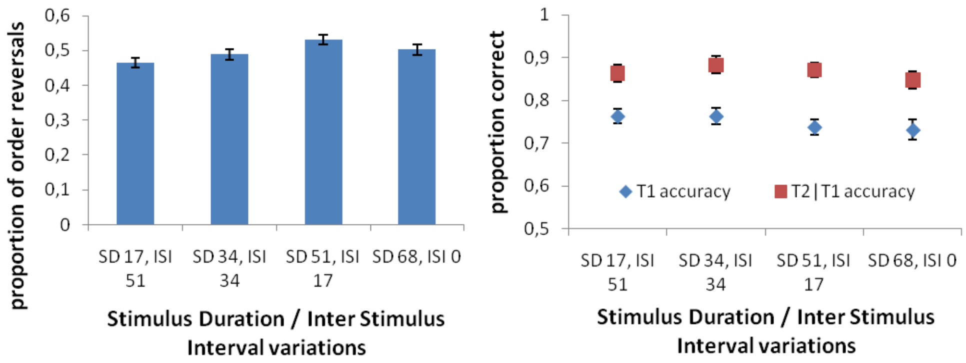


Figure 7: results of the "SD_ISI Variation" control experiment. Left: Proportion of order reversals. Right: T1 and conditional T2 accuracy. Error bars represent standard errors of the mean. As can be seen, variations in stimulus duration and inter stimulus interval do not have any major influence on target detection or perceived order.

All in all, the experiments reported so far indicate that order reversals are not the result of too high task demands and that the AB as such is not influenced by the additional order-judgment task.

Next, I will tackle the question whether order reversals between T1 and T2 are due to T2 being the next item in the stream or due to the temporal distance between the two targets. As Bowman & Wyble (2007; also see Potter, Staub & O'Connor, 2002; Nieuwenhuis, Gilzenrat, Holmes & Cohen, 2005) evidenced, the so-called "lag 1 sparing" is not constrained to the lag 1 position, but to about 100 ms Target Onset Asynchrony (TOA). They tested this by speeding up the RSVP stream to about 20 items / second. This means that when T2 was presented at lag 2, it was only presented 100 ms after T1. Unfortunately, these authors did not report order reversals, hence it is unclear whether this temporal misperception will spread to the T1+2 position as well, provided the temporal distance between the two targets is still around 100 ms. To test this, I chose a design close to Bowman and Wyble (2007) and manipulated the speed of the RSVP stream as well. In addition to the "50 ms" condition and the "100 ms" condition utilized by Bowman and Wyble, I also employed an intermediate "75 ms" condition as well as a "150 ms" condition. As can be seen in Figure 8, I was able to replicate Bowman and Wyble's finding about lag-1 sparing spreading to lag 2 as long as it came within about 100 ms of T1 onset. There are some discrepancies between the result found in our lab and the ones reported by Bowman and Wyble, but the important finding in the present context is that temporal order reversals between T1 and T2 can indeed spread to later lags, and are not bound to situations in which T1 and T2 are presented right after each other. As with lag-1 sparing, the important variable seems to be the temporal distance between T1 and T2, and not the number of intermediate distractors between them.

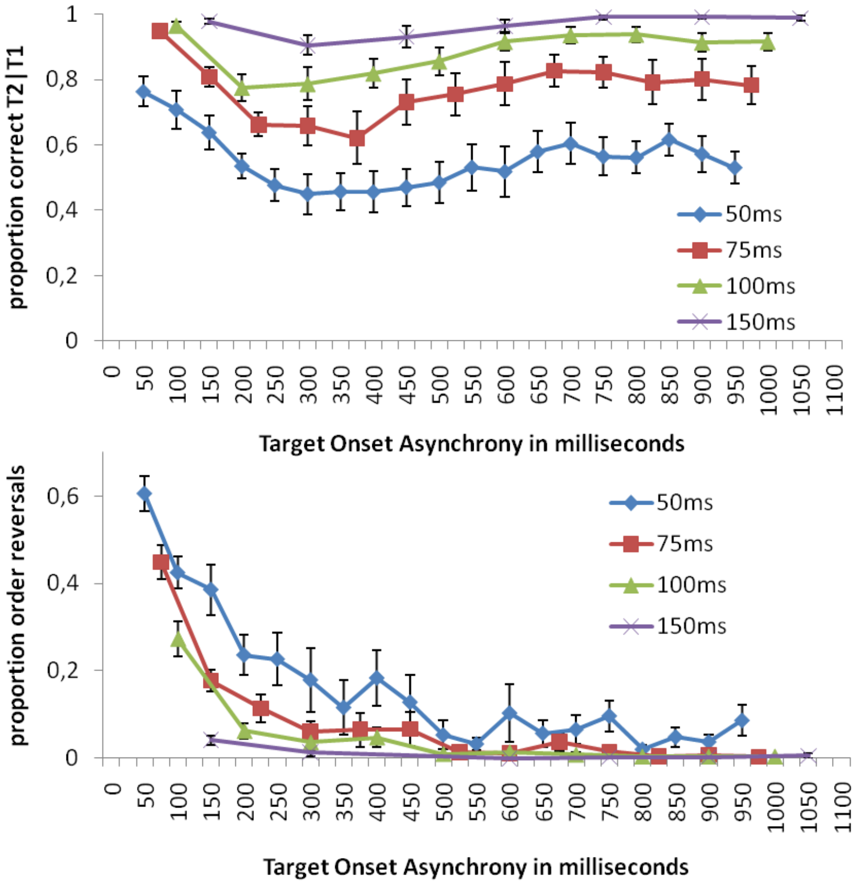


Figure 8: Results of the "RSVP-Speed" experiment as a function of RSVP speed and target onset asynchrony. Top: conditional T2 accuracy. Bottom: proportion of order reversals. Error bars represent standard errors of the mean.

experiment:
RSVP-Speed

stream:
a) SD 50ms; ISI 0
b) SD 50ms; ISI 25
b) SD 50ms; ISI 50
d) SD 50ms; ISI 100

lags:
complete range from 50 - 1000 ms

targets:
black letters

distractors:
black digits

conditions:
4 different RSVP speeds, done in seperate blocks

main results:
AB takes longer to recover with faster presentation

order reversals are mainly a function of time, but faster speed leads to more reversals, even when the targets are delineated by intermediate distractors

Figure XXIX: summary of experiment "RSVP-Speed"

What is surprising in this context is the finding that at the same TOA there are more order errors for faster presentation speeds. This means that there are more order reversals even though the targets are delineated by more intermediate distractors. For instance, at a TOA of 200 ms, T1 and T2 are delineated by one distractor in the standard 10 Hz stream condition, but delineated by three distractors in the faster 20 Hz condition. Nevertheless, there are significantly more order reversals in the latter compared to the former condition.

This brings us to our next aspect: the importance of backward masking. The presentation speeds employed in this experiment do not only differ in the number of distractors between the targets at a given TOA, they also systematically vary in the strength of backward masking. The different RSVP speeds were realized by varying the inter stimulus interval. This means that the stimulus duration was set to 50 ms in all conditions. In the “50 ms” condition the ISI was therefore 0 ms, whereas it was 50 ms in the “100 ms” condition. As a result, the distractor trailing the second target came much quicker in the “50 ms” condition than it came in the “100 ms” condition, impairing the visibility of T2. This impaired visibility indirectly causes the higher proportion of order reversals: Note that for the computation of order reversals we only take trials into account in which both targets are identified. So in the trials that we consider, backward masking did not hinder T2 on being identified. In the relatively hard “50 ms” condition this might indicate that the identified T2s are strongly activated (elsewise, they would not get identified in the first place). These strongly activated T2s then (because they are so strongly activated) often win the race to awareness against T1, i.e.

they are perceived as earlier. When backward masking is weaker, as for instance in the "100 ms" condition, also less activated T2s get identified. These T2s race against their respective T1s as well, but they more often lose this race to awareness, i.e. T1 is perceived as first and T2 is perceived as second, leading to a reduction in the relative proportion of order reversals.

The order-error results of the already described "T2+1 blank" experiment (see Figure 2) are consistent with this interpretation as well: When the distractor trailing T2 is omitted, backward masking is much weaker. This leads to better T2 performance (presumably because less activated T2s get identified as well, since they have more time to save themselves from becoming overwritten) and also to a reduction in the proportion of order reversals (presumably because these weakly activated T2s cannot make up for the headstart T1 has in the race to awareness).

There are a number of other findings from our lab that can also be interpreted in the light of T2 backward masking: For instance, the proportion of order reversals at lag 1 is significantly lower when T1 and T2 are both colored in red, compared to when all stimuli are black. This is possibly due to the fact that when T2 is red and the T2+1 distractor is black, backward masking is weaker compared to when both T2 and the T2+1 distractor are black. This difference between colored targets and black targets is gone when target-color and distractor-color are isoluminant and backward masking thus does not differ between these conditions (also see Shih & Reeves,

experiment:
Target_Colors

stream:
SD 100ms; ISI 0

lags: *1*

targets:
black digits or red digits

distractors:
black letters

conditions:
Either both targets were red, or both targets were black, mixed into a single block

main results:
Order reversals decrease when both targets are red

Figure XXX: summary of experiment "target_colors"

2007). Additionally, in these conditions forward masking for T2 remains nearly identical. In both cases the T1 stimulus has the same color as T2. This does not mean that forward masking does not play any role for order reversals; but, as also indicated by the already discussed T2+1 experiment, it shows that manipulating backward masking is sufficient to influence the proportion of order reversals.

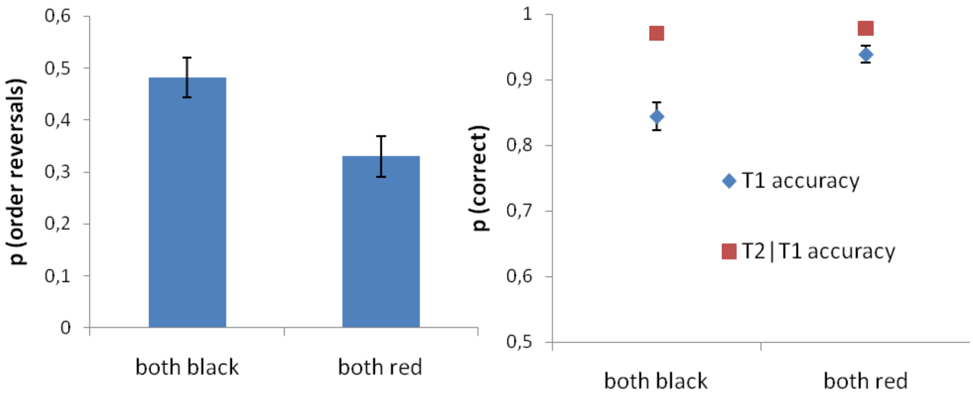


Figure 9: Results of the “target colors” experiment as a function of color condition. Left: proportion of order reversals. Right: T1 and conditional T2 accuracy. Error bars represent standard errors of the mean.

Another piece of evidence comes from an experiment in which we compared conditions with targets in one location to targets in different locations, both with and without surrounding distractors. In both cases order reversals significantly increased when the target were presented among distractors. In this experiment I cannot disentangle the effects of forward masking and backward masking, but the result can again be interpreted in light of the backward-masking hypothesis. Later on, I will come back to the issue of targets at the same location versus targets at different locations, but for the moment let us consider another possible implication of this data:

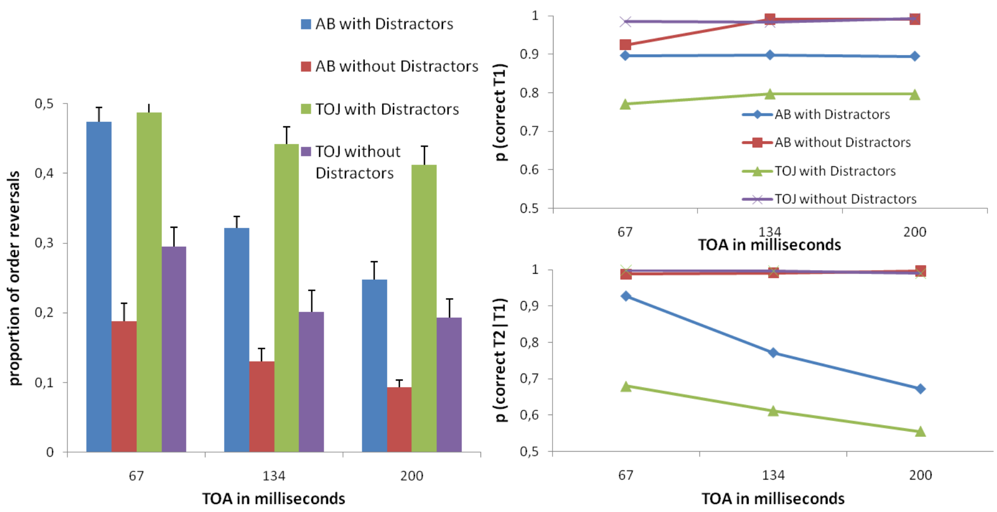


Figure 10: Results of the “single vs. dual stream” experiment as a function of condition and target onset asynchrony. Left: proportion of order reversals. Right (top): T1 accuracy. Right (bottom): conditional T2 accuracy. Error bars represent standard errors of the mean.

In Hilkenmeier, Scharlau, Weiß, and Olivers (2011) we argued that one of the main differences between the temporal-order judgment paradigm (TOJ) and the AB paradigm is the size of the task set. Therefore, it seemed plausible that the higher identification demands in the AB task lead to the significantly higher proportion of order reversals compared to similar temporal distances in the TOJ task. However, as was shown there as well as in the present manuscript, the size of the task set did not influence the proportion of order reversals in the hypothesized direction. On the contrary: order errors increase with smaller task set size. Thus, this factor cannot explain the difference between TOJ and AB. Another obvious difference is the presence of distractors in the AB task and their absence in the TOJ task: When the TOJ task is modified to include distractors as well, order errors increase to a similar level as in the AB task. On the

experiment:
single vs dual stream

stream:
SD 66ms; ISI 0

lags: *1,2,3*

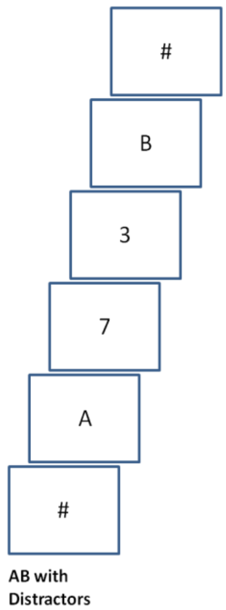
targets:
black digits

distractors:
black letters (if any)

conditions:
2x2 design,
factor 1: distractors present or absent
factor 2: items prensented at single location or 2 different locations

main results:
1) *order reversals decrease without distractors*
2) *more order errors when targets are at different locations*

Figure XXXI: summary of experiment “single vs. dual stream”



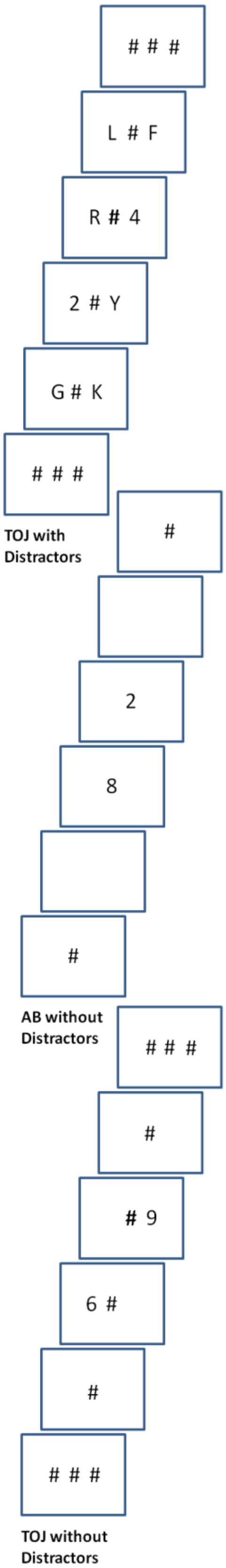


Figure XXXII: representation of the 4 different conditions in “single vs. dual stream”

other hand, when the AB task is modified in a way that distractors are omitted, order reversals decrease to a similar level as in the TOJ task. Further research is needed, but it seems that the presence or absence of distractors (and especially the T2+1 distractor) is one of the key differentiators between the TOJ and the AB task.

Let us return to the aspect of same target location vs. different target locations: As can be seen in Figure 10, the proportion of order reversals is higher when the two targets are at different locations. This is true both for conditions with surrounding distractors and for conditions without distractors. In fact, the absolute amount of order errors (i.e. not divided by the number of trials in which both targets are identified, but divided by the absolute number of trials per condition) does not differ between the single-stream with distractors and the dual stream with distractors (t<1). Even though subjects have additional information (location), they cannot use this information to accurately determine the temporal order of events. On the contrary, the actual order judgment is even worse. This finding seems odd in light of Spence and colleagues’ results, which evidenced that redundant spatial information can facilitate temporal discrimination (Spence, Baddeley, Zampini, James & Shore, 2003; Zampini, Guest, Shore, & Spence, 2005). However, at least the conditions with distractors of the present experiment can again be explained in the light of target strength. Consider the following example: at the beginning of the trial attention is (or at least: should be) at fixation between the two streams. When T1 is presented at the left stream, attention shifts to that location. When T2 is presented at the right stream shortly after (keeping in mind that in this experiment the maximum TOA was 200 ms), attention again has to switch its location. A weakly activated T2 is therefore often missed. When T2 is strongly activated, it will get identified as well. And because it is so strongly activated, it again has a better chance of overtaking T1 in the race to awareness. On the other hand, when T1 and T2 are in the same stream, also less activated T2s get identified (after all, attention does not have to change locations). But again, these lesser activated T2 more often lose the race to awareness against T1. The finding that the absolute number of order errors does not differ between the two conditions with distractors seems to corroborate this hypothesis: in addition to the strongly activated T2s, more weakly activated T2s get identified when T1 and T2 appear at the same location. These weakly activated T2s increase the conditional T2 performance, but they are too weak to overtake T1 in the race to awareness, i.e. the absolute number of order reversals remains constant, but the relative proportion of order reversals decreases. The same is true for the already described RSVP-Speed experiment: for example, the absolute number of order reversals at a TOA of 100 ms does not significantly differ between the "50 ms condition" and the "100 ms condition". The relative proportion of order reversals in the latter one is lower because the weaker masking of T2 leads to a higher T2 performance.

The idea of target strength is not a new one. It is incorporated in several theories of the attentional blink, for instance the interference model (Shapiro et al., 1994), the attention cascade model (Shih, 2008, 2009; also see Reeves & Sperling, 1986) or the eSTST model (Wyble, Bowman, & Nieuwenstein, 2009, also see Bowman, Wyble, Chennu, & Craston, 2008; Wyble & Bowman, 2005). The target strength I propose here has a different twist than the definitions of target strength before: In Wyble et al. (2009, p.9; Figure 11) replacing the T2+1 distractor with a blank increases the target strength of T2, leading not only to a reduced blink but also to an increment in the proportion of order reversals (see Figure 11 for simulations of the eSTST model).[5, 6]

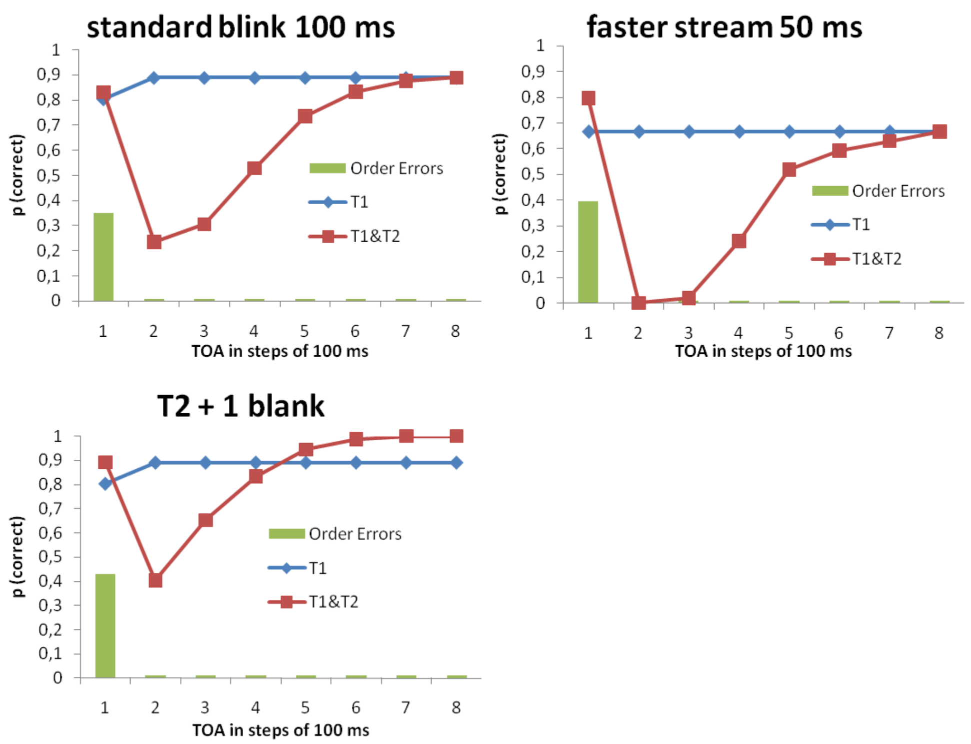


Figure 11: Order error, T1 performance, and T1&T2 performance simulations of the eSTST model as a function of target onset asynchrony. Left (top): standard attentional blink with 10 items / sec. Right (top): attentional blink with 20 items / sec. Left (bottom): 10 items / sec stream, but the T2+1 distractor is replaced by a blank.

This means that target strength is directly bound to visibility of a target. Here, I suggest decoupling this relationship. The longer a target is visible, the greater the chances of that target of becoming processed. This is well in line with a number of findings reported here (e.g. the T2+1 blanks experiment or the RSVP-Speed experiment) as well as in the literature (e.g. Giesbrecht & Di Lollo, 1998; also see Wyble et al., 2009, p. 9). This visibility, which can only be determined after stimulus offset (or, more precisely, after the stimulus is backward masked) does not necessarily translate to target strength. Target strength might be determined within a shorter time-span, even before stimulus offset. A similar approach was taken by Olivers and Meeter (2008). Their computational model only takes the sensory activity during the first 15 ms of presentation as a measure of perceptual strength of a stimulus (in their model this strength is used to determine the amplitude of the boost or the bounce, respectively). Only this target strength, which is determined shortly after onsets of the targets, is relevant for the perceived temporal order of the targets. Variations in target length or post target masking effects only influence the visibility of a target (and therefore have a strong influence on target performance), but not its strength. In terms of the attention cascade model (Shih, 2008; 2009, personal communication) this means that the temporal order is determined by the initial strength value and not, as proposed by Shih, by the weighted strength at the end of the consolidation process. All empirical data presented in this manuscript so far, especially the order reversal data, are explainable within this definition of strength. Later on, I will introduce a basic computational model that was drawn up to account for the distribution of order reversals in Hilkenmeier, Scharlau, Weiß, and Olivers (2011). This model can also account for a number of order-reversal findings presented here and is largely compatible with this definition of target strength. I will discuss the computational model in more detail when I present the findings of Hilkenmeier, Scharlau, Weiß, and Olivers (2011).

As just described, many AB theories that subscribe to the concept of target strength hypothesize that this strength is determined at the end of a consolidation process in which T1 and T2 are both processed within the same batch (Shih, 2008, p. 214, p. 219; Shih, 2009; Akyürek, Toffanin, and Hommel, 2008 p. 575; Shapiro et al., 1994; Bowman & Wyble, 2007). In the following, I will argue that it is not necessary to assume such a late determination of perceived order. In fact, it is not necessary to assume episodic integration within a common batch at all.

The theoretical framework for this claim is the already outlined Boost and Bounce theory of temporal attention (Olivers & Meeter, 2008). As other recent theories about the attentional blink this model assumes that a task-relevant event (e.g. a target among distractors) starts a transient attentional enhancement (in the standard attentional blink task that stimulus is T1). This attentional “boost” is delayed: it starts about 25 ms after stimulus detection and peaks another 75 ms later (i.e. at around 100 ms; also see Bowman & Wyble, 2007; Nakayama & Mackeben, 1989; Wyble, Bowman, & Potter, 2009; Reeves and Sperling, 1986 for earlier implementations of transient attentional enhancement). Due to the temporal characteristics of the RSVP paradigm, T1 is already overwritten by the next item when most of the additional attention arrives. In case of Lag 1, this post-T1-item is T2. Thus T2 receives even more attention than T1 and can therefore easily outperform T1. Put differently: the attentional facilitation, originally triggered to ensure T1 processing, "accidentally" enhances the target strength of T2 and leads to higher identification accuracies for the second target. In this sense, attention can manipulate target strength.

As discussed previously, target strength determines the perceived temporal order between the two proximal targets. This means that the delayed attentional enhancement which accidentally hits T2 can account for the substantial number of trials in which T2 wins the race to awareness. The mechanics and timing of the gating mechanism assumed in B&B theory (or, for that matter, in any other theory of transient attentional enhancement) are thus ample to explain the order errors and lag-1 sparing.

This explanation of order errors implies that a relative shift of attention in favor of one of the targets should have an impact on the amount of order errors as well, a hypothesis well in line with one of the "fundamental laws of attention": prior entry. As I briefly touched previously in this manuscript, the law of prior entry states that "the object of attention comes to consciousness more quickly than the objects that we are not attending to" (Titchener, 1908, p. 251). The prior-entry effect was one of the initial topics of experimental psychological research. When Titchener included it into his seven fundamental laws of attention, he could already look back at more than 50 years of experimental research on that topic (Scharlau, 2007; Sternberg & Knoll, 1973). There are several theories explaining the phenomenon of prior entry, for instance the asynchronous updating model (Neumann & Scharlau, 2007a, b) or the temporal profile model (Stelmach & Herdman, 1991; for an overview, see Scharlau, 2007). Unfortunately, these theories as well as the models of Sternberg and Knoll (1973) cannot be applied to the RSVP design used in our line of research. The model of Sternberg and Knoll assumes that the two to-be-judged stimuli are presented in two independent channels (1973, p. 635, p. 659ff). These "channels" need not to be thought of as different modalities (p. 637). In the visual domain for instance, it is sufficient to assume that the two stimuli appear at two different locations. In RSVP all items appear at the same location and the targets usually belong to the same category. It is therefore implausible to assume that T1 and T2 are presented in different channels. Thus, the independent channel model cannot be utilized here.

Likewise, the asynchronous updating model (Neumann & Scharlau, 2007a, b) requires that the two target-stimuli are presented at different locations. Prior entry occurs because the precue presented at one of the target-locations already directs attention towards its location (e.g. Scharlau, 2007, p. 679f). Again, in RSVP distractors and targets all appear at the same location, so the asynchronous updating model should assume that attention is already directed to that location before the first target even appears.

In Stelmach and Herdman's model (1991) attention is allocated to one of two locations by instruction. Thus, this model concentrates on the temporal profiles of the two target stimuli and how attention changes these two profiles (Stelmach & Herdman, 1991, Figure 10; Weiß & Scharlau, 2010, Figures 2 & 3). It is unclear how the model would deal with other forms of cueing. Would an additional cue get a temporal profile as well? Would it still change the temporal profile of the target in the same way? Would the temporal profile of the cue interact with the temporal profile of the target at the same location?

Since these theoretical questions remain open, the model in its current form cannot be employed to the RSVP paradigm.

Here, I focus on the perceptual retouch model (PRM, Bachmann, 1989) since PRM is most compatible with the RSVP design employed in attentional blink studies (Bachmann & Hommuk, 2005). Moreover, PRM comes with a plausible neurophysiological basis which centers on the different nuclei of the thalamus. Later on, I will speculate how this neurophysiological basis can be used to account for the attentional blink as well.

The PRM originated as a theory to explain nonmonotonic backward masking (Bachmann, 1984, p. 69), i.e. the phenomenon that when a second stimulus (the "mask") is presented briefly (~ 30 – 80 ms) after another stimulus (the “target”), visibility of the first stimulus is often severely reduced (for an overview, see Breitmeyer & Öğmen, 2006, 2007). According to Bachmann’s theory, backward masking as well as prior entry occur because of the asynchrony of two parallel afferent processes: On the one hand, there is specific processing (SP) which is fast, spatially precise and encodes the specific features of an object like color or orientation. The neurophysiological counterpart of the SP process for vision is the lateral geniculate nucleus / corpus geniculatum laterale (LGN / CGL), the first relay station for signals sent from the retina on their way to the visual cortex (e.g. Nolte, 2002).

The other afferent process in Bachmann’s theory is the modulatory nonspecific activation (NSP). NSP is necessary to modulate the SP information, otherwise the SP information could not become consciously available. NSP acts like a spotlight equipped with an energy-saving lamp: As a spotlight, it not only illuminates a certain stimulus, but the area around it as well, i.e. it is spatially imprecise. As an energy-saving lamp, it also is not instantly on, but takes some time until it reaches its full energy, i.e. it lags 50 – 80 ms behind the SP. Although assumed to operate faster, this delayed modulation has the same effect as the “boost” in Boost & Bounce theory or the “blaster” in eSTST: It enhances stimulus information, but not necessarily the ones (or at least not exclusively) that triggered the modulation. If a second stimulus is presented in close spatiotemporal proximity, it benefits from this modulation as well and its latency to consciousness is shortened. On the neurophysiological side the NSP is represented by the intralaminar nuclei, the reticular nuclei (TRN) and the pulvinar. These nuclei do not participate directly in the operations of encoding the contents of specific sensory information, but modulate the level of activity in the LGN (Bachmann, Luiga, Põder, & Kalev, 2003, p. 283). Surprisingly, more than 90 % of synaptic inputs on the LGN are modulatory in nature (Van Horn, Erisir, & Sherman, 2000), meaning that there are relatively few synapses that get the basic visual information from the retina to relay cells. These few specific synapses can be adjusted by many weak modulatory synapses that can be combined in numerous ways to allow for many forms of modulation. The drastic disparity between synapses carrying actual content and synapses modulating that content suggests that the major role of the thalamus is not only to relay information, but to gate the flow of information to cortex (Sherman, 2006; also see Crick, 1984). Moreover, this process is highly efficient: For each relay cell in the LGN, there are roughly 160 neurons in primary visual cortex (at least in the cat; Sherman, 2006). Thus, modifying the information flow at the level of the thalamus is much more efficient than doing so after the information has reached the cortex, making the thalamus an ideal starting-point for attentional processes. As already mentioned, the spatial resolution of the non-specific nuclei is quite poor. Not only the specific receptive field of the SP is modulated (boosted) but also neighboring ones. As the LGN, the primary visual cortex is organized in retinotopic maps, meaning the NSP really modulates the actual neighboring receptive fields, i.e. the retinal area around the stimulus that elicited the SP and the NSP in the first place. This allows PRM to account for a number of spatial phenomena like the illusory-line-motion (Figure VIII); the flash-lag-effect, in which a briefly flashed object, which is aligned with a moving object is typically perceived as lagging behind the moving one; or the Fröhlich effect, in which a laterally moving object will appear not at its first physical position, but shifted in the direction of motion (see e.g. Bachmann, 1999, 2010, for the flash-lag effect also see Priess & Scharlau, 2009).

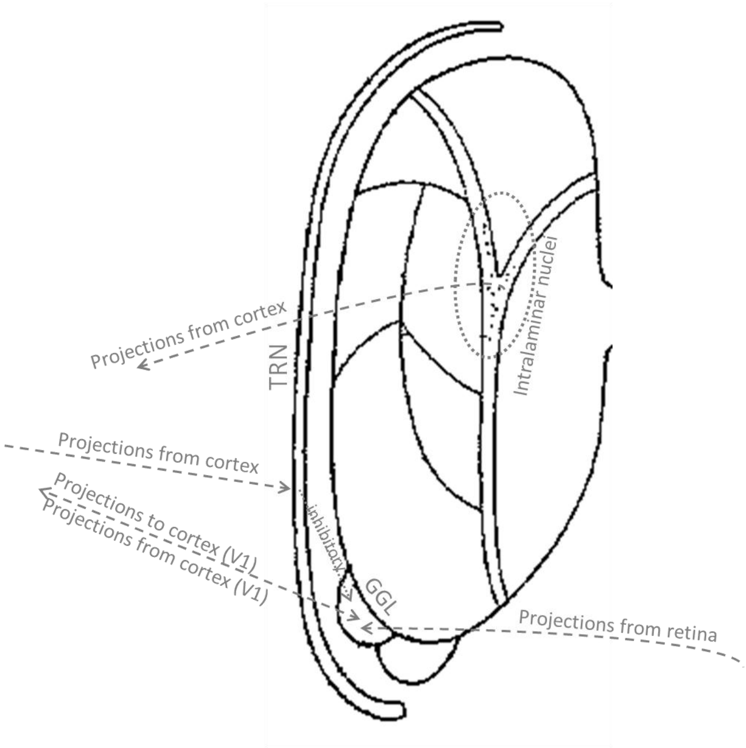


Figure 12: Schematic view of the thalamus. Relevant nuclei for visual information processing and their projections to and from the cortex.

All of the processes assumed in PRM can happen without attention. In PRM any stimulus, not just an attended one, elicits both the SP and the NSP process (Bachmann, personal communication); but there are several ways to incorporate attention into the model: For instance, attention could trigger extra NSP and thus facilitate the target stimulus. Returning to the metaphor of a spotlight equipped with an energy-saving lamp to describe the NSP-process, NSP + attention would mean that this energy-saving lamp now has 60 W instead of 40 W (NSP without attention). It is the same mechanism, only stronger. In the following, I will describe the effects of the additional attentional modulation on the perceived order of two target stimuli in close temporal proximity.

To manipulate attention (and therewith target strength) in the RSVP paradigm, we chose a design with colored stimuli close to the ones used by Nieuwenstein and colleagues (Nieuwenstein, 2006; Nieuwenstein et al., 2005) and Olivers and colleagues (Olivers, van der Stigchel, & Hulleman, 2007; also see Olivers & Meeter, 2008, p. 24 “rapid reversal of the blink”). The two target stimuli were colored letters, always presented right after each other in lag 1. Distractors were black letters and digits, preceding and trailing the two targets. In the crucial cueing condition, the distractor digit prior to T1 was colored as well, i.e., it carried one target-defining property (color), and one distractor-defining property (category).

Analogous to T1 starting the enhancement and T2 benefitting from it in the standard AB, we hypothesized that the cue would start the

experiments:
Olivers et al., 2010

stream:
SD 100 ms; ISI 0

lags: *1*

Cueing SOA:
100 ms

targets:
colored letters

distractors:
black digits & letters

cue:
colored digit preceeding T1

task:
identify the two colored letters in correct order

main results:
reversals decrease when T1 is precued, even in the absence of shared features between cue and T1

Figure XXXIII: summary of the experiments in Olivers et al., 2010

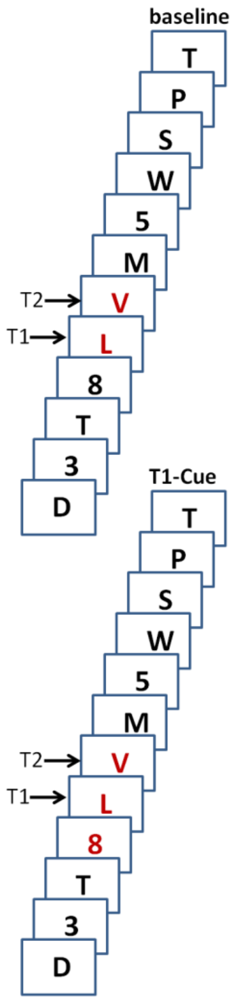


Figure XXXIV: Baseline and T1 cue condition used in Olivers et al., 2010

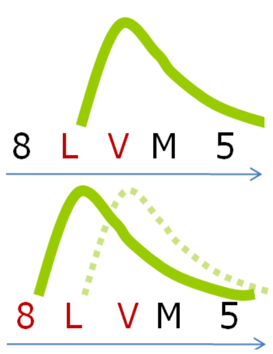


Figure XXXV: Hypothesized attentional enhancement for the baseline and T1 cue condition

enhancement and T1 should be the main profiteer from it. Thus, the relative attentional weights should shift in favor of the first target, resulting in less target-order reversals between T1 and T2. As predicted, we found significantly less order reversals in the cueing condition compared to a baseline condition in which the two targets were not preceded by a cue (Olivers, Hilkenmeier, & Scharlau, 2010, Experiment 1). The same was true for cue and T1 did not sharing the same color, showing that cueing can occur in the absence of shared features, as long as the cue carries a task-relevant property (Olivers, Hilkenmeier, & Scharlau, 2010, Experiment 3). Moreover, we found a substantial correlation between T2 accuracy and order reversals. Participants who reported T2 more often than T1 also showed a greater proportion of order reversals. In addition, the subjects that showed the strongest reduction in order reversals due to the cue also showed the strongest increase in T1 accuracy relative to T2 accuracy in the same condition. These results suggest that, in line with the law of prior entry, order reversals at lag 1 are modulated by the relative proportion of attention received by the two targets: Order reversals occur when T2's representation is strong enough to overcome T1 in the race to awareness.

However, prior entry is not the only possible explanation for these data patterns. The findings of Olivers et al. (2010) are largely consistent with an episodic integration account: The colored precue matches a task-relevant aspect of the target stimulus. Thus, it is likely that the cue initiated an episode, particularly because the occurrence of a color singleton always was a valid predictor for the first target (it either was T1 or it was at least signaling the very imminent onset of T1). If we assume that episodes have a limited duration, the cue and T1 are most likely processed in one episode, but in most cases, T2 will come too late to be included as well. In that case, T2 will have to start its own episode. Then, order errors are less likely, as T1 and T2 are not part of the same event and thus not very vulnerable to temporal confusion (Hommel, personal communication). In this line of argument, T2 accuracy should decrease when T1 is precued, a finding that is indeed present in the data and cannot easily be explained by a straightforward prior-entry account. The argumentation in favor of episodic integration relies on a number of implications, though. For instance, as already mentioned, it requires that the episode has a limited duration; otherwise, the cue, T1, and T2 could all be part of the same episode, which would result in no difference between the cue and the baseline condition (a similar mechanism is assumed in the eSTST model of Wyble, Bowman, & Nieuwenstein, 2009. In there, the attentional episode remains open as long as task-relevant information, in this case colored items, come in). Moreover, this argumentation assumes that in a considerable number of trials T2 at lag 1 can trigger a second episode, such that T2 can be given its own cognitive time stamp. It is unclear why in this case T2 should be able to start a second episode while T1 is being consolidated, but not in the

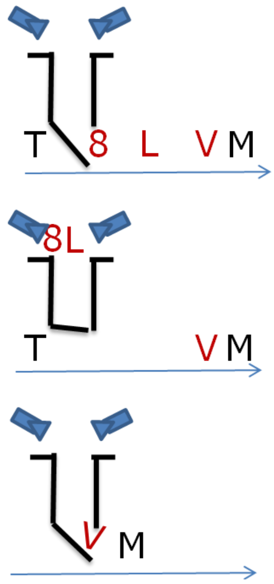


Figure XXXVI: precue and T1 are processed in one episode, T2 at lag 1 manages to start a second episode and gets processed separately

standard attentional blink task, in which processing of T1 is said to cause the blink in the first place.

Furthermore, note that in the precue as well as in the baseline condition the relevant T1 information occurs at exactly the same temporal position. Even if the episode starts early in the precue condition, it starts with an irrelevant distractor item. The T1 identity-information is available only at the same moment as in the baseline condition. Thus, T1 consolidation (which is assumed to be the cause for the blink in most episodic integration theories) should not end faster in the precue than in the baseline condition,[7] unless we assume that the precue somehow accelerates T1 processing. But such an acceleration would come close to the prior entry account championed here, namely the order of report being determined by the relative amount of attention each target gains (for more information regarding the episodic integration explanation see the General Discussion in Olivers, Hilkenmeier, & Scharlau, 2010).

To summarize: the predictions of the prior entry account and the predictions of the episodic integration account for T1 precueing data are too similar and the results are too indecisive to exclude one of the theories just yet. Nevertheless, at the very least this first set of experiments shows that it is not necessary to assume episodic integration to explain order reversals in RSVP. The results can at least be equally well explained by prior entry and transient attentional enhancement.

Next, I will present experimental conditions that will delineate the prior entry predictions from the episodic integration predictions more clearly.

To that end, we included conditions in which T1 and T2 are still presented right after each other at lag 1, but instead of T1, T2 is precued. In our interpretation of episodic integration this T2 cue should not influence the proportion of order reversals. After all, the T2 cue is presented after the episode already having started (elicited by T1). Since T1 and T2 are presented at the same temporal distance, episodic integration should occur to a similar degree, regardless whether an additional cue is presented in between or not. If, on the other hand, the temporal order of the two proximal targets is determined by the relative distribution of attention between them (as suggested by the law of prior entry), not only should precueing T1 lead to decreased order errors, but, by the same token, precueing T2 should lead to an increase in order reversals (see Hilkenmeier, Olivers, & Scharlau, 2011, p. 7 lines. 111 - 114).

To integrate a cue in the temporal space between T1 and T2 at lag 1, we decided to present each stimulus twice in succession for half the usual presentation time. This allowed us to color each of the stimulus “halves” individually. In specific, we colored only the first halves (the first 50 ms) of each target stimuli. As in Experiment 3 of Olivers et al. (2010), the two targets always had different colors. For instance the first half of T1 was red, whereas the second half was black again. Then the first half of the following T2 was green and the second half of T2 again black. To precue T2, we colored the second half of T1 in

experiment:
Hilkenmeier et al., in press

stream:
2x SD 50 ms; ISI 0

lags: *1*

Cueing SOA:
50 ms

targets:
first halves of T1 and T2 target- letters were colored

distractors:
black digits & letters

cue:
second half of T1 was colored to cue T2

task:
identify the two colored letters in correct order

main results:
reversals increase when T2 is precued, even in the absence of shared features between cue and T1

Figure XXXVII: summary of experiment 1 in Hilkenmeier et al., 2011

the same color as T2. We reasoned that, just like in a baseline condition without any additional cues, the attentional enhancement would be triggered by the first half of T1. But this enhancement should be reinforced by the colored second half of T2, resulting in more enhancement for the subsequent T2 and thus in a reduction of order reversals.

As predicted by prior entry, the proportion of order reversals indeed increased when T2 was precued (Hilkenmeier, Olivers, & Scharlau, 2011, Experiment 1). This result is again not limited to trials in which the cue and T2 share the same color, indicating that at least part of this effect must be attentional and not due to some kind of lower-level sensory priming (Hilkenmeier et al., 2011, Experiment 3).[8]

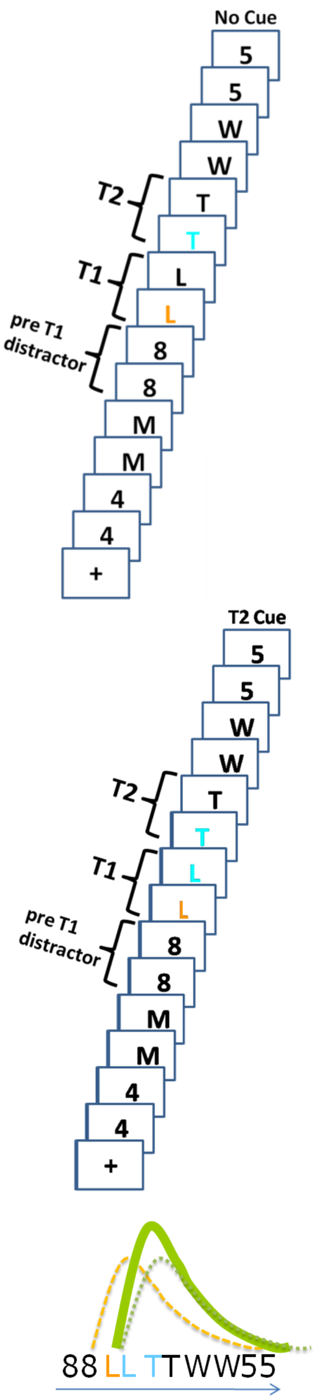


Figure XXXVIII: baseline and T2 cue condition used in Hilkenmeier et al., 2011, Experiment 1

The design employed in these experiments is vulnerable to one critical objection: As already described, in the baseline condition only the first half of T1 and the first half of T2 were colored. In between, the second half of T1 was presented in distractor-black. In the T2 cueing condition on the other hand, the second half of T1 was colored as well, resulting in an uninterrupted sequence of colored (i.e. task-relevant) stimuli. One might object that in the baseline condition the “distractor-like” second half of T1 might have caused an early closure of the integration episode. Put differently, the integration episode might be prolonged in the T2 cue condition as long as task-relevant information was presented. In any case, this argumentation leads to the claim that the T2 cue condition utilized in Experiments 1 and 3 of Hilkenmeier et al. (2011) does not actually increase the proportion of order reversals, but that the baseline condition employed artificially underestimates the proportion of order errors.

To counter this objection, Experiment 2 in Hilkenmeier et al. (2011) additionally included a modified baseline condition in which both halves of T1 and T2 were colored. As in the T2 cue condition, this modified baseline contained no distractor features between the two targets. According to our interpretation of episodic integration, this constant stream of "task-relevant information" should allow for a single, prolonged episode, just as in the T2 cue condition. Therefore, an episodic integration account should not predict any difference in order errors between this modified baseline and the T2 cue condition. These two conditions should significantly differ from the old baseline in which the second half of T1 was colored in distractor-black. Therefore the amount of order errors should be underestimated. Prior entry on the other hand predicts that the T2 cue should still enhance T2 processing relative to T1, and thus increase the number of order reversals regardless to which baseline it is compared to.

The empirical data strongly support the prior entry hypothesis and refute the objection of the cueing results being due to the specific baseline condition utilized.

As described at the beginning of this manuscript, the mechanisms underlying lag-1 sparing can be seen as key to understanding the attentional blink. Unfortunately, most empirical results regarding lag-1 sparing can to some degree be interpreted both in light of episodic

experiment:
Hilkenmeier et al., in press, Experiment 2

stream:
2x SD 50 ms; ISI 0

lags: *1*

Cueing SOA:
50 ms

conditions:
1) *only the first halves of T1 and T2 are colored*
2) *T1 and T2 are completely colored*
3) *second half of T1 is colored as T2*

main results:
T2 cue still increases reversals, suggesting that the cueing results cannot be explained by a prolonged episode

Figure XXXIX: summary of experiment 2 in Hilkenmeier et al., 2011

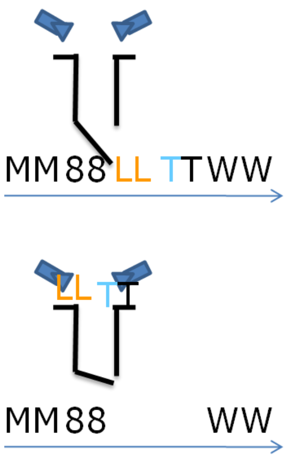


Figure XL: modified baseline

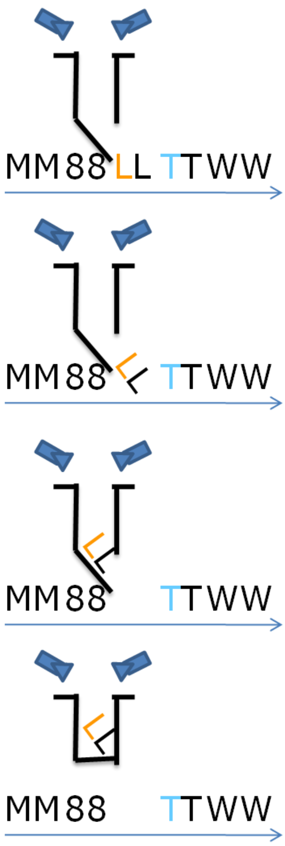


Figure XLI: old baseline

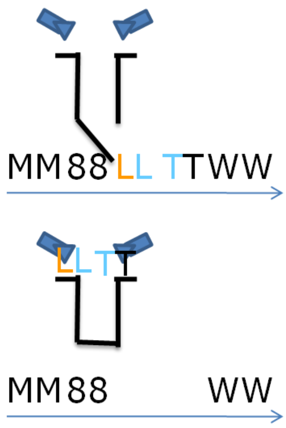


Figure XLII: T2 cue

integration and in light of attentional enhancement. In our own experiments we chose not to focus on the phenomenon of lag-1 sparing itself, but on the accompanying phenomenon of target order reversals.

In our view, the present results cannot consistently be explained by episodic integration. Even though the reduction in order reversals when employing a T1 precue are fairly compatible with an integration account, it is hard to imagine how an increment in order reversals can be explained by episodic integration. Problematically, theories of the attentional blink that promote the idea of resource depletion cannot easily drop the assumption of episodic integration, since it is not only used to explain order reversals, but lag 1 sparing itself. When T2 at lag 1 cannot be processed together with T1, how can it be spared when T1's hunger for resources should be maximal?

The empirical evidence presented in Olivers et al. (2010) and Hilkenmeier et al. (2011) first and foremost indicates that order reversals in the RSVP paradigm are indeed best explained by the law of prior entry: An attended stimulus enters consciousness prior to an unattended one, i.e., attention alters the temporal features of the perceived stimuli. In Titchener's words: "the stimulus, for which we are predisposed, requires less time than a like stimulus, to produce its full conscious effect" (Titchener, 1908, p.251).[9] This means, the well known and reliable effect of prior entry does not only affect experimental paradigms with distributed spatial locations in which a cue draws attention to a certain location. It can equally well be applied to temporal attention paradigms in which stimuli all appear at the same location but at distinct moments in time. Importantly, the effects of attention on the perceived order of events are not restricted to experiments conducted in our own labs. After reanalyzing some of the data of Akyürek, Abedian-Amiri, and Ostermeier (2011), the same effect is visible in that data as well (Akyürek, personal communication), even though that experiment was designed for a different purpose and used a different kind of cue. This again emphasizes the influence of cueing on the relative attentional weights each target gets and thus the proportion of order reversals.

To summarize, models that assume transient attentional enhancement offer straightforward explanation of key findings of the attentional blink: lag-1 sparing, the actual blink, and (thanks to prior entry) order reversals. All these aspects seem to be related to the relative strength of the respective stimuli. This strength can be manipulated in numerous ways, for instance, as done in the present experiments, by the deployment of attention.

For the rest of this manuscript, I will work under the premise that order reversals in the RSVP paradigm can indeed be manipulated by attention, just as in paradigms with distributed locations.

Next, I will tackle the time course of attentional facilitation. The reason for this is two-fold: first, theories of transient enhancement predict a distinct time-course: the facilitation should rise rapidly and reach its maximum somewhere around 100 ms. More precisely, the

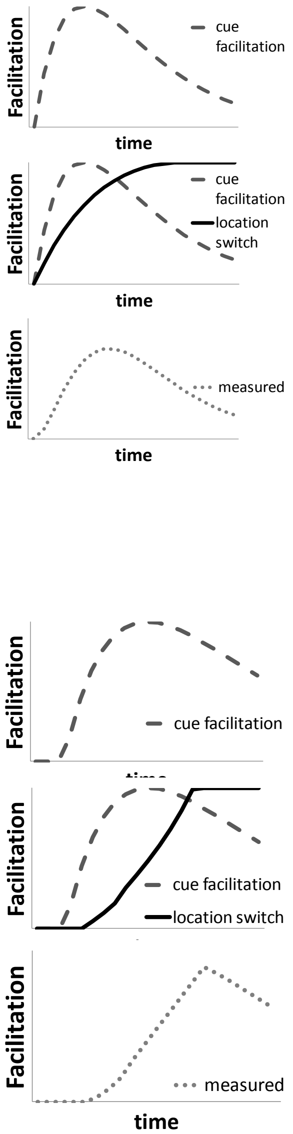


Figure XLIII: two hypothetical distributions of cue facilitation and spatial shift

PRM expects the maximum to coincide with the asynchrony between specific and nonspecific processes, which is hypothesized between 50 – 80 ms. eSTST and B&B stay in line with earlier results of Müller and Rabbitt (1989), Sperling and Weichselgartner (1995), and Nakayama and Mackeben (1989; also see (Kristjansson, Mackeben, & Nakayama, 2001; Kristjansson & Nakayama, 2003) and predict the peak between 95 ms (Olivers & Meeter, 2008, p. 14) and 110 ms (Wyble, personal communication) after cue detection. All theories hypothesize that facilitation should quickly decrease and be completely gone after a few hundred milliseconds.

The few studies that systematically investigated the temporal aspect of prior entry (e.g. Scharlau, Ansorge, & Horstmann, 2006; Hikosaka, Miyauchi, & Shimojo, 1993; also see Scharlau & Neumann, 2003 b) found a more sustained time course. In Scharlau et al., (2006) the size of the prior-entry effect rose with cueing SOAs up to about 130 ms, remained constant up to roughly 250 ms and then slowly decreased with some residual effect even after 1000 ms.

However, all of these studies utilized different locations. Attention was either exogenously or endogenously directed to one of these locations. Therefore, their measure of the time course of prior entry might be confounded by a spatial switching component: If the spatial shift to the new location takes longer than the temporal facilitation elicited by the cue, the peak of the measured facilitation is shifted to a later point in time (see the GD in Hilkenmeier, Weiß, Scharlau, & Olivers, 2011, for a extended discussion). Since in the present paradigm all stimuli appear at the same location, we can measure the time course in the absence of any spatial switching effects. Thus, the present design may provide us with a purer estimate of the dynamics of prior entry.

o study the time course of prior entry at one location, we again used the cueing paradigm already utilized in Olivers et al. (2010) and Hilkenmeier et al. (2011). While refining this paradigm for longer cueing SOAs, we encountered some difficulties. For one, we cannot employ this paradigm to measure the time course of any T2 cueing effect. Since all stimuli are presented at the same location, the T2 cue has to be presented after the onset of T1. Otherwise, we cannot ensure that it only facilitates T2 and not “accidentally” facilitates T1 as well. On the other hand, T1 and T2 have to be presented in close succession; or else the temporal distance becomes too large, resulting in hardly any reversals between the two targets. Thus, we are restricted to precueing T1. Still, which kind of cue should be used? Should the cue range over the complete cueing SOA, i.e. vary in length? Or should it have a fixed duration? If so, should the distractor items between cue and target be colored as well? Or should they be eliminated? Should the colors between cue and target change? Or stay the same? Should participants be able to refrain from their judgment in case they are uncertain? Do higher task-demands influence the cueing effect?

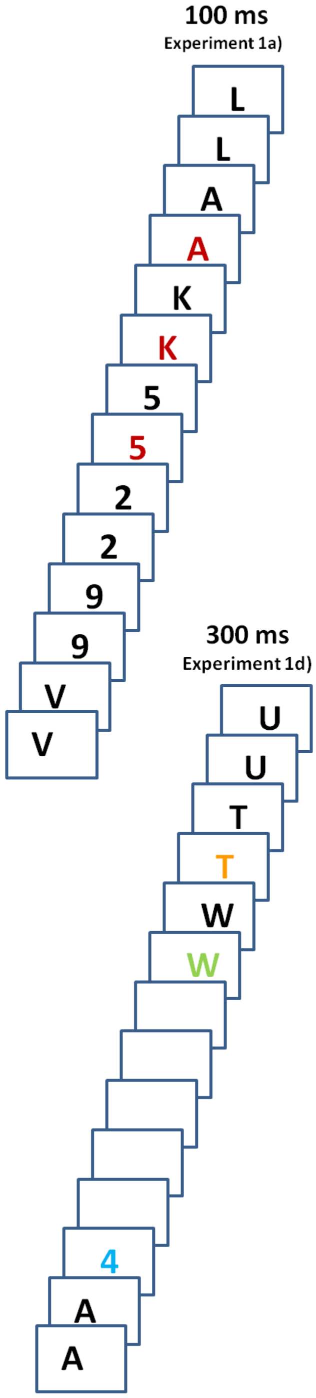


Figure XLIV: two of the cueing conditions used in Hilkenmeier, Scharlau et al., 2011

As it turns out, none of these factors (nor any tested combination) significantly influenced the time course of prior entry at one location.

experiment:
Cueing SOAs on a fine scale

stream:
10x SD 10 ms; ISI 0

lags: *1*

cueing SOA:
0 – 100 ms in steps of 10 ms

targets:
red letters

Distracotrs:
black letters and digits

Cue:
red digit

main results:
ideal cueing SOA somewhere between 30 and 50 ms.

Figure XLIV: summary of experiment "cueing SOAs on a finer scale"

As can be seen in Experiment 1 of Hilkenmeier, Scharlau, Weiß, and Olivers (2011), each type of cue led to qualitatively the same result: The peak of facilitation was always in the 50 ms cue condition. At a cueing SOA of 100 ms, there was virtually no facilitation left. A further experiment measuring on a finer time scale confirmed that the ideal cueing SOA seems to be quite early, somewhere between 30 and 50 ms.

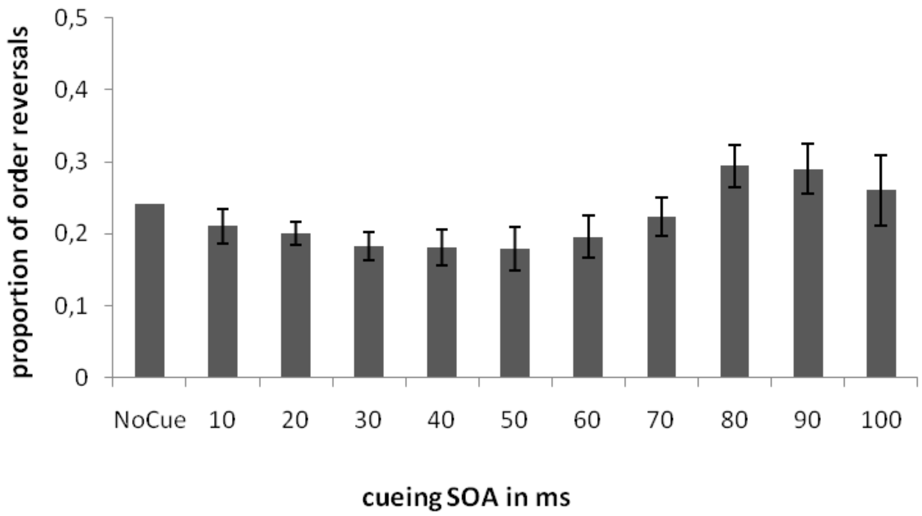


Figure 13: proportion of order reversals for the "cueing on a finer scale" experiment. Error bars represent standard errors of the mean.

Moreover, the facilitatory effect is rather short-lived, with no significant reduction of order reversals for cueing SOAs longer than 100 milliseconds. Obviously, this time course of prior entry is strikingly different from the one measured with distributed locations. This indeed suggests that studies utilizing a paradigm with different locations might overestimate the peak of prior entry facilitation.

To evaluate whether these findings are in line with theories of transient enhancement, as opined by the author, we incorporated a basic computational model that captures the gist of this class of theories. More precisely, it is a simplified derivative of the recent boost and bounce theory (Olivers & Meeter, 2008), but omits more complex effects like masking and sustained activity. Basically, it consists of two parts: bottom-up saliency of the cue and the targets, which are modeled as gamma distributions peaking 40 ms after target detection; and transient attentional responses, which are modeled as gamma distributions peaking 90 ms after stimulus detection.

The actual target evidence at a given point in time is operationalized as the cumulative product of the target's bottom-up saliency and its transient response, multiplied by the transient responses of all preceding cues and targets. Due to this multiplicative approach the target evidence of T2 at lag 1 eventually overtakes the target evidence of T1. Precueing T1 can postpone the point in time at which target evidence of T2 surpasses target evidence of T1. The underlying hypothesis here is that the longer it takes T2 to overcome T1, the greater the chances of T1 entering working memory first.

This model is also compatible with the distinction between target strength and target visibility. As stated earlier in this manuscript, target strength, which is relevant for the perceived temporal order, is determined earlier than target visibility, which is only determined after the offset of a target and is relevant for the identification performance. With this distinction we were able to explain a number of empirical findings; for instance that omitting the T2+1 distractor leads to higher T2 accuracy, but not to a higher amount of order reversals (T2+1 blanks experiment, Figure 2, also see Figure 11 for modulations of the eSTST model). Figure 14 shows how our model would handle this data. The left panel shows a baseline condition in which each item is presented for 100 ms and immediately replaced by the following. The right panel shows the experimental condition in which the T2+1 item is replaced by a blank. This was done by extending the bottom-up saliency of T2 (bottom panels).[10] As can be seen in the top-panels of Figure 14, the cumulative target evidence for T2 rises much higher when the distractor trailing T2 is replaced by a blank. I would argue that, in line with the empirical results, this higher target evidence leads to higher identification accuracies for T2.[11] Importantly, although the cumulative target evidence of T2 increases, the point in time at which T2 overtakes T1 does not change between these conditions. This means that the proportion of order reversals should not increase, which is also in line with the empirical data, but contrary to the model-simulations of eSTST.

The simulations of our model also show that order reversals at lag 1 increase with faster streams, exactly as the empirical evidence of the RSVP-Speed experiment suggests (Figure 8).[12]

Importantly, the model can explain strong facilitatory effects as soon as 50 ms after cue onset, despite the attentional enhancement reaching its peak only 90 ms after cue onset. The reason for this is that the bulk of bottom-up activity occurs during the first 50 ms. It is this bottom-up activity which interacts with the current attentional activity. Even if attention is not quite optimal yet, the product of the interaction is already some substantial activation. Thus, the early drop in order errors is in fact predicted by a straightforward transient attention model.

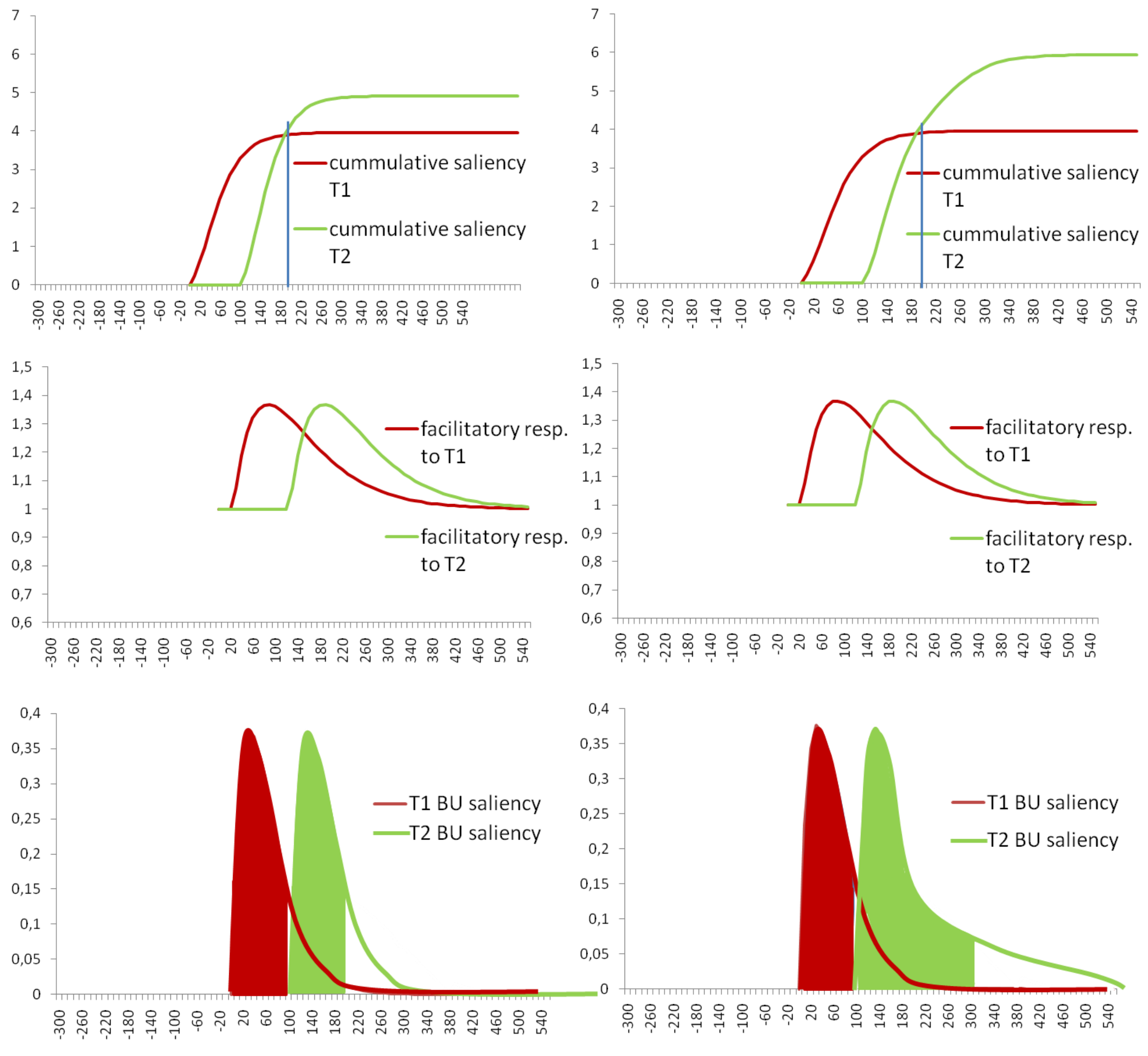


Figure 14: simulations of the computational model. Left: standard AB with 10 items / sec. Right: The T2+1 distractor was replaced by a blank. From bottom to top: Bottom-Up Activity, Top-Down Response, Cumulative Target Evidence for T1 and T2, respectively.

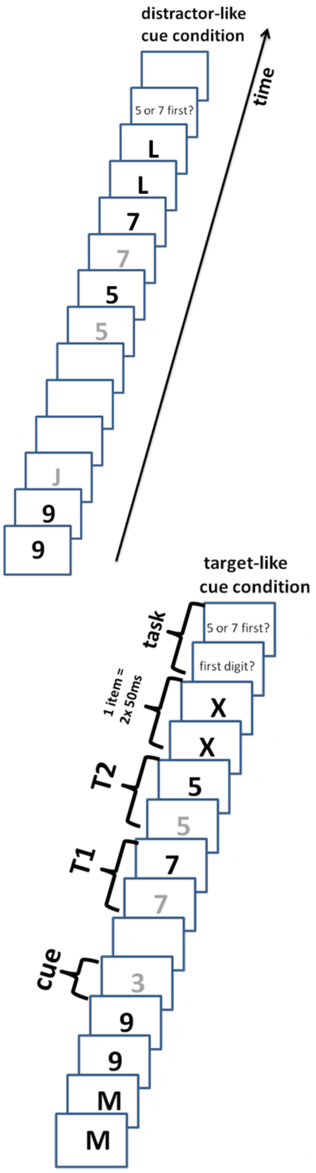


Figure XLV: representation of the kinds of cues used in Experiment 2 of Hilkenmeier, Scharlau et al., 2011

The model predicts a substantial reduction of order errors also at 100 ms cueing SOA, almost on a par with the effect for 50 ms. Clearly, this was not the case in Experiment 1 of Hilkenmeier, Scharlau, Weiß, and Olivers (2011), nor in the experiment investigating the cueing effect on a finer time-scale. The model predicts this time course because it treats the cue as if it was a normal target, and thus as if it triggered a full attentional response. Note that in the experiments reported so far, the cue was a distractor even though it carried the target color. It is therefore possible and perhaps even likely that the cue initially triggers an attentional response, but that upon detection of its distractor-like properties, either attention is rapidly disengaged (Theeuwes, 2010), or even suppressed (Olivers & Meeter, 2008).

To account for such inhibitory effects, we allowed that a single stimulus cannot only trigger facilitation, but also delayed inhibition. The inhibition was modeled as the enhancement, only with a negative algebraic sign and 50 ms offset. With this additional assumption we were able predict the pattern found in Experiment 1of Hilkenmeier, Scharlau, et al. (2011), i.e. a peak of facilitation at a cueing SOA of 50 ms.

In turn, this means that when we use a different and more task relevant cue that does not trigger such inhibition, the facilitation should extend to 100 ms. This is indeed what we found in subsequent experiments, employing a third target. In these experiments, T2 and T3 were always presented right after each other (at lag 1, if you will), whereas the temporal distance between T1 and the target-pair was varied in the same way as the cue-T1 distance was varied in the previous experiments. T1 could be one of the digits “2,3,4,6,8,9”, whereas T2 and T3 always consisted of the digit pair “5,7”, or “7,5”. Since the cue-identity (T1) had to be reported, it was now highly task relevant. At the same time, by reducing the identification task of T2 and T3 to a temporal order judgment (“which one came first, the 5 or the 7?”) we kept the overall task demands relatively low (see the “Task-Set” experiment and the related discussion). With this experimental setup, the facilitation sustained to 100 ms. There was no significant difference in order errors between the 50 and 100 ms cueing SOA. This suggests that the more task-relevant cue (the additional target) extended, but not amplified the enhancement, just as predicted by the computational model.

An alternative view is that the equal facilitation at 50 and 100 ms is the result of an overlay of two very different processes: a short-lived sensory priming effect and a somewhat slower starting attentional effect. In this view, the “distractor-like cue” just elicits the sensory effect since it is colored and therefore quite salient. There might be some developing attentional enhancement as well, but this enhancement is again stopped as soon as the system realizes that it is not dealing with a real target. The “target-like cues” on the other hand profit from both the sensory priming (again, all targets are colored whereas the distractors are black) and the developing

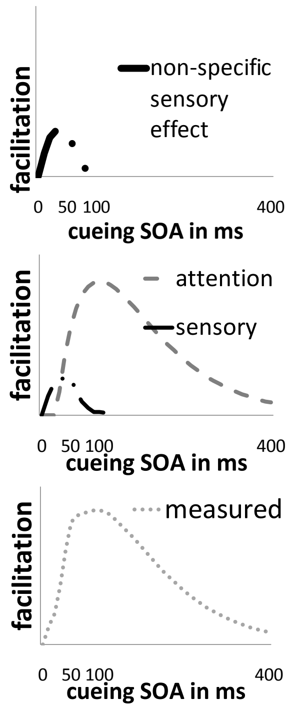


Figure XLVI: hypothetical interaction between sensory activity and attention

attentional facilitation. Whereas the sensory effect again peaks at 50 ms, the attentional effect peaks at 100. This results in the measured facilitation both at 50 and 100 ms cueing SOA.

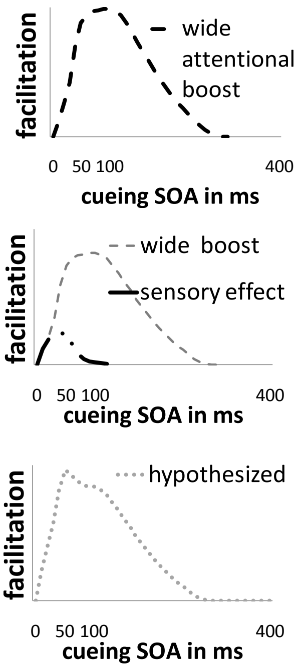


Figure XLVII: hypothetical interaction between sensory activity and a wide attentional boost

However, this explanation is unlikely. A further control experiment in which all stimuli were black (i.e. the targets are just defined by category, Experiment 3b in Hilkenmeier, Scharlau, et al, 2011) led to a qualitatively similar time course. Thus, a sensory priming effect induced by a color change cannot be responsible for our data pattern. In fact, we were unable to find any facilitatory effect of additional color information, as can be seen by the nonsignificant saliency x cueing SOA interaction in Experiment 3a of Hilkenmeier, Scharlau, et al. (2011); however, this might be due to a power problem.

To sum up, the experiments of Hilkenmeier, Scharlau et al (2011) show a time course that is consistent with rapid and transient facilitation. In general, such boosts are predicted by perceptual retouch theory as well as recent theories of temporal attention in RSVP processing (e.g. eSTST, Wyble et al., 2009; B&B, Olivers & Meeter, 2008). The peak of facilitation was found at about 50 ms when using a task-irrelevant cue. Facilitation sustained to 100 ms with a task-relevant cue. Both of these results are consistent with a basic computational model which assumes that evidence for a target accumulates as a result of a rapid transient bottom-up signal, which is gated by a slower, but still transient top-down signal. The only additional assumption we have to make is that stimuli that carry a distractor-defining feature cannot only trigger facilitation, but also inhibition.

To my understanding, such inhibitory effects are not part of Bachmann’s perceptual retouch model, even though there is an obvious neurophysiological counterpart: As already discussed, Bachmann’s theory centers around different nuclei in the thalamus region. One of these structures is the reticular nucleus (TRN). Each information from the thalamus to higher-order structures in the cortex must project through this thin sheet of inhibitory neurons that form a capsule around the thalamus (see Figure 12). If some higher-order cortex area realizes that instead of a target, it actually deals with a colored distractor, it could very well project to the TRN to inhibit further input (as can be seen in Figure 12, the TRN receives projections from the cortex and in turn has inhibitory projection into the LGN, the relay station for visual information coming from the retina). In this way, the TRN would act like the bounce described in B&B theory. Indeed, there is some empirical evidence that supports this view: For instance O’Connor, Fukui, Pinsk, and Kastner (2002) used fMRI to investigate attentional response modulation in the LGN. As expected, LGN activity was enhanced when subjects attended to the stimuli, but was also suppressed when they ignored them. Unsurprisingly, the V1 activity mirrored this pattern, but interestingly, the attentional effects in V1 were smaller than the ones in the LGN. O’Connor et al. (2002) argued that this indicates that LGN modulation must be influenced by factors other than cortico-thalamic feedback from V1 to the LGN, and suggested a strong role of the TRN in this process.

Another piece of evidence comes from McAlonan, Cavanaugh and Wurtz (2008). As already described, TRN has an inhibitory influence on the LGN. Thus, stronger LGN activity should be associated with lower TRN activity. That was exactly what these authors found when they recorded visually responsive neurons in the TRN and LGN of awake macaque monkeys performing a simple spatial attention task. Earlier results of the same authors (McAlonan et al., 2006) can also be interpreted in light of the modulatory TRN role. In this earlier study, monkeys had to attend to a tone while ignoring a visual stimulus or vice versa. This task increased the firing of the inhibitory TRN cells. I would argue that this increased TRN-firing was due to inhibiting (bouncing) the non-relevant dimension, but for now, this remains speculative. However, it would fit in well with the proposed view that TRN could represent the neurophysiological counterpart of the bounce in B&B theory: As long as no target-relevant stimuli are presented (either nothing or distractors in RSVP) there is medium TRN activity lightly inhibiting the visual information. When a target is presented, the TRN activity (and therewith the inhibition) is lowered. When a distractor is presented afterwards, TRN activity is amplified to inhibit that distractor. This hypothesis is further corroborated by the fact that the TRN modulation, just like the bounce, takes some time until it reaches its full effect (see McAloan et al., 2008).

The integration of inhibitory effects into perceptual retouch (a retouch & bounce theory, if you will) would have some distinct advantages over the current PR model and B&B theory. By including a bounce, the PR model would be able to explain a number of recent RSVP findings, not only the time course of cueing presented here, but also the standard attentional blink, the rapid recovery of the blink, and the whole-report vs. partial report findings of Nieuwenstein and Potter (2006). Moreover, this more inhibitory role of top-down attention would fit in well with Belopolsky et al.'s (2010, p. 340) conclusion that "the primary role of the top-down set is to control the disengagement of attention from the features that do not match it." By including the spatial fuzziness of perceptual retouch, B&B theory on the other hand would gain the ability to account for a number of spatial distributed phenomena as well, thus extending from the RSVP design to related paradigms as for instance the flash-lag-effect (Bachmann & Põder, 2001) or illusory line motion (Bachmann, 1999). Moreover, there is an upper limit of enhancement in PR. Once it is reached, further enhancing stimuli can just maintain the level of enhancement, but do not increase it any further. In my opinion, this is an advantage over B&B, where (at least in the computational model) every facilitatory stimulus just increases the level of enhancement, making it difficult to compute the influence of cueing on order reversals within this model.[13]

One might object that the processes assumed in perceptual retouch are all relatively early. After all, the thalamus is the first relay station

experiment:
monoptic/dichoptic blink

stream:
10 items/sec
targets either shown to one, or to different eyes

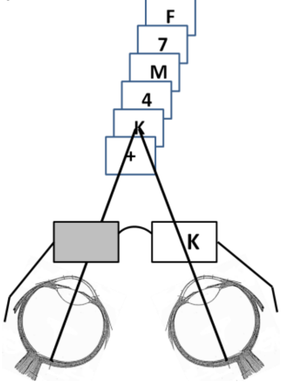
lags: *1,2,3,6*

targets:
Black letters

Distracotrs:
black digits

main results:
The blink is weaker with weaker masking
lag 1 sparing is stronger when both targets are presented to the same eye

Figure XLVIII: summary of experiment "monoptic/dichoptic blink"



of visual information coming from the retina. On the other hand, biasing or gating information is often seen as a higher order process that takes place in the prefrontal cortex (e.g. Miller, Erickson, & Desimone, 1996; Miller & Cohen, 2001; Awh & Vogel, 2008; Olivers & Meeter, 2008; but see Sherman, 2006; Crick, 1984). Maybe this apparent discrepancy is not so hard to overcome after all: as can be seen in Figure 4 of Hazy, Frank, and O'Reilly (2006), thalamus and prefrontal cortex are connected via the basal ganglia in a complex loop. Thus, any activity in the thalamus is mirrored in the prefrontal cortex and vice versa, suggesting that early influences on the level of the thalamus could fit in with current empirical evidence and theory.

One last experiment that can be seen as indication for such early influences on the attentional blink shall be discussed here: In a standard RSVP design, all stimuli are presented at the center of the screen to both eyes. By employing shutter glasses, we are able to present different visual information to each eye. We can present one item to only one eye whereas the other eye only sees grey background. This way, we can contrast conditions in which two consecutive stimuli were presented to the same eye, to conditions in which they are presented to different eyes. This means, we can selectively change masking on eye level, leaving other factors like stimulus duration, stimulus intensity, inter stimulus interval, and location all unchanged. This use of the shutter technique is a promising line of work since it enables us to disentangle different aspects of stimulus presentation that were previously confounded.

As discussed earlier, masking has a strong influence on the attentional blink. Thus, the original purpose of this experiment was to explore the influence of early masking effects that occur before binocular integration (e.g. Lumer, 1998). As hypothesized, during the blink period (200 – 300 ms), the second target deficit was stronger when masking for T2 was stronger, i.e. when the distractors immediately preceding and trailing T2 were presented to the same eye, compared to when they were presented to the other eye.

When the two targets were presented at lag 1 and both to the same eye (i.e., strong masking), conditional T2 performance was significantly higher than when the two targets were presented to different eyes (i.e., weak masking). Likewise, there were significantly more order errors when the two targets were presented to the same eye.

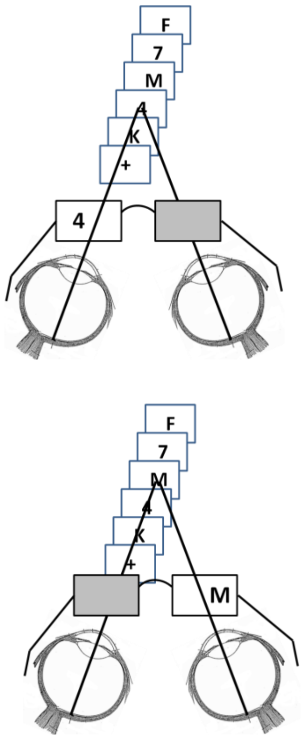


Figure XLIX: representation of monoptic viewing condition used in "monoptic/dichoptic blink"

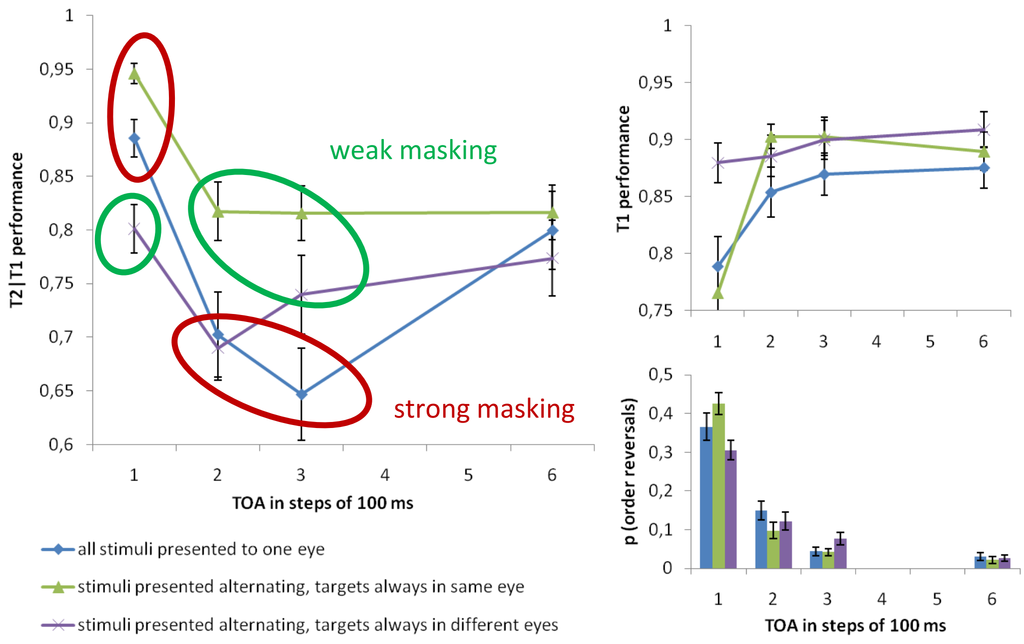


Figure 15: Results of the “monoptic/dichoptic blink” experiment as a function of viewing condition and lag. Left: conditional T2 accuracy. Right (top): T1 accuracy. Right (bottom): proportion of order reversals. Error bars represent standard errors of the mean.

As discussed previously, increased T2 accuracy combined with an increased proportion of order reversals is indicative for transient enhancement elicited by T1. Yet, the facilitation triggered by T1 only seems to hit T2 when the second target is presented to the same eye. When T2 is presented to the different eye, the facilitation does not reach it, indicating that the boost primarily uses monocular reentrant channels (Bachmann, personal communication).

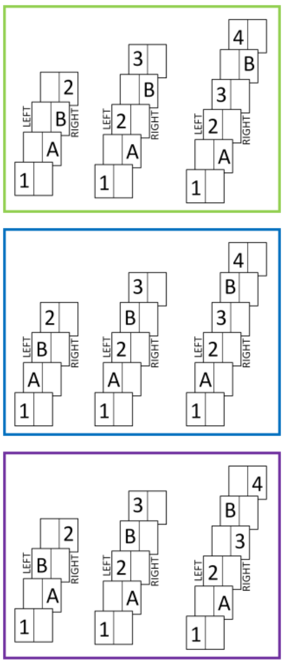


Figure XL: representation of the lags used inmonoptic “monoptic/dichoptic blink”

In this line of argumentation, these findings can be seen as some of the early thalamic effects described within Bachmann’s perceptual retouch model: T1 is presented to the fovea of the left eye, and even though the fovea has projections to both thalami, thalamo-cortical as well as cortico-thalamic retouch effects are laterally biased to the eye of the input (Bachmann, 2007, Bachmann, personal communication). As a consequence, the nonspecific modularly effect triggered by T1 in the left eye is stronger for T2 when it is presented to the left eye as well, compared to when T2 is presented to the right eye. Again, this interpretation is not undisputed and further research in this direction as well as further controls are necessary. Nevertheless, the results indicate that early influences (occurring even before binocular integration) do play a role in the attentional blink and in RSVP processing as a whole. This suggests that merging the neurophysiological assumptions of perceptual retouch with the computational model of boost and bounce theory might be a promising line of work.

To summarize: Selecting relevant over irrelevant information is one of the crucial functions of our brain. It allows us to efficiently deal with a limited number of objects while ignoring other information in our environment. The mechanisms that allow for this selection are collectively known as attention. How exactly attention works has been one of the major topics of psychological research since the days of Helmholtz and James. Much of the earlier work has concentrated on how attention is distributed in space. Interest in the temporal aspects of attention has only risen in the last 25 years or so. To investigate the temporal dynamics of attention, the RSVP design, and especially its two-target version, has become a fruitful experimental paradigm.

In our own work we have taken a different approach. Instead of concentrating on target-identification accuracy, we investigated the proportion of temporal order reversals between the two targets. These order reversals were originally seen as strong evidence for episodic integration; however, we found that they can at least equally well be explained by transient attention, via the “law of prior entry”, thereby demonstrating that this law does not only apply to paradigms utilizing different spatial locations, but also to the RSVP paradigm in which all items are presented at one location but at distinct moments in time. After testing the influences of different manipulations such as task-demands, stimulus duration, presentation speed, or location on the proportion of order reversals, we created precueing conditions that lead to different predictions for resource-depletion/ episodic-integration theories and transient-attention models.

The present results do not decide the argument between resource-depletion / episodic-integration on the one, and transient attention models on the other hand.[14] However, they represent evidence that can much more easily be explained by transient attention than by episodic integration, indicating a strong role of the former one in the dynamics of serial visual processing. Thus, the results presented here can be seen as pieces of empirical evidence that inspired new research and have therefore added to the scientific progress. And this is really all one can aim for. To put it in Popper’s words (1945, p. 12): “In science, we never have sufficient reason for the belief that we have attained the truth”.

Footnotes

1)

An alternative to the spotlight model is the so-called zoom-lens model (Erikson & St. James, 1986). In analogy to the zoom lens of a photo camera, the size of the attentional focus can be adjusted. Instead of moving the attentional focus from one location to another, the system could simply “zoom out” to cover both spatial areas. However, as with the photo camera, zooming out means losing details, which in this context means that processing of an individual object takes longer the larger the focus of attention is.

2)

We will come back to rapid and transient deployment of attention in more detail to explain lag-1 sparing and order reversals in the attentional blink.

3)

In attentional-blink studies, the temporal distance between the two targets is usually specified in “lag”. Lag refers to the serial position after T1. For instance, the stimulus presented at the T1+2 position is presented in “lag 2”. Since all stimuli in the RSVP stream are presented for the same duration (typically for 100 ms), lag can without further ado be converted in target-onset interval. The term “lag-1 sparing” suggests that it is really only the first item after T1 that gets spared. However, studies that doubled the rate of presentation from 100 to 50 ms per item evidenced that sparing extends out to lag-2. That is, the second target is spared not because it is directly adjacent to T1, but because it occurs within 100 ms (e.g. Bowman & Wyble, 2007). Therefore, when I use the term “lag-1 sparing” I mean the unimpaired T2 accuracy within the first 100 ms after T1 presentation.

4)

The post hoc power analysis estimated a power of about 80% to find a significant effect, assuming the effect size in our sample is equal to the effect size in the underlying population.

5)

The discrepancy between empirical and computational data is especially troubling for the eSTST theory, since modeling the T2+1 blink data (or, more precisely the T2 end-of-the-stream data) was in particular emphasized by the authors.

6)

A similar mechanism is assumed in Shih (2008, p. 214, p. 219). In there, the relative strength of two targets encoded in the same consolidation process determines the perceived temporal order. However, it is unclear whether T2 is processed in the same batch as T1 when the T2+1 distractor is omitted (Shih, personal communication). Therefore, it is possible that the attentional cascade model would predict less order reversals in the T2+1 blank experiment as well.

7)

On the contrary: A straightforward resource competition model would assume that the more difficult T1 is to detect, the stronger the inhibition for T2 should be. Since in the precue condition, the item immediately preceding T1 had the same color as T1. Thus, it was more similar to T1. Therefore, it should take longer until T1 is read out, resulting in a prolonged and deeper blink.

8)

Please note that such a lower-level mechanism would not even be problematic for the overall notion of target-strength. Brightness summation or priming could as well strengthen the representation of a target. The results at hand simply indicate that target strength can be manipulated in absence of shared features between the cue and the target, stressing the influence of attention (see Hilkenmeier et al., 2011, lines 522-529; also see Nieuwenstein, 2006).

9)

This does not necessarily mean that episodic integration plays no role in RSVP order errors; the existence of prior entry does not preclude the existence of integration.

10)

Omitting the T2+1 distractor could result in another bottom-up pattern as the one shown in Figure 14. Yet, the modeling turns out in a similar way for a number of different distributions as long as extending the visibility only influences the latter part of the pattern (the one where visibility actually changes) and not the overall distribution.

11)

At this moment, target accuracies cannot be simulated within the simple computational model. But since the long-term goal is to integrate the order-error model back into the computational model of boost and bounce, the T2+1 blank experiment data could proof useful in testing that model and differentiate it from the latest implementation of eSTST.

12)

Unfortunately, I was not able to simulate any other data than lag 1, since the model does not account for items other than cues and targets.

13)

The computational model presented here and in Hilkenmeier, Scharlau et al. (2011) reduces the value of this statement. However, as long as the current model is not implemented in boost and bounce, this is still a valid point.

14)

“Scientists have thick skins. They do not abandon a theory merely because facts contradict it. They normally either invent some rescue hypothesis to explain what they then call a mere anomaly or, if they cannot explain the anomaly, they ignore it, and direct their attention to other problems.”Lakatos, 1978, p.3

Experiments

T2+1 blank Experiment

The purpose of this experiment was to test Bowman and Wyble's (2007, p. 36) claim that inserting a blank after the second target would attenuate the blink. So far, empirical data for this specific hypothesis was not available, only data about T2 being the last item in the stream (Giesbrecht & Di Lollo, 1998), which basically abolished the blink.

Method

Participants: Twelve students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus, Design, and Procedure: Stimulus generation and response recording were done using the Tscope programming library. Backgrounds were gray. After a blank period of approximately 1000 ms, a 0.5 x 0.5˚ black fixation cross was presented for another 1000 ms in the center of the display and replaced by a rapid stream of 15 black digits and letters, presented in Courier New (approximately 0.8 x 0.8˚ in size). The letters I, O, Q, S, and Z were excluded, as was the number 1. Each item was presented for 100 ms and then immediately replaced by the following item, resulting in 10 different items / sec. T1 was placed at position 4-9 in the stream. T2 followed at lag 1, 2, 3, or 6. The two target-digits were always different. In half of the trials the distractor-letter immediately trailing T2 was replaced by a blank. Each lag was repeated 60 times: 30 times with a T2+1 distractor and 30 times without one. All trials were randomly intermixed into a single block lasting about 40 minutes. The participants' task was to report the two target-digits in the correct order at the end of the trial; unspeeded, and with feedback.

Results and Discussion

T1 accuracy, conditional T2 accuracy and proportion of order errors as a function of lag can be seen in Figure 2, separately for the baseline and the T2+1 blank condition. A repeated-measures ANOVA showed no significant main effect of condition on T1 accuracy ($F < 1$), nor a significant interaction of condition with lag ($F < 1$). As expected, the main effect of lag was significant ($F[3,33] = 9.8$, $p < 0.05$), showing the usual reduced T1 accuracy at lag 1. The same analysis on T2|T1 accuracy revealed significant main effects for condition ($F[1,33] = 29.2$, $p < 0.05$) and lag ($F[3,33] = 3.9$, $p < 0.05$), as well as a significant interaction ($F[3,33] = 8.0$, $p < 0.05$). As can be seen in Figure 2, there was no blink when the T2+1 item was replaced with a blank. This confirms Bowman and Wyble's prediction. However, the data do not fit that well into their computational model. According to the model (standard settings), the blink should be attenuated, but not abolished as when T2 is the last item in the stream. Contrast analyses confirm this picture: when using the values estimated by the computational model as contrast weights, the t-value becomes negative (-2.1), indicating that the trend in the observed pattern is opposite to the one suggested by (e)STST. In fact, the values estimated when T2 is the last item in the stream fit our empirical results better (competing contrast analysis $t_{diff}[11] = 1.6$, $p < 0.05$ one-tailed), but still far from perfect. Interestingly, omitting the T2+1 distractor also affected the proportion of order reversals. The repeated measures ANOVA showed significant main effects for condition ($F[1,33] = 22.5$, $p < 0.05$) and lag ($F[3,33] = 26.4$, $p < 0.05$), as well as a significant interaction ($F[3,33] = 8.6$, $p < 0.05$). One could assume that T2, which persists longer when the trailing distractor is omitted, is perceived as first more often since its visibility increases. But contrary to that, there are less order reversals when T2 is followed by a blank and is therefore more visible. This finding might also shine light on the order-error results of the “RSVP-Speed” Experiment. Order reversals increased when the RSVP stream was presented with higher speed. This was realized by shortening the inter-stimulus-interval, which in effect means that the T2+1 distractor is presented more quickly.

To summarize, replacing the distractor immediately after T2 with a blank basically abolishes the attentional blink. Thus, the effect is much stronger than expected by Wyble and colleagues. It more closely resembles the condition in which T2 is the last item in the stream and not backward masked at all (Giesbrecht & Di Lollo, 1998). Omitting the T2+1 distractor also decreased the proportion of order reversals. Maybe the underlying mechanism can also explain the order-error results in the “RSVP-Speed” experiment. Here and there, order errors decreased when the inter-stimulus-interval between T2 and the following distractor increased, i.e. T2 backward-masking was reduced.

Explicit Order Experiment

This experiment was designed to invalidate the objection that the attentional blink task with the explicit instruction to report the two targets in the correct order differs from the “classic” attentional blink task without this order instruction. Since we were aiming for a null-result, we conducted an a-priori power analysis to ensure we had sufficient power to find an effect of at least medium size.

Method

Participants: Twenty one students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus and Procedure was identical to the previous experiment; the *Design* differed in several ways: The experiment consisted of two separate blocks. The order of these blocks was counterbalanced between subjects. In both blocks participants had to report the two target-digits embedded in the stream of distractor-letters. T2 could appear at lag 1,2,3, or 6. In one block subjects were explicitly told to report the targets in the perceived order. In the other block the instruction emphasized that the order of report did not matter.

Results and Discussion

T1 accuracy, conditional T2 accuracy and proportion of order errors as a function of lag can be seen in Figure 4, separately for the blocks with and without order instruction. For T2|T1 accuracy and order reversals, the main effect of block did not get significant (both $F < 1$).

The same was true for both interactions between block and lag ($F < 1$, and $F[3,87] = 1.2$, $p = 0.33$). The main effects of lag were of course significant ($F[3,87] = 23.3$, $p < 0.05$, and $F[3,87] = 165.4$, $p < 0.05$, respectively). Surprisingly, for T1 accuracy the main effect of the factor block did get significant ($F[3,87] = 11.2$, $p < 0.05$). So did the main effect of lag ($F[3,87] = 15.7$, $p < 0.05$). However, T1 accuracy actually improved when participants had to report the two targets in correct order. If anything, we had expected that the addition of the judgment task would be more demanding and therefore accuracies should be impaired compared to the condition without order instruction. To summarize, the time course of the attentional blink (i.e. the conditional T2 accuracy) and the time course of order reversals is not influenced by the addition of the explicit instruction to report the two targets in correct order. Subjects seem to do that anyway.

Task-Set Experiment

The purpose of this experiment was to test whether the demands of the target-identification task had an effect on the subsequent order judgment task. We speculated that a more difficult identification task could consume more resources. Therefore there would be fewer resources left for the order judgment, leading to more order reversals due to a higher proportion of order guesses. To realize different demands for the identification task we manipulated the target-set size. In the baseline condition all digits from 1 – 9 served as targets; in the experimental condition the task set was reduced to the digits “5” and “7”. This means “5” and “7” were presented in each trial and the subject’s only task was to determine which of these two digits came first.

Method

Participants: Twenty one students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus, Design, and Procedure was identical to the previous experiment except for the following changes: Each item was presented for 50 ms. After an ISI of 20 ms the following item was shown, resulting in about 14 different items / sec. T1 was placed at position 5-10 in the stream. T2 followed at lag 1, 2, or 3. The experiment consisted of two separate blocks. The order of blocks was counterbalanced between subjects. In the baseline block, the target set consisted of the digits 1-9. The participants' task was to report the two target-digits in correct order (2 out of 9). In the experimental block, the targets were always the "5" and the "7" in random order. The participant's task was to report which digit came first (1 out of 2). Each lag in each block was repeated 40 times.

Results and Discussion

The proportion of order reversals can be seen in Figure 5. A repeated measures ANOVA revealed significant main effects of condition ("2 out of 9" vs. "1 out of 2") and lag ($F[1,40] = 26.4$, $p < 0.05$ and $F[2,40] = 14.3$, $p < 0.05$, respectively). The interaction between these factors was nonsignificant ($F < 1$). Unexpectedly, order reversals increased when the task set was smaller and the task therefore easier. This could be due to guessing since participants in the "1 out of 2" condition could have simply guessed the order on every trial without even paying attention to the stream. However, additional experiments indicate that this effect holds true even when participants have the opportunity to refrain from their judgment (Hilkenmeier, Weiss, Olivers, Scharlau, 2011).

SD-ISI Variation Experiment

This experiment was originally motivated by Chua (personal communication) who argued that the relatively high proportion of order reversals found in our lab might be due to the fact that we usually present the stimuli without inter stimulus interval. He predicted that a reduced stimulus duration combined with longer ISI should lead to a clearer separation of the two targets and thus less order reversals.

Method

Participants: Twenty three students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus, Design, and Procedure was identical to the previous experiment except for the following changes: The combination of stimulus duration and inter stimulus interval was held constant to about 68 ms / item. Within these 70 ms, we changed the SD/ISI in four steps: SD 17 ms, ISI 51 ms; SD 34 ms, ISI 34 ms; SD 51 ms, ISI 17 ms; SD 68 ms, ISI 0 ms. These four possible conditions were intermixed into a single session. T2 always followed T1 at lag 1 and was repeated 30 times per condition.

Results and Discussion

The proportion of order reversals can be seen in Figure 7 (left). A repeated measures ANOVA revealed no significant main effect of

SD / ISI variation ($F<1$). The same was true for T1 and conditional T2 accuracy (right side of Figure 5; $F[3,66] = 1.3$, $p = 0.28$ and $F[3,66] = 1.5$, $p = 0.22$, respectively). This indicates that a longer ISI and thus an apparent easier separation between the targets does not influence target performance or perceived order at all.

RSVP-Speed Experiment

The rationale of this experiment was to replicate and extend the finding of Bowman and Wyble (2007) that lag-1 sparing is not bound to the T1+1 position, but to the first 100 ms after T1 presentation, regardless of the number of items presented within this time-span. Here, we wanted to test whether this is true for temporal order reversals between T1 and T2 as well.

Method

Participants: Twenty one students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus, Design, and Procedure: Stimulus generation and response recording were again done using the Tscope programming library; ancillary conditions like stimulus size and color were as in the original experiment of Bowman and Wyble, 2007. The experiment consisted of four separate blocks which varied the presentation speed of the RSVP stream by manipulating the inter stimulus interval. In the fastest condition the stimulus duration was 50 ms and the ISI 0 ms, resulting in 20 different items / second. In the next condition SD was again 50 ms and ISI was 25 ms, resulting in about 13.3 items / second. In the third condition, SD was 50 ms and ISI was 50 ms as well. Here, 10 items / second were presented, replicating a standard attentional blink. In the last condition, SD was again held constant to

50 ms, but ISI was increased to 100 ms, resulting in about 6.7 items / second. In each condition the TOAs up to 1000 ms were covered. This means that in the “50 ms” condition, T2 could appear at a TOA of 50 ms, 100 ms, 150 ms, 200 ms and so on, leading to 20 lags in that condition. In the “75 ms” condition, T2 could appear with a TOA of 75 ms, 150 ms, 225 ms and so on up to a TOA of 975 ms. The equivalent was true for the “100 ms” and the “150 ms condition”. Each lag in each condition was repeated 20 times, leading to 1000 experimental trials, divided in two sessions lasting about an hour each.

Results and Discussion

The proportion of conditional T2 accuracy can be seen in Figure 8. As is clear from a visual inspection, we could replicate Bowman and Wyble’s first main finding that lag 1 sparing can spread to later lags when the presentation speed increases. However, what is also clear from a visual inspection is that we could not replicate their second main finding, i.e., that the time course of the AB is independent from presentation speed (Figure 19 in Bowman & Wyble, 2007). The bottom of the curve seems to be wider and the slope less pronounced, i.e. the second target does not recover as much. For better comparison I conducted a repeated measures ANOVA with the same data-points as Bowman and Wyble did, i.e. I focused on the “50 ms” and “100 ms” condition and only compared the TOAs 100 ms, 200 ms, 300 ms, 400 ms, 500 ms, 600 ms, 700 ms, and 800 ms.

As expected, there was a significant main effect of lag ($F[7,112] = 10.5$, $p < 0.05$) and a significant main effect of presentation speed ($F[1,112] = 89.9$, $p < 0.05$). The latter one simply means that, unsurprisingly, the overall accuracy in the faster condition was lower. However, unlike in Bowman and Wyble, the interaction between speed and lag showed a significant effect as well ($F[7,112] = 2.3$, $p < 0.05$). The shape of the AB curve differed in the two presentation speeds. It is yet unclear what causes the discrepancy between the results in our own lab and the ones found by Bowman and Wyble (2007).

The answer to the main question, however, can be seen in the lower part of Figure 8. Order reversals seem to spread to later lags as well. As with lag-1 sparing, the important variable seems to be the temporal distance between T1 and T2, not the number of intermediate distractors between them. More interestingly and more surprisingly is the finding that at the same TOA there are more order errors for faster presentation speeds. This means that there are more order reversals, even though the targets are delineated by more intermediate distractors. Holm-Bonferroni corrected t-tests show that this is true for the whole spectrum in which order errors occur, i.e. up to a TOA of 400 ms (all $t[16] > 2.2$, all $p < 0.05$). As speculated previously, this might have to do with the effect that T2 backward masking gets stronger with faster presentation times. However, please note that we only take trials into account in which both targets were identified. In the trials that consider, backward masking did not hinder T2 on being identified. It just seems to selectively hinder a correct order judgment.

Target Colors Experiment

In this experiment, I wanted to test the effect of target-color on the proportion of order reversals.

Method

Participants: Sixteen students from Paderborn University, Germany with (corrected-to-) normal vision participated for course credits or €6 an hour.

Stimulus, Design, and Procedure was identical to the T2+1 blank experiment described earlier except for the following changes: In half of the trials both target items were colored red, whereas they stayed black in the remaining half. T1 and T2 always followed each other in lag 1. Each condition was repeated 50 times, mixed into a single session lasting less than twenty minutes.

Results and Discussion

T1 accuracy, conditional T2 accuracy and proportion of order errors can be seen in Figure 9, separately for trials in which both targets were black and for trials in which both targets were red. Unsurprisingly, T1 accuracy improved when T1 and T2 differed in color from the surrounding distractors ($t[15] = 4.9$, $p < 0.05$). T2|T1 performance did not improve significantly. This might be due to a ceiling effect ($t < 1$). The proportion of order errors was also strongly influenced by the color manipulation: when both targets were colored, there were significantly less order reversals ($t[15] = 3.8$, $p <$

0.05). As discussed in the main text, this might be due to different backward masking conditions of T2.

Single vs. Dual Stream Experiment

In this experiment I wanted to test the influence of distractor presence and target location on the proportion of order reversals. These two factors as well as task-set size are the main differences between the TOJ paradigm and the AB paradigm. Since we already rejected task-set size as the source for the different time courses of order reversals in these two paradigms, I figured that one of the other factors (or at least their interaction) should have a major influence on order reversals.

Method

Participants: Participants were students from Paderborn University, Germany. As evidenced by a simple visual test, all had normal or corrected-to-normal vision and were paid 6€ / hour for participation. Twenty participants took part in this experiment.

Apparatus: The experiment took place in a dimly lit room. The participants sat at a distance of 57 cm – set by a chin rest – from a 19’’ CRT screen. The centre of the monitor was at eye level and its resolution set to 800 x 600 pixels at 60 Hz. The experimental program was written in MATLAB 7.7.0 including the PsychToolbox (Brainard, 1997). The observers responded by pressing keys on the keypad.

Stimuli: Stimuli were black on a medium grey background. The digits 1 to 9 provided the target set. Distractors were chosen from the letters of the Roman alphabet (except for I, O, Q, B, S). All stimuli subtended approximately 1° in visual angle. Each stimulus was presented for 66 ms and immediately followed by the next item. This yielded a presentation rate of 15 items/sec. The presentation rate therefore is in between the speed of a typical attentional blink which is about 10 items/sec and a standard TOJ paradigm, which usually presents stimuli at about 33 ms. This was a compromise to gain enough order errors in the TOJ task (which decrease with increasing SOA between the two target-stimuli), and also to ensure for the AB task not being too difficult.

Design: There were four separate blocks in this experiment, each initiated by a 30 practice trials and a separate instruction. In the standard AB block, both target digits appeared in a single stream at the center of the screen among letter-distractors. The two targets were shown immediately after each other (66 ms target-onset asynchrony (TOA) / lag 1), with one intervening distractor (TOA 132 ms / lag 2) or with two distractors between them (TOA 198 ms / lag 3). The AB without distractors block was identical to the standard AB condition, just without distractors. In the standard TOJ block the two targets appeared at different locations without any distractors. Fixation was marked by a “#” sign exactly between the two locations. In the TOJ with distractors condition, there were two streams of distractors. T1 was presented in one, T2 in the other stream. The lags between the two targets were the same in all conditions. The order of the four blocks was counterbalanced between subjects. Each lag in each block was repeated 30 times resulting in 360 experimental trials in total. Both targets were selected randomly from the digits 1-9 while never being identical. Distractors – if present – were also selected randomly with the constrain that no single letter was presented twice in succession within a trial.

Procedure: Participants initiated each trial by pressing the space bar. After a delay of about 1000 ms, a fixation cross (a black “#”-sign) was presented at the center of the screen for approximately another 1000 ms. Each stream began and ended with a # sign. In between these signs there always were 2 targets as well as either 0 or 4 distractors, depending on block. After each trial the observers identified the two targets in order of appearance by pressing the corresponding keys on the keypad. In case they had not recognized one or both targets, they were encouraged to guess. The experiment lasted about an hour and was conducted within a single session.

Results and Discussion

The lower right part of Figure 10 shows the conditional T2|T1 accuracy as a function of lag separately for each condition. As expected, participants had no difficulties identifying both targets if they were not embedded in a stream of distractors (“AB without Distractors” and “TOJ without Distractors”, respectively). The T2|T1 accuracy for the standard AB with distractors also follows the usual pattern: T2 is spared at lag 1. T2 accuracy then decreases at lag 2 and 3. The T2|T1 accuracy in the “TOJ with Distractors” condition is lower since T2 is in a different stream and is therefore missed more often. The “TOJ with Distractors” condition also shows lag-1 sparing, but a weaker one than in the standard AB condition. This finding is in line with Shih (2008) and Jefferies and colleages (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007) who claim that lag-1 sparing with targets in different streams can be found when observers have no foreknowledge of T1's location. The left part of Figure 10 shows the proportion of order errors separately for each lag and condition. A three-way repeated measures ANOVA of arc-sine transformed order errors including Distractor Presence, Task (AB/TOJ) and Lag as factors found a main effect of Lag ($F[2, 38] = 46.6$, $p < .01$), meaning that order errors decreased with increasing temporal distance between the targets. The ANOVA also showed a main effect of distractor presence ($F[1, 19] = 113$, $p < .01$). As clear from Figure 10, participants made much more order errors in conditions in which distractors were present. The main effect of task was also significant ($F[1, 19] = 39.6$, $p < .01$), indicating that it was more likely to reverse the order of the two targets when they were shown at different locations. More importantly, distractor and task did not interact ($F < 1$), indicating that the presence of distractors influences both tasks in a similar vain. The interaction of distractor and lag just failed to reach significance ($F[2, 38] = 2.9$, $p = 0.065$), the influence of lag on the distractor effect is therefore not reliable. The two-way interaction between task and lag ($F[2, 38] = 3.9$, $p < .05$) and the three way interaction ($F[2, 38] = 6.2$, $p < .01$) both showed significant effects.

Cueing SOAs on a fine scale

To more precisely determine the peak of prior entry in RSVP we looked at cueing SOAs between 0 and 100 ms in 10 ms steps. Since all six subexperiments of Experiment 1 in Hilkenmeier, Scharlau, Weiß, and Olivers (2011) led to qualitatively the same results, we only ran one variation, namely the sustained cue of Experiment 1b.

Method

16 participants from Paderborn University took part in this experiment.

Stimulus, Design, and Procedure: Stimulus generation and response recording were programmed in C using the Tscope programming library. After an approximately 1000 ms blank period, a 0.5 x 0.5° black fixation cross was presented for another 1000 ms in the center of the display. It was replaced by a rapid serial visual presentation (RSVP) of 18 digits and letters, presented in Courier New (approximately 0.8 x 0.8° in size). The letters I, O, Q, S, and Z were excluded, as was the number 1. Each item was presented ten times in succession for 10 ms each, without any ISI. The item was then immediately replaced by the next one, resulting in 10 different items/sec. Splitting each item into ten pieces allowed us to color each piece independently. T1 and T2 were letters, whose first halves (50 ms) were always colored, whereas the second halves were black again. The two targets, following each other in lag 1, were embedded in a stream of black distractor letters and digits. T1 was placed at position 8-13 in the stream. The distractor preceding T1 was always a digit. The participant’s task was to report the colored letters at the end of the trial, unspeeded, and with feedback (for which order errors were counted as correct).

There were eleven cueing SOAs: The “No Cue” condition in which only the first halves of the two targets were colored red, a “10 ms” condition in which the last tenth of the distractor-digit immediately preceding T1 was colored red, a “20 ms” condition, in which the two last tenth of the distractor-digit preceding T1 were colored, and so on. The longest cueing SOA was 100 ms, i.e. the complete distractor-digit preceding T1 was colored in red. Each of the eleven different cueing conditions was repeated 40 times and randomly mixed in a single session. The experiment lasted about 50 minutes.

Results & Discussion

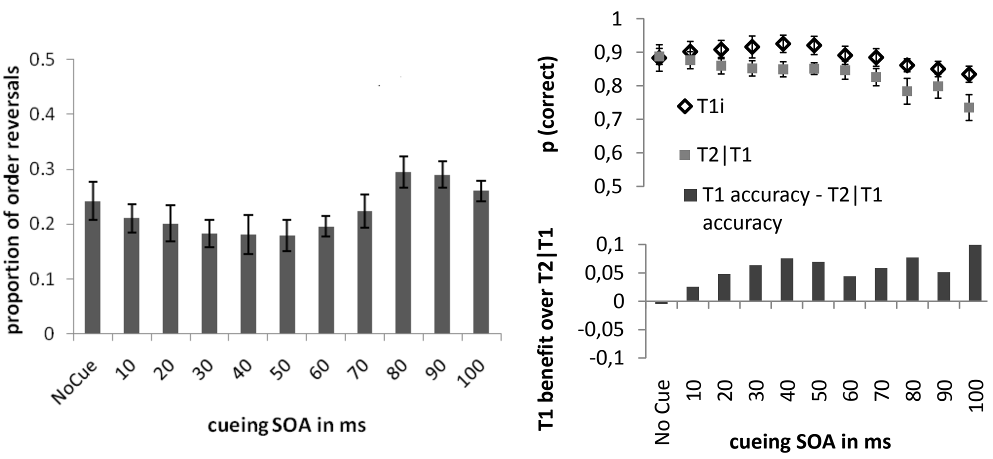


Figure 16: Left: Proportion of order reversals as a function of cueing SOA. Right: T1 accuracy, T2|T1 accuracy and T1 benefit over T2|T1 as a function of cueing SOA.

Figure 16 (left) shows the proportion of order reversals as a function of cueing SOA. A repeated-measures ANOVA with the same factor revealed a significant effect. ($F[10, 150] = 4.2$, $p < 0.05$). Since we have to correct the pairwise comparisons for at least 10 t-tests, none of them reached significance when using Holm-Bonferroni correction. However, uncorrected, the 20 ms, 30 ms, 40 ms, and 50 ms cueing SOAs all showed a significant reduction in order reversals compared to the No cue condition (all $t[15] > 2.3$, all $p < 0.05$, uncorrected). Since all of these data-points neighbor each other, we would argue that the strongest reduction is indeed quite early, although not statistically reliable. As can be seen in Figure 16, order reversals monotonically decrease up to the cueing SOA of 50 ms and then start to increase again. Thus, from a visual inspection of Figure 16, the peak should be somewhere between the 30 and 50 ms cueing SOA. T1 accuracy and T1 benefit over T2|T1 somewhat mirror the time course of order-reversals. However, the strong T1 benefit at longer cueing SOAs is due to a reduced T2 accuracy, not due to an increased T1 performance.

In terms of modeling, the results are disillusioning at first. As can be seen in Figure 17, a distractor like cue (i.e. eliciting facilitation and inhibition with 50 ms offset) predicts the by far strongest cueing effect for the earliest cueing SOAs of 10 and 20 ms.

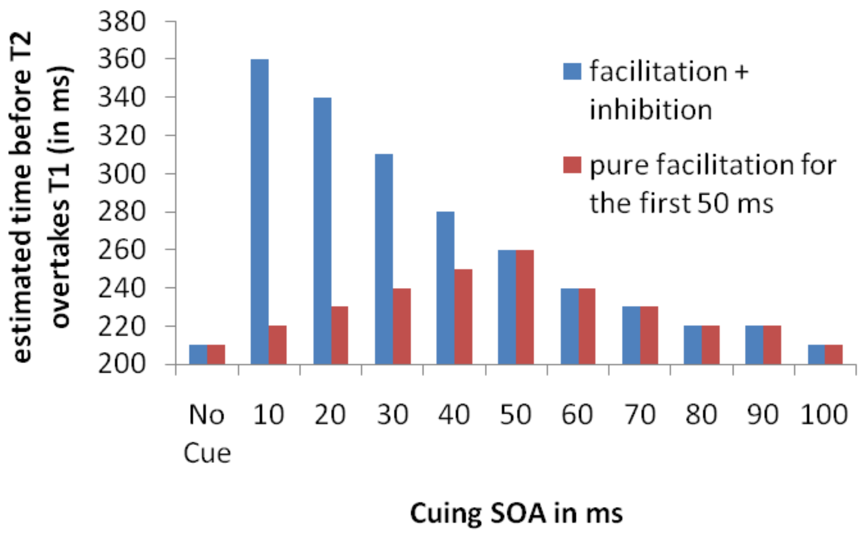


Figure 17: estimated time before T2 overtakes T1 as a function of cueing SOA. Blue: the cue elicits both a facilitatory and an inhibitory effect. Red: cues < 50 ms trigger only facilitation.

But why should we assume that such a shortly presented cue elicits inhibition at all? As already described, the system starts inhibiting as soon as it realizes that it is dealing with a colored distractor and not with a real target. This process is assumed to take about 50 ms. Thus, the start of the inhibition is 50 ms after distractor-cue onset. In turn, I would argue that cues < 50 ms do not trigger any inhibition. Before the system realizes that it was tricked by a colored distractor, this distractor is overwritten by a real target. Thus, the system has no reason to start inhibition. The red bars of Figure 17 show the predicted time course of facilitation when cues < 50 ms only trigger facilitation. The estimated time course nearly perfectly matches the empirical one (Figure 16). In both the simulated and the empirical data, the strongest facilitation is at 50 ms. Moreover, in both cases the increase in facilitation for the first 50 ms is less steep than the decrease for cueing SOAs > 50 ms.

Monoptic/dichoptic blink

The original purpose of this experiment was to explore the influences of early masking effects that occur before binocular integration (e.g. Lumer, 1998) on the shape of the attentional blink.

Method

23 students from Paderborn University took part in this experiment.

Stimulus, Design, and Procedure:

The experiment was run on a 120 Hz TFT monitor. Participants wore active shutter glasses (synchronized with the refresh rate of the monitor) that opened and closed 60 times per second. Thus, a single frame was presented to only one eye for 8.3 ms. For this time the glasses of the other eye were closed. This way, we could present different visual information to each eye. The RSVP stream consisted of 10 items / sec. Each item was only presented to one eye. When a stimulus was presented to the left eye, it appeared for 8.3 ms while the left glass of the shutter glasses was opened. When the left glass closed and the right glass opened, the stimulus disappeared for 8.3 ms. All that was presented to the right eye was the background color (grey). When the right glass closed and the left glass opened again, the stimulus was again presented, so that the left eye could see it. Thus, each stimulus was presented for 6 x 8.3 ms (with 8.3 ms between each repetition).

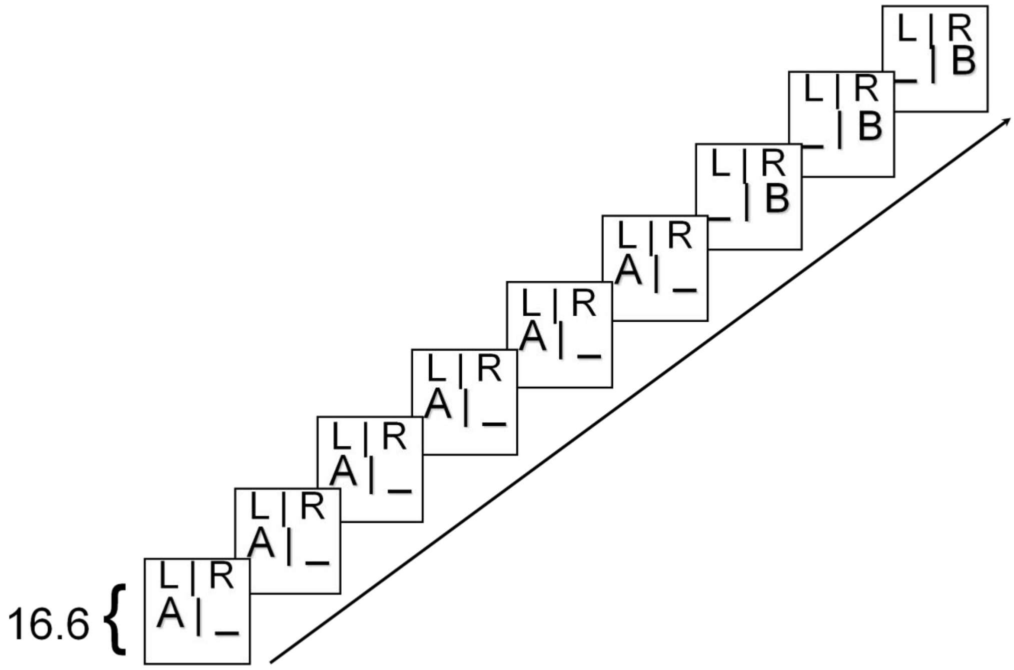


Figure 18: schematic representation of a single item presented in the "monoptic/dichoptic blink" experiment

The experiment consisted of three conditions: a) all stimuli were presented to one eye, b) the stimuli were presented alternating to each eye, but both targets were always presented to the same eye, c) the stimuli were presented alternating to each eye, but the targets were always presented to different eyes.

In each condition, T2 could appear in lag 1, 2, 3, or 6. Each lag in each condition was repeated 30 times. The participant's task was to report the two taget-letters at the end of the trial.

Results and Discussion

T1 accuracy, conditional T2 accuracy and proportion of order errors as a function of lag can be seen in Figure 15, separately for the baseline condition (all stimuli presented to one eye) and the two experimental conditions (stimuli alternating between the eyes, targets either both presented to the same eye or to different eyes). To better understand the different masking conditions utilized in each lag, Figure 19 shows a schematic representation of these trials. A repeated measures one way analysis of variance showed a significant main effect of condition on T1 accuracy ($F[2,66]= 8.6$, $p < 0.001$), a significant main effect of lag ($F[3,66]= 26.4$, $p < 0.001$), and a significant interaction of condition with lag ($F[6,66]= 4.1$, $p < 0.001$). The same analysis on T2|T1 accuracy revealed significant main effects for condition ($F[2,66]= 14.4$, $p < 0.001$)and lag ($F[3,66]= 17.1$, $p < 0.001$), as well as a significant interaction ($F[6,66]= 6.0$, $p < 0.001$). For order reversals, the main effect of condition showed no significant effect ($F<1$) whereas lag as well as the interaction of lag and condition were again significant ($F[3,66]= 169$, $p < 0.001$ and $F[6,66]= 6.5$, $p < 0.001$, respectively). However, more important than the mere analyses of variance between the conditions are planned t-tests between two conditions at a given lag.

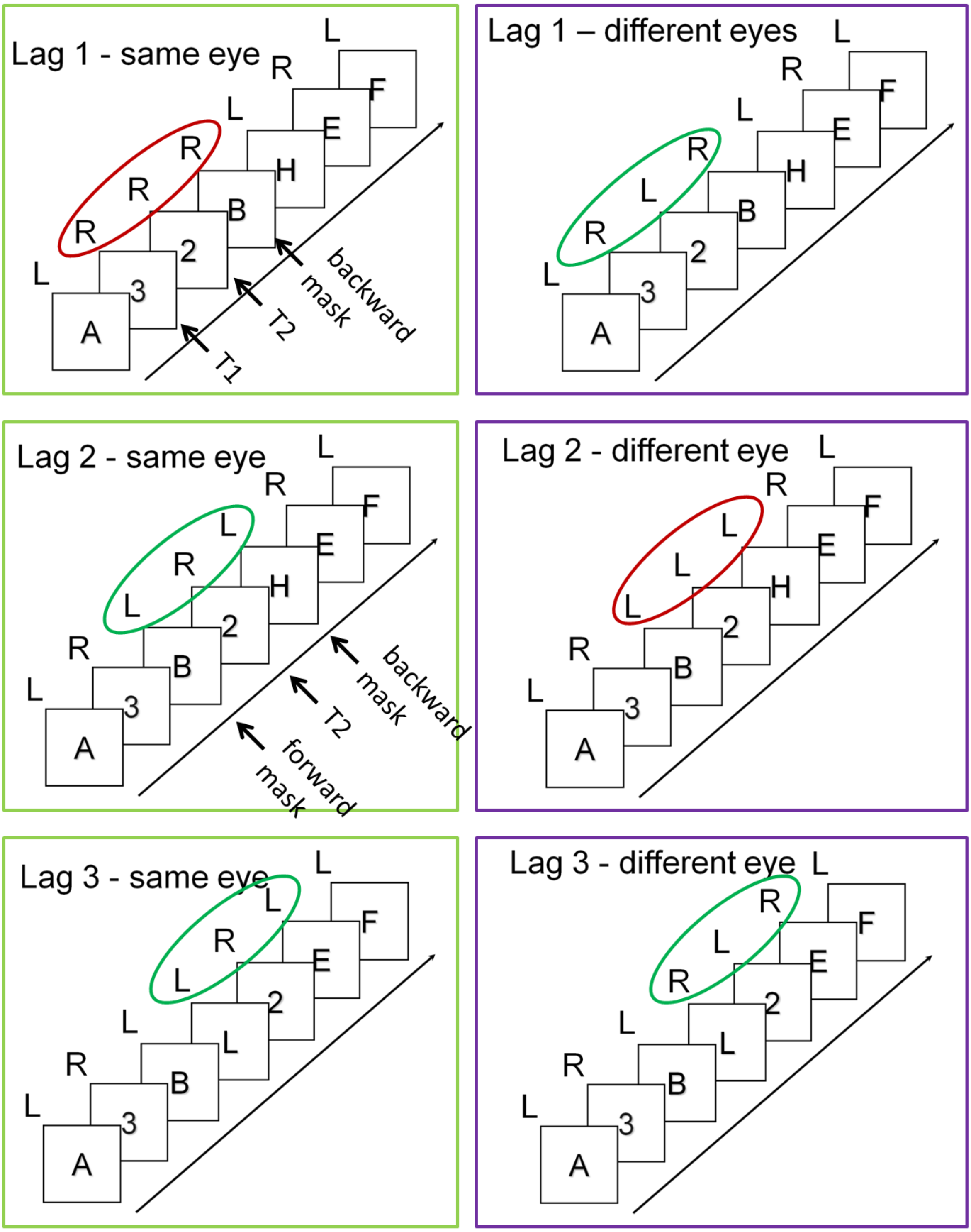


Figure 19: schematic representation of lag 1, 2, and 3 of the “alternating stimuli, targets presented to the same eye” (left) and the “alternating stimuli, targets presented to different eyes” (right) conditions. The baseline condition in which all stimuli are presented to one eye is not shown.

As can be seen in Figure 19, T1 performance at lag 1 is worse when T2 is presented to the same eye compared to T2 being presented to a different eye ($t[22] = 4.2$, $p < 0.001$ and $t[22] = 3.5$, $p < 0.01$ for all stimuli presented to one eye and stimuli alternating but targets in one eye, respectively). The reversed pattern is found for the conditional T2 accuracy. Here, performance decreased when T2 was presented at a different eye than T1 ($t[22] = 6.4$, $p <0.001$ and $t[22] = 2.5$, $p < 0.05$, respectively). These findings, in combination with the result that there are more order reversals when the two targets are presented to the same eye ($t[22] = 4.3$, $p < 0.001$ for alternating stimuli, targets in the same eye) strongly suggests that interdependence between the two targets is much stronger when T1 and T2 are presented to the same eye. As already discussed in the main text, these findings were not necessarily to be expected since the fovea (with which the targets are most likely fixated) has projections in both hemifields. However, as Bachmann (2007, personal communication) pointed out, thalamo-cortical as well as cortico-thalamic retouch effects are most likely laterally biased to the eye of the input, suggesting that increased T2 accuracy and increased proportion of order reversals are indeed due to a facilitatory modulation elicited by T1.

However, we also found evidence for the a priory assumed influence of early masking: at lags 2 and 3, when the blink is most pronounced, T2 accuracy was stronger impaired when masking for T2 (and especially backward masking, as argued earlier in this manuscript) was stronger: At lag 2, in the “alternating stimuli, targets in the same eye" condition, the distractors immediately preceding and trailing T2 were presented to the other eye. Thus, masking was weak and T2 performance high. In the "alternating stimuli, targets in different eyes" condition, the stimulus preceding T2 was presented to the other eye, but the stimulus trailing T2 was presented to the same eye as T2. Thus, forward masking of T2 was weak, whereas backward masking was strong. Nevertheless, T2 performance in this condition was as impaired as in the baseline condition in which all stimuli were presented to one eye, i.e. forward and backward masking were strong ($t < 1$; comparisons to the weak-masking "alternating stimuli, targets in different eyes" condition: $t[22] = 3.9$, $p < 0.001$ and $t[22] = 5.5$, $p < 0.001$, respectively), again indicating that first and foremost the distractor trailing T2 has a strong influence on the shape of the blink. At lag 3 the picture is qualitatively the same: in both alternating targets conditions the distractors immediately preceding and trailing T2 are presented to the different eye. Thus masking is low and T2 performance in both conditions is relatively good ($t[22] = 2.3$, nonsignificant after correction). When all stimuli are presented to the same eye and thus masking is stronger, T2 performance consequently decreases ($t[22] = 4.8$, $p < 0.001$ and $t[22] = 3.0$, $p < 0.01$, respectively).

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The dynamics of attention in serial visual processing

Zusammenfassung der Dissertation auf Deutsch

vorgelegt von

Dipl.-Psych. Frederic Hilkenmeier

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Informationen aus unserer Umwelt aufzunehmen, auszuwählen und gegeneinander abzuwägen sind fundamentale Bestandteile der menschlichen Wahrnehmung und eine notwenige Voraussetzung um erfolgreich mit unserer Umgebung interagieren zu können. Obwohl uns das Ergebnis dieser Prozesse, unsere alltägliche Wahrnehmung, so mühelos erscheint (wir öffnen einfach unsere Augen, und schon sehen wir ein scheinbar vollständiges, detailreiches, scharfes, und farbiges Bild unserer Umwelt), so ist doch ein großer Anteil unseres Gehirns damit beschäftigt, diesen Eindruck zu erzeugen, den unser Sinnesapparat (unsere Augen) aufgrund seiner Physiologie gar nicht liefern kann. Ein entscheidender Aspekt in der Erzeugung unserer Sinneseindrücke ist, dass momentan wichtige Information von momentan weniger Information getrennt wird. Dieser Prozess ist allgemein bekannt als selektive Aufmerksamkeit. Wie und nach welchen Kriterien Aufmerksamkeit arbeitet, ist eines der meistbeforschten Themen der Psychologie und reicht zurück bis zu den Anfängen unserer Disziplin zu Hermann von Helmholtz (1867) und William James (1890). Der Großteil der frühen Arbeiten beschäftigt sich mit der Frage, welche Reize Aufmerksamkeit an sich ziehen und wie Aufmerksamkeit im Raum verteilt wird, wenn mehrere Stimuli gleichsam um Aufmerksamkeit konkurrieren(z.B. Posner, 1980; oder Jonides, 1981). Das Interesse an zeitlichen Aspekten von Aufmerksamkeit hat erst in den vergangenen 25 Jahren stark zugenommen. Was passiert, wenn nicht alle Reize gleichzeitig, sondern nacheinander dargeboten werden? Um die zeitliche Dynamik von Aufmerksamkeit zu untersuchen, hat sich vor allem das „schnelle, serielle visuelle Präsentation“-Paradigma (rapid serial visual presentation; RSVP; Potter & Levy, 1969) etabliert. In diesem Paradigma wird eine große Anzahl von Reizen (typischerweise zwischen 15 und 25) sequenziell hintereinander am selben Ort präsentiert. Jeder Reiz wird für ca. 100 Millisekunden (ms) gezeigt und dann unmittelbar vom nächsten Stimulus überschrieben. Dieses Paradigma kann mit einer Vielzahl von Reizklassen verwendet werden, beispielsweise alphanumerischen Zeichen, Bildern oder Wörtern, aber auch Tönen oder taktilen Reizen (für einen Überblick, siehe z.B. Martens & Wyble, 2010). Ein weitverbreitetes Versuchsdesign ist es, die Versuchsperson zwei zuvor spezifizierte Zielreize in einer Reihe von Ablenkerreizen (Distraktoren) berichten zu lassen, beispielsweise zwei farbige Buchstaben in einer Reihe von schwarzen Zahlen. Während die Versuchsteilnehmer mühelos den ersten Zielreiz erkennen können, berichten sie oft den zweiten

Zielreiz nicht gesehen zu haben, wenn er dem ersten in einem Abstand von ca. 200 – 600 ms folgt. Dieses Phänomen wird als „Aufmerksamkeitsblinzeln“ (Attentional Blink; AB; Raymond, Shapiro, & Arnell, 1992) bezeichnet.

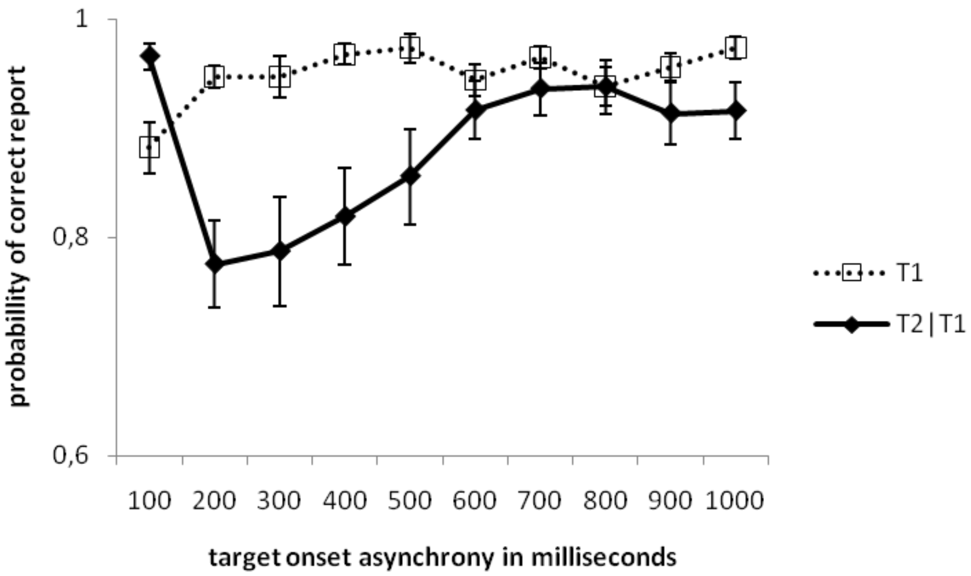

Abbildung 1: Links: Schematischer Ablauf eines Versuchsdurchgangs. Rechts: Identifikationsleistung für den ersten (gepunktet) und den zweiten (durchgezogen) Zielreiz in Abhängigkeit vom zeitlichen Abstand zwischen den beiden Reizen.

Ursprünglich wurde die schlechte Erkennensleistung des zweiten Zielreizes dadurch erklärt, dass dem kognitiven System nicht genügend Ressourcen zur Verfügung stünden, um beide Zielreize zu verarbeiten: Wenn der zweite Zielreiz kurz nach dem ersten kommt, hat der erste schon nahezu alle Ressourcen verbraucht, der zweite geht folglich leer aus und kann nicht adäquat verarbeitet werden (z.B. Ward, Duncan, & Shapiro, 1996; Duncan, Ward, & Shapiro, 1994).

Wie allerdings in Abbildung 1 zu sehen ist, ist die Erkennensleistung des zweiten Zielreizes sehr gut, wenn dieser direkt nach dem ersten gezeigt wird (das sogenannte „lag-1 sparing“, Potter, Chun, Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). Um diesen reliablen Befund erklären zu können, wurden die Theorien, die begrenzte kognitive Ressourcen als Ursache für den Attentional Blink ansehen, um zusätzliche Annahmen erweitert: Die wichtigste Annahme ist, dass die Verarbeitung in zwei Schritten, oder Stufen abläuft. Auf einer ersten, kapazitätsfreien Stufe können alle dargebotenen Reize parallel verarbeitet werden. Damit ein Zielreiz aber berichtet werden kann, also bewusst wahrgenommen wird, muss dieser erst in eine zweite Stufe überführt und dort konsolidiert werden. In dieser zweiten Stufe sind die Ressourcen dann wieder, wie im vorherigen Modell, stark beschränkt, d.h. die zweite Stufe kann die eingehenden Informationen nur seriell bearbeiten. Wenn nun der erste Zielreiz auf der ersten Stufe erkannt wird, öffnet er ein „Aufmerksamkeitsfenster“ und wird zur weiteren Verarbeitung auf die zweite Stufe transferiert (z.B. Chun & Potter, 1995; Jolicoeur, Tombu, Oriet, Stevanovski, 2002; Visser et al, 1999; Akyürek, Riddell, Toffanin, & Hommel, 2007). Solange der erste Zielreiz auf der zweiten Stufe verarbeitet wird, muss der zweite Zielreiz auf der ersten Stufe verharren und ist dort der Gefahr ausgesetzt, überschrieben oder vergessen zu werden. Doch das Fenster, welches den ersten Zielreiz auf die zweite Stufe transferiert, schließt nicht direkt nach dem ersten Zielreiz. Der Stimulus, der direkt nach dem ersten Zielreiz kommt, wird oft ebenfalls mit in die zweite Stufe transferiert. Falls dies der zweite Zielreiz ist, wird dieser also mit dem ersten Zielreiz zusammen verarbeitet. Diese gemeinsame Verarbeitung, bekannt als „episodic integration“ kann den Zeitverlauf des Attentional Blink, wie in Abbildung 1 dargestellt, ohne große Schwierigkeiten erklären.

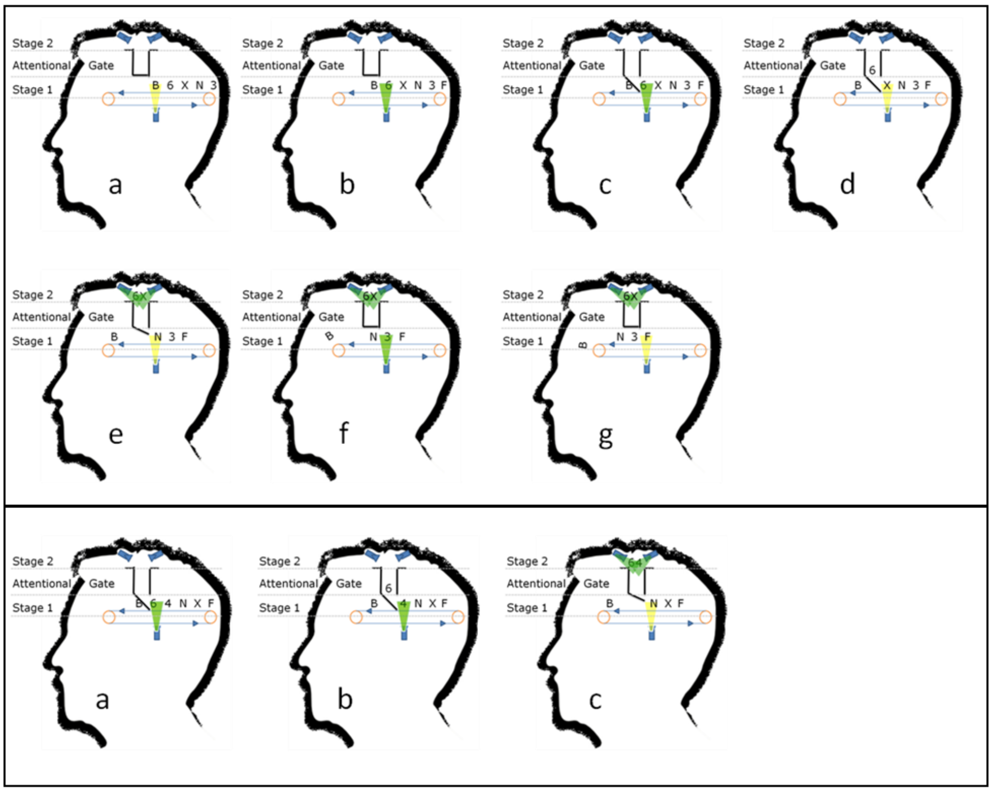

Abbildung 2: Bildliche Darstellung des Attentional Blink (oben) und des lag-1 sparing (unten) in Modellen, die eine gemeinsame Verarbeitung annehmen.

Eine Begleiterscheinung des „lag-1 sparing“ ist, dass die Reihenfolge der beiden berichteten Zielreize von den Versuchsteilnehmern oft vertauscht wird. Dieser Befund wird oft ebenfalls im Sinne der gemeinsamen Verarbeitung interpretiert: Wenn beide Zielreize in einer Episode verarbeitet werden, geht die Reihenfolgeinformation notwendigerweise verloren (Chun & Potter, 1995; Bowman & Wyble, 2007; Hommel & Akyürek, 2005; Akyürek & Hommel, 2005).

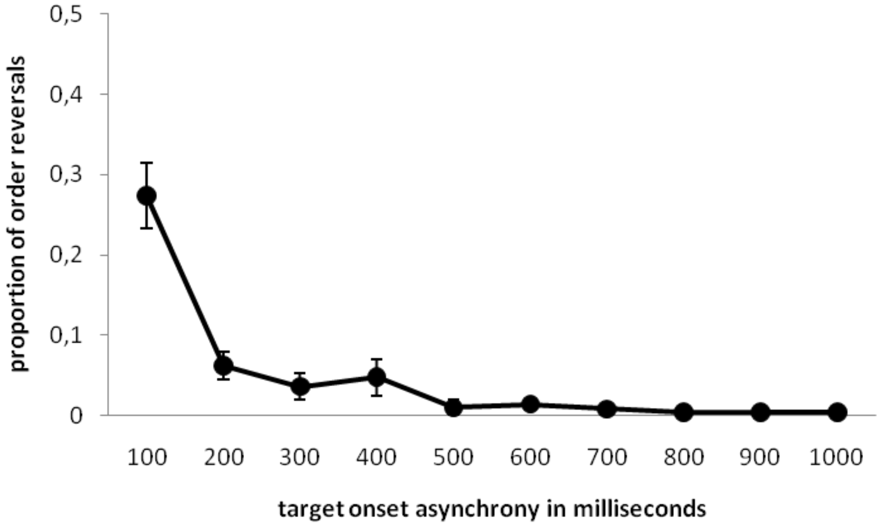

Abbildung 3: Anteil der Reihenfolgefehler in Abhängigkeit vom zeitlichen Abstand zwischen den beiden Reizen.

Dies ist allerdings nicht die einzig mögliche Erklärung: Anstatt anzunehmen, dass die Reihenfolgeinformation schlicht verloren-gegangen ist, ist es durchaus möglich, dass Versuchspersonen einen klaren Reihenfolgeeindruck haben, nur eben oftmals den falschen (siehe Caldwell-Harris & Morris, 2008). Dies wäre konsistent mit Theorien, die anstelle einer gemeinsamen Verarbeitung einen kurzzeitigen Aufmerksamkeitsschub vorhersagen (transient attentional enhancement; z.B. Reeves & Sperling, 1986; Nakayama & Mackeben, 1989). Einer der verblüffenderen Effekte von Aufmerksamkeit ist, dass sie die wahrgenommenen zeitlichen Eigenschaften der Reize verändern kann. Ein beachteter Reiz kann also als früher wahrgenommen werden, selbst wenn er gleichzeitig oder sogar etwas später dargeboten wird, als ein gleichartiger, aber unbeachteter Reiz. Dieses Phänomen des „früheren Eintritts“ (prior entry; Titchener, 1908) sagt folglich ebenfalls Reihenfolgefehler voraus, jedoch über einen komplett anderen Mechanismus: Anstatt davon auszugehen, dass die kognitiven Ressourcen stark limitiert sind, und der zweite Zielreiz nur zufällig und unter dem Verlust der zeitlichen Information mit dem ersten zusammen verarbeitet werden kann, gehen Theorien des kurzzeitigen Aufmerksamkeitsschubs davon aus, dass der erste Zielreiz erleichternd für den zweiten wirkt: der erste Zielreiz löst den Aufmerksamkeitsschub aus, doch bevor dieser seine Wirkung voll entfalten kann, ist der erste Zielreiz bereits durch den zweiten überschrieben worden.

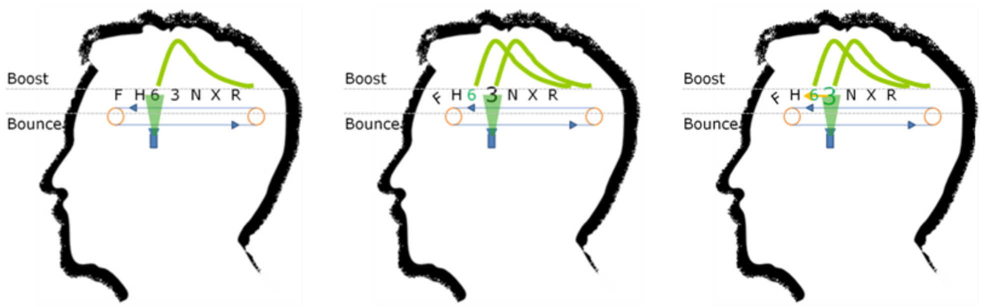

Abbildung 4: Bildliche Darstellung des kurzfristigen Aufmerksamkeitsschubs und seines Einflusses auf die wahrgenommene Reihenfolge.

Im hier vorgestellten empirischen Promotionsprojekt wurde anhand der zeitlichen Reihenfolgefehler näher zwischen den oben beschriebenen großen Theoriesträngen (begrenzte kognitive Ressourcen auf der einen, kurzzeitiger Aufmerksamkeitsschub auf der anderen Seite) unterschieden. Dazu wurden Experimentalbedingungen kreiert, für welche die beiden Theoriezweige unterschiedliche Vorhersagen machen.

Dabei wurde das Cueing-Paradigmas benutzt, das schon von Nieuwenstein, Chun, van der Lubbe, und Hooge (2005), Nieuwenstein (2006), und Olivers und Meeter (2008) eingesetzt wurde. Theorien des kurzfristigen Aufmerksamkeitsschubs vermuten, dass der erste Zielreiz einen Aufmerksamkeitsschub einleitet, vom zweiten Zielreiz jedoch schon überschrieben wird, bevor sich der Großteil der Erleichterung auswirken kann. Der zweite Zielreiz profitiert von der gesteigerten Aufmerksamkeit, wird schneller verarbeitet und daher in einer Reihe von Durchgängen als früher wahrgenommen. Falls es zutrifft, dass das Ausmaß an Reihenfolgefehlern also durch das relative Verhältnis von Aufmerksamkeit zwischen den beiden Zielreizen bestimmt wird, sollten Reihenfolgefehler abnehmen, wenn mehr Aufmerksamkeit auf den ersten Zielreiz verlagert wird. Dies wurde erreicht, indem ein Hinweisreiz zeitlich direkt vor dem ersten Zielreiz platziert wurde, um Aufmerksamkeit auf diesen zu lenken. Von dieser Aufmerksamkeit sollte vor allem der erste Zielreiz profitieren. Das relative Verhältnis von Aufmerksamkeit sollte sich damit zu seinen Gunsten verschieben, d.h. Reihenfolgefehler sollten seltener auftreten.

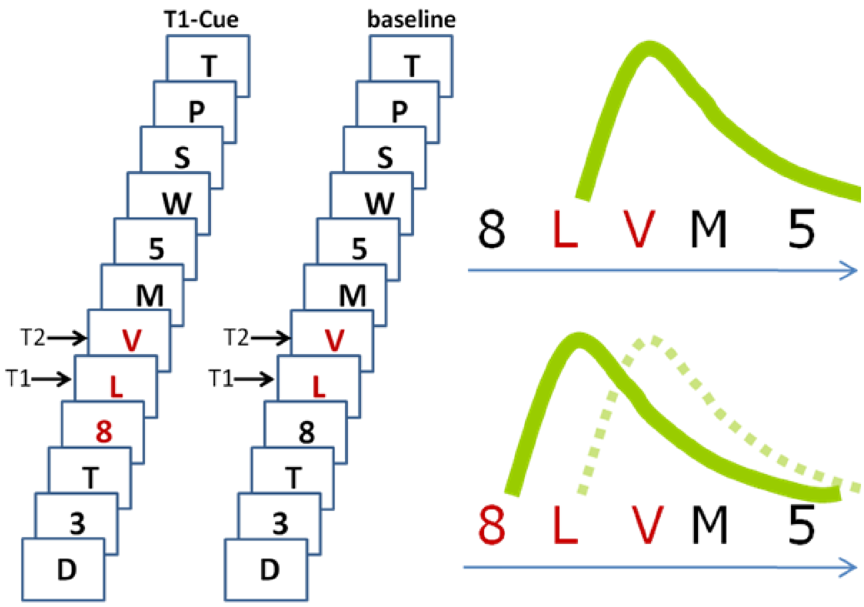

Abbildung 5: links: Schematischer Ablauf eines Versuchsdurchgangs für die Standard Attentional-Blink Bedingung ohne Hinweisreiz und für die Experimentalbedingung mit Hinweisreiz. Rechts: Angenommene Aufmerksamkeits-Erleichterung für Durchgänge ohne und mit Hinweisreiz.

Wie erwartet wurden in Durchgängen mit Hinweisreiz weniger Reihenfolgefehler gefunden als in Durchgängen ohne einen solchen Hinweisreiz (Olivers, Hilkenmeier, & Scharlau, 2010). Dies ist ein klares Indiz dafür, dass die Reihenfolgefehler im Attentional Blink tatsächlich durch einen kurzzeitigen Aufmerksamkeitsschub und „prior entry“ erklärt werden können.

Allerdings können die Ergebnisse aus Olivers et al. (2010) in gewisser Weise auch durch „episodic integration“ erklärt werden: Da der Hinweisreiz gewisse Eigenschaften mit den Zielreizen teilt (in diesem Fall die Farbe), ist es plausibel anzunehmen, dass dieser Hinweisreiz ebenfalls ein Aufmerksamkeitsfenster öffnen kann, und dass der Hinweisreiz gemeinsam mit dem ersten Zielreiz auf der zweiten Stufe verarbeitet wird. Der zweite Zielreiz wird nicht mit auf die zweite Stufe transferiert, sondern muss sein eigenes Aufmerksamkeitsfenster öffnen. Falls dies gelingt, hat der zweite Zielreiz einen anderen Zeitstempel als der erste. Gelingt es nicht, kann er nicht berichtet werden. Die Befunde zeigen, dass die Erkennensleistung des zweiten Zielreizes tatsächlich abnimmt, wenn vor dem ersten Zielreiz ein Hinweisreiz eingeblendet wird (Olivers et al., 2010). Dies könnte für eine gemeinsame Verarbeitung in einer Episode sprechen, auch wenn für diese Vermutung noch einige Zusatzannahmen nötig sind (siehe Olivers et al., 2010; Hilkenmeier, Olivers, & Scharlau, 2011).

Abbildung 7: Hinweisreiz und erster Zielreiz werden in einer gemeinsamen Episode verarbeitet. Obwohl der zweite Zielreiz direkt hinter dem ersten kommt, gelingt es ihm, in einer neuen Episode ebenfalls in die zweite Stufe zu gelangen und dort separat verarbeitet zu werden.

In der ersten Studie konnte also „prior entry“ als Alternative zur weit verbreiteten Annahme der „episodic integration“ etabliert werden. In einem zweiten Schritt wurden Experimentalbedingungen herangezogen, die klarer zwischen diesen beiden theoretischen Annahmen unterscheiden können. In Hilkenmeier, Olivers und Scharlau (2011) wurde einen Hinweisreiz direkt vor dem zweiten

Zielreiz dargeboten. Laut „episodic integration“ sollte sich diese Manipulation nicht von einer Kontrollbedingung ohne Hinweisreiz unterscheiden, da der Hinweisreiz erst nach dem ersten Zielreiz, also wenn die Episode bereits begonnen hat, präsentiert wird. Die „prior entry“ Erklärung hingegen sagt voraus, dass dieser Hinweisreiz dazu führen sollte, dass der zweite Zielreiz mehr Aufmerksamkeit bekommt, Reihenfolgefehler also zunehmen sollten.

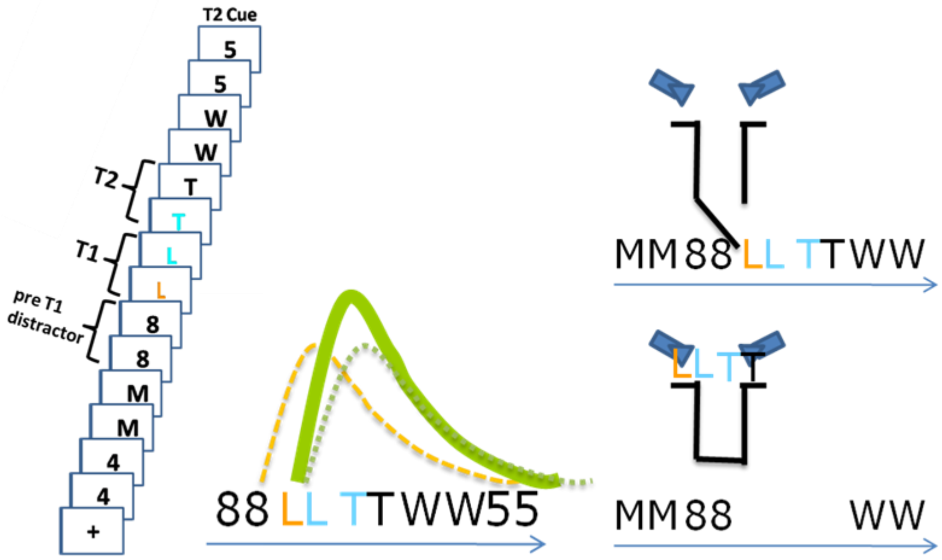

Abbildung 6: links: Schematischer Ablauf eines Versuchsdurchgangs für die Experimentalbedingung mit Hinweisreiz vor dem zweiten Zielreiz. Mitte: Angenommene Aufmerksamkeits-Erleichterung für Durchgänge mit Hinweisreiz vor dem zweiten Zielreiz. Rechts: Angenommene episodische Verarbeitung. Beide Zielreize werden, wie in der Kontrollbedingung ohne Hinweisreize, in einer gemeinsamen Episode verarbeitet.

Die empirischen Daten zeigen eine klare Zunahme von Reihenfolgefehlern, belegen also die Theorie der kurzfristigen Aufmerksamkeitserleichterung. Dies hat weitreichende Folgen für die theoretischen Erklärungen des Attentional Blink: Wie bereits beschrieben wurde die Zusatzannahme der gemeinsamen episodischen Verarbeitung getroffen, um „lag-1 sparing“ im Rahmen begrenzter kognitiver Ressourcen erklären zu können. Die begleitenden zeitlichen Reihenfolgefehler wurden als einer der Hauptbelege für diese theoretische Erklärung herangezogen. In den vorliegenden Studien wurde gezeigt, dass die Manipulation von Reihenfolgefehlern im Attentional Blink nicht schlüssig durch gemeinsame episodische Verarbeitung erklärt werden kann. Einer der Hauptbefunde für „episodic integration“ fällt also weg. Ohne diesen Mechanismus kann der komplette Zeitverlauf des Attentional Blink allerdings nur noch schwerlich durch begrenzte Ressourcen erklärt werden. Stattdessen erhärtet dieser Befund neuere Theorien, die den Attentional Blink nicht als Beleg für begrenzte Ressourcen, sondern als vorübergehenden Kontrollverlust (Di Lollo, Kawahara, Ghorashi, & Enns, 2005), oder als Resultat der Distraktor-Verarbeitung ansehen (Olivers & Meeter, 2008).

Nachdem nun ein Einfluss von „prior entry“ auf die zeitlichen Reihenfolgefehler im Attentional Blink belegt ist, wurde in einer weiteren Studie dem Zeitverlauf dieser Erleichterung untersucht (Hilkenmeier, Scharlau, Weiß, & Olivers, 2011). Dabei konnte gezeigt werden, dass Hinweisreize, die nicht nur Zielreiz-, sondern auch Distraktoreingenschaften besitzen, eine nur kurzfristige Erleichterung auslösen. Diese Erleichterung erreicht ihren Höhepunkt schon nach ca. 50 ms. Falls der Hinweisreiz hingegen nur Zielreizeigenschaften besitzt, verlängert sich die Erleichterung auf ca. 100 ms. Dieses

Befundmuster konnte durch ein einfaches computationales Modell vorhergesagt werden, das auf bisherigen Theorien der kurzfristigen Aufmerksamkeitsverlagerung aufbaut (Bachmann, 1984; Reeves & Sperling, 1986; Nakayama & Mackeben, 1989; Olivers & Meeter, 2008, Wyble, Bowman, & Nieuwenstein, 2009).

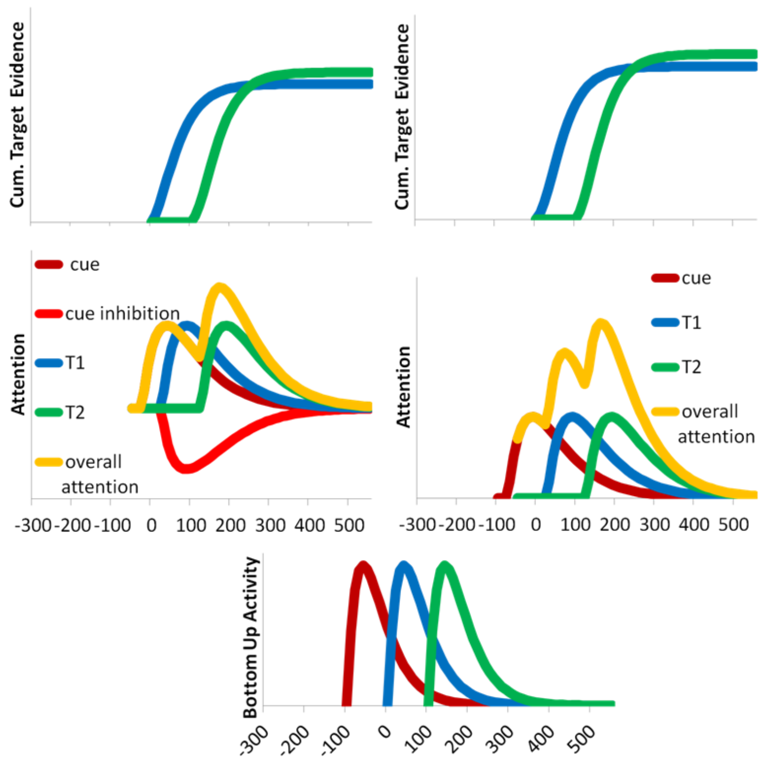

Abbildung 7: links: Simulationen des computationalen Modells. Links: Hinweisreiz mit Distraktoreigenschaften. Dieser Reiz löst nicht nur eine Erleichterung, sondern auch eine verzögerte Inhibierung aus. Rechts: Hinweisreiz nur mit Zielreizeingeschaften. Dieser Reiz löst ausschließlich Erleichterung aus.

Zusammenfassend kann man sagen, dass es im hier vorliegenden Promotionsprojekt gelungen ist, den Einfluss einer kurzfristigen Aufmerksamkeitserleichterung auf Reihenfolgefehler im Attentional Blink nachzuweisen. Dies hat nicht nur für Theorien des Attentional

Blink eine gewisse Bedeutung, sondern zeigt darüber hinaus auch, dass sich verschiedene experimentelle Paradigmen auf gemeinsame Aufmerksamkeitsmechanismen zurückführen lassen.

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