Technical University of Denmark

Temporal constraints on visual perception: A psychophysical investigation of the relation between attention capture and the attentional blink

Nielsen, Simon; Andersen, Tobias; Hansen, Lars Kai

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Temporal constraints on visual perception: A psychophysical investigation of the relation between attention capture and the attentional blink

Simon Nielsen

Kongens Lyngby, 2012
IMM-PHD-2012-279

Technical University of Denmark
DTU Informatics, Cognitive Systems Section
Building 321, DK-2800 Kongens Lyngby, Denmark
Phone: +45 253351 E-mail: reception@imm.dtu.dk

Foreword

Together with the two articles below this theoretical report comprises my PhD dissertation submitted to DTU Informatics, Technical University of Denmark.

Nielsen, S., & Andersen, T. S. (Submitted). Target saliency and attention capture in the attentional blink. Psychological Research.

Nielsen, S., & Andersen, T. S. (2011). The attentional blink is modulated by first target contrast: Implications of an attention capture hypothesis. Proceedings of the Cognitive Sciences Society's Annual meeting 2011.

Simon Nielsen
Cognitive Systems Section
Lyngby, August 6th, 2012

Abstract

While the richness of our visual perceptions is nearly boundless, the rate with which we can perceive information is limited. For instance when we are required to perceive two consecutive target objects following briefly after each other, the accuracy with which we can report the second target is often reduced in the first half second. This phenomenon is known as the attentional blink (Raymond, Shapiro & Arnell, 1992) and as suggested by the name is assumed to pertain to how fast attention can be reallocated. Bottleneck models suggest that the attentional blink is caused by limited capacity in processing targets, which effectively causes a perceptual bottleneck (Chun & Potter, 1995). According to bottleneck models, making the first target easier to perceive should improve processing in the bottleneck and reduce the attentional blink. However, recent studies suggest that an attentional blink may be triggered by attention capture to the first target (Folk, Leber & Egeth, 2008) and that if making the first target easier to perceive increases its saliency this may increase the attentional blink (Chua, 2005).

This thesis examines the attention capture hypothesis with focus on empirical investigations and a theoretical review. Specifically this work present studies in which first target contrast is varied in two different attentional blink paradigms, while potential influences from bottleneck effects are controlled. Publication 1 describes findings using the two-target paradigm (Duncan, Ward & Shapiro, 1994) where two masked targets are presented in different locations. Here we find that the attentional blink increases with first target contrast, however, only when no mask follows the first target. To further examine the effect of first target contrast, we disentangle the potential influence of bottleneck effects and vary first target contrast while maintaining target difficulty constant. Again we find that the attention blink increases with first target contrast. Publication 2 describes findings using the rapid serial visual presentation paradigm (Potter & Levy, 1969), in which two targets are presented centrally in the same location embedded in a stream of distractor objects. These findings replicate those from Publication 1, and suggest

that the effect is not entirely spatial, since the rapid serial visual presentation paradigm does not require a spatial shift of attention to a new location. In addition to the findings in Publication 1, Publication 2 shows that the effect of first target contrast can be cancelled by the opposing effect of second target contrast.

Thus the results presented here are consistent with an attention capture hypothesis and suggest that the first target can trigger an attentional blink, and that the size of the blink increases with first target contrast.

Populært resumé

Vores syn er næsten ubegrænset når det kommer til dybden og omfanget af sansninger vi kan opleve, hvorimod der er en klar begrænsning når det kommer til hastigheden med hvilken vi kan percipere information. Denne ph.d. afhandling undersøger et fænomen, der er kendt som opmærksomhedsblinket, hvilket viser at hvis to objekter vises inden for et halvt sekund, er præcisionen med hvilken vi kan rapportere det andet objekt ofte reduceret. Det er uklart hvilken rolle det første objekt har i at skabe opmærksomhedsblinket, hvilket er hvad denne afhandling fokusere på. Specielt undersøges det om opmærksomheds blinket kan opstå som følge af at det første objekt fanger opmærksomheden i en sådan grad, at den ikke kan genallokeres effektivt til det andet objekt. Til dette formål præsentere denne afhandling en teoretisk gennemgang af den relevante litteratur samt en række forsøg. Resultaterne fra afhandlingen viser, at opmærksomhedsblinket kan forårsages af, at det første objekt fanger opmærksomheden, og at opmærksomhedsblinket øges med lys kontrasten af det første objekt. Disse resultater er overensstemmende med nyere teorier for opmærksomhedsblinket, og viser at der kan ske en uhensigtsmæssig allokering af opmærksomhed til objekter, som er specielt synlige, hvor uhensigtsmæssigt henviser til at opmærksomheden engageres i objektet i en større grad end hvad der er nødvendigt for at se objektet - hvilket kan have en konsekvens for evnen til at se efterfølgende objekter.

Acknowledgements

I wish to thank DTU Informatics and the ITMAN PhD School for granting me the scholarship to pursue this project, and to my supervisors Tobias Andersen and Lars Kai Hansen for supporting me and agreeing to supervise it.

I extend my gratitude to my main supervisor Tobias Andersen, for his invaluable mentoring which have taught me what it means to be a good scientist, for always taking the time to discuss matters I found relevant, and not the least for his dedication and sound critique when reviewing my manuscripts.

I thank all of people at the Cognitive Systems Section for their good company during the past three years. Also, I wish to thank the administrative organ at the Cognitive Systems Section, especially Ulla Nørhave, Sine Ingemann and Marian Solrun Adler, who have made the less scientific matters nearly transparent.

The Center for Visual Cognition, Copenhagen University, has been my 'second home' during my PhD studies. I wish to thank all of the people for making me feel welcome, for good company, an inspiring working environment, fruitful discussions and great fun.

I wish to thank Barry Giesbrecht for an inspiring stay in his lab at the University of California, Santa Barbara, and to the guys in the lab: James Elliott, Tom Bullock, and Ryan Kasper for introducing me to electrophysiology in practice, for fruitful discussions and lots of fun.

Thank you to all of my caring family for your support and for trying to sympathise with the joys and frustrations of the less ordinary PhD life. In addition I thank Bjarne and Johanne, for providing a refugee at their wonderful place where I've spend many hours of productive work in warm and joyful surroundings.

On a very personal account I wish to thank my beautiful Andrea, for her loving and caring nature, which is an everlasting inspiration. Thank you for enthusiastically and supportingly having shared this journey with me! Also, I extend my warm thanks to our affectionate dog Batman, who consistently overthrows me with his love upon entering the door, which disarms even the stressful of days. Last but by no means least, Viggo, my loving little terrorist, my heart on two legs - thank you for putting science in a sound perspective by constantly reminding me about everything that is so beautiful in life.

Table of Contents

1 Introduction

This thesis aims at better understanding the temporal constraints on visual attention that limits our perception of information occurring within a short period of time. The attentional blink phenomenon (Raymond, Shapiro & Arnell, 1992) shows that when we are required to perceive two target objects occurring within half a second, perception of the second object is limited. Bottleneck models suggest that the attentional blink is caused by limited capacity for processing targets, which effectively causes a perceptual bottleneck (Chun & Potter, 1995). According to bottleneck models, making the first target easier to perceive should improve processing in the bottleneck and reduce the attentional blink. However, recent studies suggest that an attentional blink may be triggered by attention capture to the first object (Folk, Leber & Egeth, 2008) and that if making the first target easier to perceive increase its saliency this may increase the attentional blink (Chua, 2005). The work presented here examines the attention capture hypothesis through empirical investigations and theoretical reviews. Specifically the thesis addresses how saliency of the first target affects the attentional blink. To this end luminance contrast of the first target is varied, while potential influences from bottleneck effects are controlled.

The main body of this thesis is organized in three main sections and a conclusion. The first section "Attentional blinks" describes the background of the attentional blink and previous findings relating to the present work. "Psychophysics of luminance contrast" treats the perception of luminance contrast and individual differences along with relevant technical issues. "Target contrast and attention capture in the attentional blink" is a summary of the two publications included in this thesis, which describes the experiments and details of the findings. In the appendix the two publications are included along with selected posters I have presented at conferences during my PhD studies.

2 Attentional blinks

The ability to efficiently perceive our environment relies strongly on the functioning of our attention system, which role is to navigate through the sensory information in our surroundings, and facilitate perception of specific information on behalf of our intention. Needless to say that currently such complex system falls short of a conceptual explanations satisfying all its aspects. One way to approach the attention system is to break it down and address the limitations of the constituent parts. Understanding the limitations, allows us to describe it within these boundaries and examine its characteristics and behaviour. The attentional blink (AB) paradigm constitutes such conceptualization of how attention behaves in time. That is, the AB suggests what the limitations are when we are required to perceive consecutive events occurring within a short period of time.

The AB was formalized and named by Raymond, Shapiro and Arnell (1992), who presented observers with a Rapid Serial Visual Presentation (Potter & Levy, 1969) stream (RSVP; see Figure 2.1 for example) of black letter distractors with a white target (T1) and a black probe ('X', T2) occurring at varying lags (the temporal position before and between targets). On some trials observers were required to report both the identity of T1 and report if T2 had appeared (experimental condition), whereas on other trials they were instructed to ignore T1 and only detect T2 (control condition). The authors found that accuracy of T2 detection was significantly lower at T1-T2 lags 2-5 relative to lags 1 and those beyond 5, in the experimental condition compared to the control condition. Because the effect on T2 detection were caused by altering instructions, as opposed to changing the stimuli conditions, the AB was, as the name implies, adopted as a higher cognitive limitation pertaining how fast attention can be reallocated to a new object. In conclusion the authors argued that attention blinks for approximately 500 ms. after being engaged in an object, and that as a consequence perception is limited during this period.

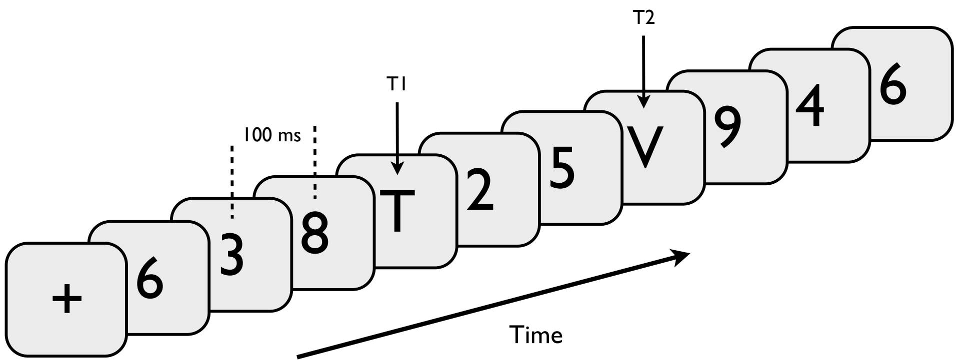

Figure 2.1. Example of RSVP paradigm where two targets (T1 & T2) are presented in a stream of digit distractors, at the rate of 10 items per second. Observers are asked to fixate on the fixation cross after which the stream is initiated on the observer's own initiative. When the stream terminates observers are asked to report the identity of T1 and T2. Several variations of the RSVP paradigm exist where target and distractor attributes vary along with the delay between item in the stream, and the type of targets and distractors.

When T2 was presented immediately after T1 the accuracy of T2 report however was equal to that of a T2 presented after 500 ms. This phenomenon was named *lag-1 sparring* since it appears that when T2 occurs at lag 1 it is sparred from the AB. A general understanding of lag-1 sparring that prevails is that T1 and T2 are processed in the same attentional window with little processing overhead added by T2 due to its close temporal proximity, and categorical and featural resemblance to T1 e.g. (Chun & Potter, 1995).

2.1 Experimental paradigms

The AB has been demonstrated across three different paradigms namely rapid the RSVP, *two-target,* and the *skeletal* paradigms. The paradigms vary in their use of distractor item (RSVP), versus masks (two-target, skeletal) and spatial displacement of target locations (two-target) versus presenting targets in the same location (RSVP, skeletal). Despite procedural differences between paradigms, it was suggested that all three paradigms reflect the same AB phenomenon (Ward, Duncan, & Shapiro, 1997), an assumption that is adopted in this thesis.

Rapid serial visual presentation

The RSVP paradigm (Potter & Levy, 1969) has dominated the AB literature in terms of number of published studies since the phenomenon was first reported. A typical RSVP paradigm constitutes two targets (T1 & T2) embedded in a stream of 20-30 distractors presented centrally at fixation rapidly after each other at approximately 10 items per second (see Figure 2.1 for example paradigm). At the end of the stream observers are required to report on the two targets appearing in the stream.

Characteristic for the RSVP stream is the selection of relevant information (targets) from irrelevant information (distractors) at a pace sufficiently high to challenge perception and produce and AB. Specifically the RSVP paradigm allows for the examination of lag-1 sparring, which is facilitated by the fact that each item is presented in the same location. That items are presented in the same location, however, makes targets in an RSVP stream prone to forward masking by preceding distractors, which may reduce target accuracy (see section on visual masking).

Two-target paradigm

Another experimental paradigm that is used for studying the AB is *the two-target paradigm* (Duncan, Ward, & Shapiro, 1994) where two masked targets are presented in different locations, selected from four locations forming an imaginary diamond (Moore, Egeth, Berglan, & Luck, 1996; Ward, Duncan, & Shapiro, 1996) or square (Nielsen & Andersen, 2011), see Figure 2.2 for example paradigm.

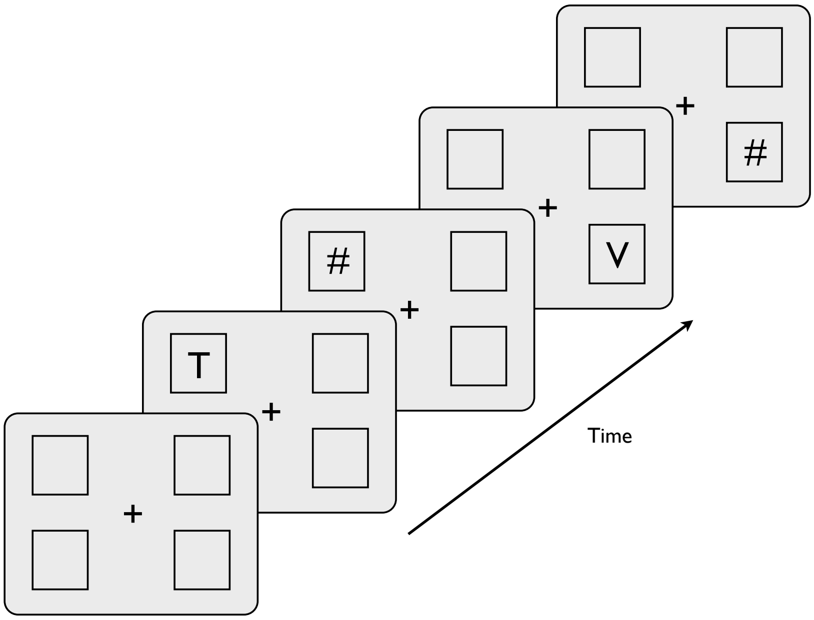

Figure 2.2. Example of a two-target paradigm where two targets are presented in different locations. Both targets are masked in this version but masking procedures vary between studies, as well does the type of mask used. The delay between targets is controlled by the stimuli onset asynchrony (SOA), which is the time between onsets of targets. Observers are asked to fixate on the fixation cross after which a trial is comenced on the observer's initiative. Typically, at the end of a trial, observers are required to report the identity of both targets.

That targets are presented in spatially distinct locations prevents effects of forward masking, and it is most likely due to the same lack in stimuli overlap that lag-1 sparring has not been demonstrated when targets are presented in different locations (Berthet & Kouider, 2012; Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Duncan et al., 1994; Moore et al., 1996; Visser & Bischof, 1999; Visser, Zuvic, Bischof, & Di Lollo, 1999; Ward et al., 1996).

Skeletal paradigm

A skeletal version of the two-target paradigm was devised by Ward et al. (1997) where the location shift of targets was eliminated to assess whether the authors previous findings using the two-target paradigm (Duncan et al., 1994; Ward et al., 1996) merely reflected the cost of shifting attention to a new location. Ward et al. (1997) found the same reliable AB effect and concluded that the effect reported in the AB is not dependent on a spatial shift of attention.

In the skeletal paradigm (see Figure 2.3 for example paradigm) two masked targets are presented centrally at fixation and observers are asked to report on the two targets appearing.

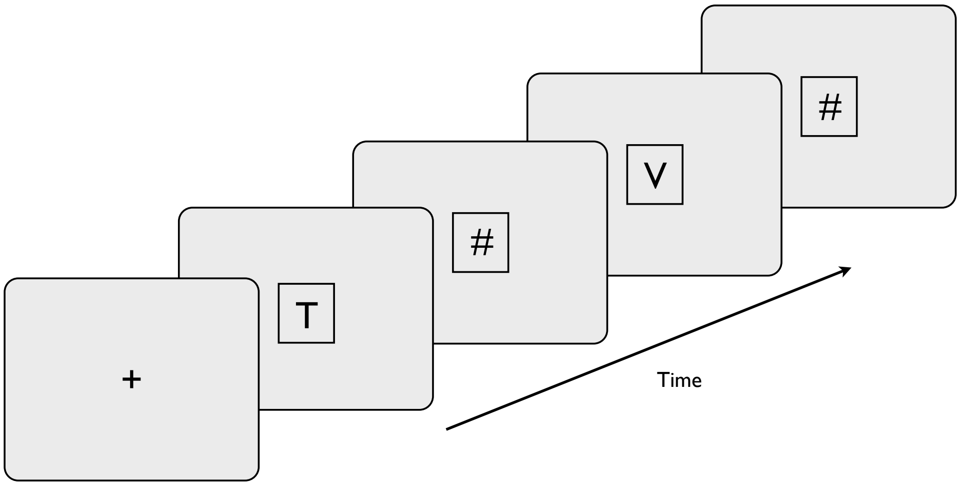

Figure 2.3. Example of a skeletal paradigm where two targets are presented centrally at fixation. Both targets are masked in this version but the masking procedures vary between studies, as well does the type of mask used. The delay between targets is controlled by the stimuli onset asynchrony (SOA), which is the time between onsets of targets. Observers are asked to fixate on the fixation cross after which a trial is initiated on the observer's own initiative. Typically, at the end of a trial, observers are required to report the identity of both targets.

Since targets are presented in the same location, the skeletal paradigm is prone to forward masking effects, however, lag-1 sparring effects is typically not seen in the skeletal paradigm (Mclaughlin, Shore, & Klein, 2001; Shore, Mclaughlin, & Klein, 2001; Ward et al., 1997) most likely due to T1's mask (Visser & Ohan, 2007).

2.2 Visual masking

Due to a slow decay in neural representation visual stimuli is available for processing beyond its physical exposure (Coltheart, 1980). Neural representation of stimuli can be traced up to 300 ms. after offset in the visual pathway, however, this visual persistence can be reduced to approximately 60 ms. by applying masking objects immediately after stimuli (Keysers & Perrett, 2002).

To control the perceptual processing time of stimuli *backward masking* is applied where the masking object is introduced after the target. However, masking effects also occur from preceding objects in the same location. When the interval between two objects is less than 150 ms. *forward masking* effects can reduce the perceptual quality of targets (Spencer & Shuntich, 1970).

Backwards masking is achieved differently across paradigms. In an RSVP stream targets are masked by subsequent distractors, while jumbled feature constructs known as *pattern masks* are used in the skeletal (Mclaughlin et al., 2001; Shore et al., 2001; Ward et al., 1997) and two-target paradigms (Duncan et al., 1994; Moore et al., 1996; Nielsen & Andersen, 2011; Ward et al., 1996). Of importance is the relationship in spatial frequency between masks and targets, which have been found critical for a mask to properly backward mask a target, such that masks with spatial frequencies that are similar to targets are more efficient that those where the spatial frequency differs (Legge & Foley, 1980; White & Lorber, 1976).

Backwards masking can have two different effects on the perceptual system depending on the temporal proximity of a mask to a target. When masks are superimposed on targets or presented immediately after targets, targets and masks are perceived as one object due to the limitations in temporal resolution of the visual system. This type of masking is referred to as *integration masking* and the effect on stimuli is degraded perceptual quality of the stimuli akin to adding noise to targets (Enns & Di Lollo, 2000).

When a delay follows between targets and masks the effect of masking is different from that of integration masking (Enns & Di Lollo, 2000; Spencer & Shuntich, 1970). At a sufficiently large delay the target and the mask are perceived as two separate objects and the effect of masking is an interruption of target processing at a later perceptual stage (Jolicœur & Dell'Acqua, 1998). For this reason this type of masking is referred to as *interruption masking*.

Influence on the attentional blink

The type of backward masking has been found critical to observe an AB in the RSVP paradigm. The first target can be masked with either integration or interruption masking, but to observer a stable AB it is critical that the second target is masked using interruption masking (Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998). The length of the delay between targets and distractors, the *inter stimuli interval* (ISI) is critical to induce proper interruption masking and it was suggested that the optimal ISI is 100 ms. (Breitmeyer, 1984). In addition, backwards pattern masking have been found to mask effects of first target manipulations, such that an effect was only present when the mask was omitted (Nielsen & Andersen, 2011; Visser & Ohan, 2007).

2.3 Theories

Several theoretical accounts have been proposed to explain the AB. Recent reviews by Dux and Marois (2009) and by Martens and Wyble (2010) provides a comprehensive overview.

Resource depletion / bottleneck models

Resource depletion models (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicœur & Dell'Acqua, 1998) suggests that target processing occurs in two stages. The first stage is fast, has inexhaustible resources and renders a superficial representation of objects in some pre-conscious volatile memory. In the second stage objects are consolidated into more durable memories necessary for conscious report, such as verbal memory. This stage is slow, and processing resources are limited, which causes a perceptual bottleneck (for this reason these models often referred to as bottleneck models). According to bottleneck models, when T2 follows shortly after T1, second stage resources are occupied by T1. When the second stage clears, the volatile first stage representation of T2 is often lost, which results in an AB.

Input filter theories

Another group of theories can be characterized as input filter theories (Di Lollo, Kawahara, Ghorashi, & Enns, 2004; Olivers & Meeter, 2008; Shapiro, Raymond, & Arnell, 1994) since they suggest that the AB occurs because distractors disrupts efficient target processing by interfering with a perceptual input filter, which is tuned for targets according to the attentional set for targets.

The *interference theory* (Shapiro et al., 1994) suggest that distractors enter visual short term memory (VSTM) due to their resemblance and temporal proximity to targets. The AB is a consequence of confusion in extracting the correct item (target) from VSTM or due to insufficient space in VSTM since T1 and distractors occupy the typical three to four slots in VSTM (Shibuya & Bundesen, 1988).

According to *the temporary loss of control* (TLC) hypothesis (Di Lollo et al., 2004) an input filter is configured to allow processing of targets and filter out distractors. However, this filter needs to be actively maintained by executive processes, which is not possible while these are occupied by consolidating T1 in VSTM. Thus during the period of T1 consolidation the filter is vulnerable to exogenous interference by distractors consequently leading to an AB.

The *boost and bounce theory* (Olivers & Meeter, 2008) suggest that VSTM is governed by gating mechanisms, which propagate feedback information to low level processing layers. If targets (according to the attentional set) arrive at VSTM a boosting mechanism enhances processing at lower layers, whereas if a distractor arrives a bounce inhibits processing thus resulting in an AB.

Attention capture hypothesis

Recently it was suggested that a conceptual link can be drawn between the AB and attention capture (Chua, 2005; Folk & Leber, 2008; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006; Maki & Mebane, 2006; Raymond et al., 1992; Shih & Reeves, 2007; Spalek, Falcon, & Di Lollo, 2006; Visser, Bischof, & Di Lollo, 2004). Attention capture typically refers to the involuntary perceptual engagement in an object that may be task relevant, thus causing task contingent capture, (Folk, Remington, & Johnston, 1992) or irrelevant resulting in stimuli driven capture (Theeuwes, 1992; Yantis & Hillstrom, 1994), see Burnham (2007) for recent review of attention capture literature.

The control condition in the AB paradigm serves as a way to examining the relation between attention capture and the AB. Here observers are asked to ignore T1 and merely report on T2 (Raymond et al., 1992). Thus by manipulating attributes of pre T2 items and observe the effect on T2 report it is possible to examine if the AB is prone to attention capture.

Evidence for both task contingent capture and stimuli driven exogenous capture have been reported in the AB literature. Support for task contingent attention capture comes from studies showing that observers fail to ignore T1, thus resulting in an AB, when T1 is shown in the same colour as T2 (Jolicœur et al., 2006) or shares target features in general (Spalek et al., 2006), when a distractor preceding T2 is outlined in a box with the same colour as T2 (Folk & Leber, 2008) or shares target features (Maki & Mebane, 2006; Visser et al., 2004). Exogenous attention capture has also been demonstrated to produce an AB, such that an irrelevant singleton object can produce and AB, and that the AB increases with the contrast of the object (Chua, 2005).

Thus the attention capture hypothesis suggests that an AB may be triggered by T1, or distractors sharing target features, which captures attention such that it cannot be reallocated efficiently in time for the appearance of T2.

Commonalities and conflicts between theories

The bottleneck models and the input filter theories generally agrees that processing occurs in two stages and that the first stage is fast and have inexhaustible resources. The dispute regards the functioning and limitations of the second stage, especially whether limited resources is at the core of the AB deficit, which is the claim of bottleneck theories (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicœur & Dell'Acqua, 1998). Critically, input filter theories (except the Interference theory) have been able to explain how lag-1 sparring can be extended to later lags such that several consecutive targets can be reported with little or no trade off on target accuracy (Olivers, Stigchel, & Hulleman, 2005), which is difficulty to explain by a limited capacity account. On the contrary recent studies have shown that an AB occurs even when no distractors precedes T2 (Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009), which is difficulty to explain by input filter theories. A key point at which the two types of theories disagrees is how the processing difficulty of T1 affects the AB. Bottleneck models suggests that the more difficult T1 is to process, the longer the processing time in the critical second stage, and thus the greater the AB, whereas the input filter theories does not makes such strong prediction since their main argument is that distractor interference is at the core of the AB.

The attention capture hypothesis stands on a different theoretical framework and have not yet been proposed as a comprehensive theory of the AB, more than a demonstration of a conceptual link to attention capture. Thus most of the evidence concerning the attention capture hypothesis in the AB literature, have sought to examine if capture manipulations would modulate the AB, and as such the hypothesis is not properly differentiated theoretically, and have not been tested on the key aspects that distinguish other AB theories e.g. spreading of lag-1 sparring, effects of T1 processing, and distractor interference. Theoretically, the attention capture hypothesis agrees with the bottleneck models, that the AB is a consequence of engaging in T1 (Folk & Leber, 2008), but contrary to bottleneck models suggest that if making T1 easier also increases T1 saliency, this should increase the AB (Chua, 2005). On the account of distractor interference the attention capture hypothesis suggests that distractors can increase the AB, if they share target features (Folk & Leber, 2008; Jolicœur et al., 2006), which is supported by input filter theories (Di Lollo et al., 2004), and bottleneck models, such that local interference of targets resembling distractors impose greater demands on second stage processing (Chun & Potter, 1995).

2.4 First target processing

The introduction of bottleneck models for the AB was offset with the two stage model (Chun & Potter, 1995) suggesting that the AB is caused by T1 processing depleting limited resources. The interference theory introduced earlier (Shapiro et al., 1994) agreed in that limited capacity was at the core of the AB, however it was implied that the depletion of resources occurred when items had to be extracted from VSTM, which is after the RSVP stream has ended. The coincidence of these theories with contrast in predictions produced a line of research examining if T1 processing indeed affected the AB, which was done by manipulating T1 difficulty.

Part of this research lends it self to an examination of the apparent contrast in predictions between the attention capture hypothesis and the bottleneck models regarding how T1 difficulty affects the AB if T1 saliency is also varied. According to bottleneck models making T1 easier to perceive should reduce the AB, whereas the attention capture hypothesis suggest that if making T1 easier to perceive increases T1 saliency, this should increase the AB.

The effects of data-limited manipulations

T1 manipulations where both difficulty and saliency is varied can be characterized as *data-limited* manipulations, for which the perceptual quality of stimuli is varied by masking, or by manipulating stimuli attributes such as target contrast and exposure duration, as opposed to *resource-limited* manipulations varying the task or introducing distractors to occupy attentional resources (Norman & Bobrow, 1975).

When reviewing of the literature concerning data-limited T1 manipulations, the results are inconsistent. Mclaughlin, Shore and Klein (2001) varied T1 exposure duration in three conditions reciprocally with the mask duration such that the total target and mask duration was constant between conditions. Observers were presented with the skeletal paradigm and the T1 manipulations were mixed within blocks, however, the authors reported no effect on the AB in this study.

Shore, Mclaughlin, and Klein (2001) conducted a similar study, in which the T1 conditions where shown between blocks, and found that in blocks where T1 exposure duration was short the AB was greater than in blocks when it was long. They interpreted their finding as being in support of the bottleneck theory, such that when T1's exposure duration was long less time in the critical second stage was required, compared to when T1's exposure duration was short. Christmann and Leuthold (2004) varied T1 contrast in three conditions in a RSVP stream and presented observers with the T1 manipulations between blocks. The authors found a greater AB when T1's contrast was low compared to when it was high, and concluded that their findings were in accordance with the bottleneck theory since the more difficulty T1 caused the greatest AB. Seiffert and DiLollo (1997) varied the difficulty of T1 between blocks in an RSVP stream by the time between T1 and its subsequent distractor, which acted to degrade the sensory quality of T1 when the time between T1 and its distractor was short compared to when it was long. In further support of the bottleneck theory, the authors found that the AB was greater in blocks where T1 was difficult compared to when it was easy.

Chua (2005) varied T1 contrast in three conditions within blocks in an RSVP stream, and found that when T1 contrast was high, T2 accuracy decreased. The author concluded that the results were according to an attention capture hypothesis, such that a high contrast T1 captures attention thus preventing efficient reallocation of resources to T2 in time for its appearance.

These findings suggests that (1) bottleneck effects of data-limited T1 manipulations thrive when conditions are blocked, and (2) that two effects with opposite direction may occur when T1 contrast is varied, such that attention capture effects increases the AB since T1 saliency increases, while bottleneck effects reduces the AB because T1 gets easier to perceive.

3 Psychophysics of luminance contrast

3.1 Perception of light

We perceive the world in a relative fashion, meaning that to distinguish two objects emitting or reflecting light a greater difference in absolute luminance between the two is required for very bright objects compared to dim ones. Thus it is easy to perceive even a very small luminance increment on a black display, but impossible on a bright display.

Steven's power law formalizes the psychophysical relationship between stimuli intensity and sensation, which state that "equal stimuli ratios produce equal subjective ratios" (Stevens, 1957). The perceptual scale for the visual sensation of light is called *brightness*. It is an arbitrary measure of the subjective sensation and has no physical interpretation. Equation 1 formulates Steven's power law relating brightness perception, B for an object presented on a dark display with luminance L.

(1) $$B = 10 \cdot L^{0.33}$$

Importantly Steven's power law captures the relative properties of sensation, which Figure 3.1 demonstrates. Here brightness perception is depicted as a function of luminance. The dashed lines illustrate that a 20 cd/m^2 luminance increment on a 0 cd/m^2 display give rise to a visual sensation which is nearly four times as great than a similar luminance increment viewed on a 20 cd/m^2 display.

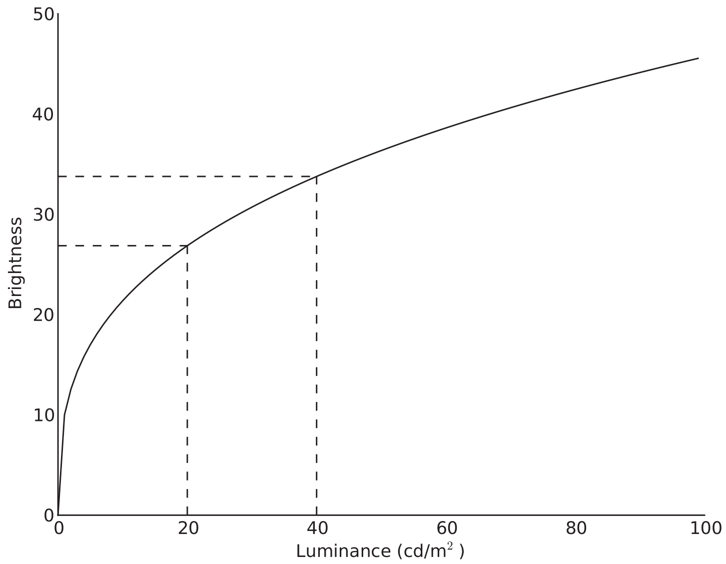

Figure 3.1. Illustration of Steven's power law relating physical light (luminance) to the subjective visual sensation of light (brightness). The relative properties of sensation is captured by Steven's power law, and it is exemplified in the figure showing that a luminance increment of 20 cd/m^2 on a black 0 cd/m^2 display give rise to an order of magnitude greater sensation that a corresponding increment on a 20 cd/m^2 display (measured by the brightness on the vertical axis).

3.2 Contrast measures

Thus it is the relative level of luminance intensity to the immediate surroundings that matters for perceiving our environment, not the absolute one. Luminance contrast refers to the relative variation in luminance intensity and determines the visibility of an object on a surface.

Weber's contrast

Depending on the application different types of contrast measures can be used. For relative small stimuli on a large homogeneous background *Weber's contrast* is suitable (see Equation 2) as it describes the difference in absolute luminance between an object, L, and its background, L_0, relative to the background luminance, L_0. Thus geometrically formulated it describes the relative distance in luminance space of an object to the background, which is what is perceived when viewing an object displayed on a homogenous background.

(2) $$Wc = \frac{L - L_0}{L_0}$$

As Equation 2 implies the measure given by Weber's contrast relies strongly on the background luminance and the measure is thus not comparable across conditions using different luminance settings for the background. Figure 3.2 illustrates this and shows Weber's contrast measures for three different background luminance settings. The range of Weber's contrast measures scales inversely with the background luminance, such that when the background approaches 0 cd/m^2 the measure approaches infinity. This means that two objects, which are equivalent in terms of visibility but displayed on backgrounds with difference luminance settings, will not yield identical Weber's contrast measures. For instance, in a condition where an object of 75 cd/m^2 is shown on a 25 cd/m^2 display the Weber contrast would be 2, whereas in the opposite situation, where the display is 75 cd/m^2 and the object is 25 cd/m^2 the contrast measure obtained using Weber's contrast is different[1], ~0.67, despite the corresponding brightness perception is the same according to Steven's power law (see Equation 1), since the stimuli ratios are the same[2]. However, that Weber's contrast scales with the background luminance gives it linear properties with respect to luminance, such that a linear step in Weber' contrast corresponds to a linear step in luminance. Also, the background luminance signifies the balance of the bright and dark polarity range, thus when the background luminance is half the luminance range of the display (as in the 50 cd/m^2 condition in Figure 3.2), the bright and dark polarity range is perfectly balanced.

[1] It may be that it is easier to perceive bright stimuli on a dark background that the other way around, however, for sake of example any polarity preferences are disregarded.

[2] In the first situation the object luminance is three times as bright as the background, whereas in the latter it is three times as dark.

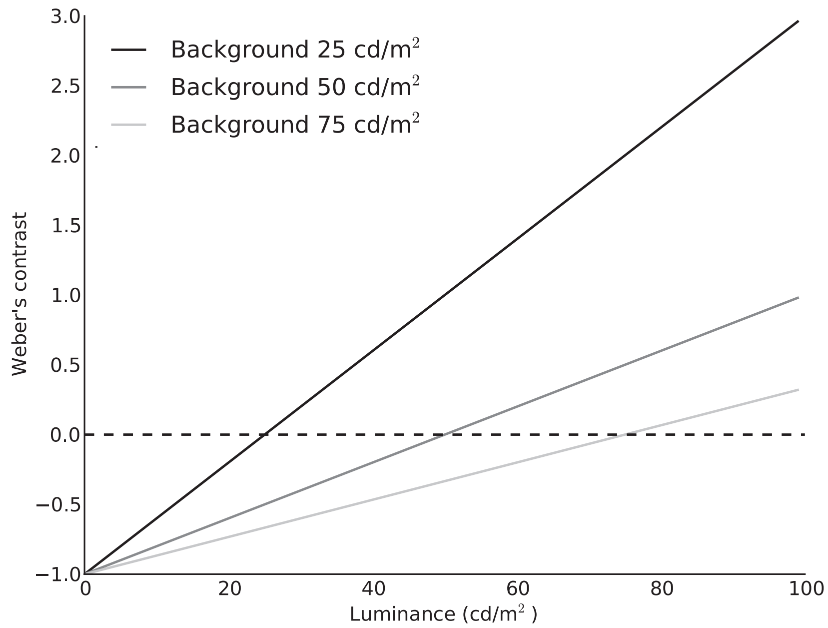

Figure 3.2. Illustration of contrast measures using Weber's contrast (see Equation 2) for three different settings of background luminance. The sign of the measure signifies the contrast polarity such that a negative value indicates that the object for which a measure is taken is darker that the background vice versa. The luminance range on the horizontal axis corresponds to the typical luminance response of a CRT monitor. Note that the contrast range scales inversely with the background luminance.

Michelson's contrast

Michelson's contrast (see Equation 3) is useful for measuring the contrast between adjacent points in space, defined by L_{max} ad L_{min}, with no assumptions of homogeneity of surroundings or background luminance. It provides a measure that can be characterized as half of the peak-to-peak luminance fluctuations across a display (Pelli, 1981).

(3) $$Mc = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

The measure is particularly useful when using sinusoidal gratings such as Gabor patches, where the desired measure is the local contrast within the object and not the contrast between the object and the background. Michelson's contrast is also useful when an object is displayed on a homogenous background, since the measure is invariant to the background luminance settings. For instance, given the situation from the previous section where two stimuli conditions had identical luminance ratios (25 cd/m^2 object on 75 cd/m^2 display or the other way around) thus yielding the same perceptual sensation, Michelson's contrast measure is 0.5 in both conditions with a negative sign on the measure describing a dark object on a bright display. However, using Michelson's contrast for objects on homogenous displays yields a non-linear luminance to contrast response vice versa, see Figure 3.3.

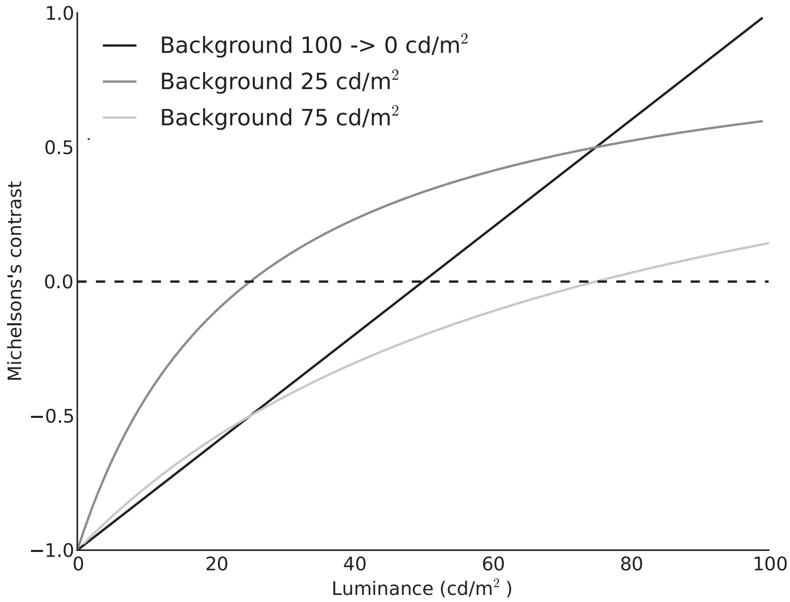

Figure 3.3. Illustration of Michelson's contrast measure for different settings of background luminance. The first condition (black line) corresponds to an object traversing the luminance range 0 -> 100 cd/m^2 (horizontal axis) while the background traverses the luminance scale in the opposite direction from 100 -> 0 cd/m^2 thus mimicking a Gabor patch where the polarity changes as the dark part of the grating goes from min to max luminance while the bright part of the grating goes from max to min luminance. The middle and light gray conditions illustrates the non-linearity of the measure when used for objects presented on static luminance background, and each represent an objects traversing the luminance range on the horizontal axis. The sign of the measure signifies the contrast polarity such that a negative value indicates that the object is darker that the background vice versa. The luminance range on the horizontal axis corresponds to the typical luminance response of a CRT monitor.

3.3 Technical issues

Precision of contrast measures

Typical graphics cards have 8 bits output resolution, which means that the luminance range of a display is represented by 256 discrete steps. This imposes constraints on the precision with which luminance can be varied on a display, which becomes particularly relevant when using adaptive procedures to estimate contrast thresholds for individuals (see section 3.4).

The resolution of numerical values on computers are typically 32 or 64 bit and have little in common with the physical reality of the displays 8 bits luminance range. Thus when using computers to approximate contrast thresholds, the estimate is quantized to the nearest luminance increment which can be realized on the display.

To assess the precision with which contrast thresholds can be reported with, the relation between the output resolution of the graphics card in luminance and the contrast measures needs to be established.

Michelson contrast can be rewritten as the difference between the background luminance L_0 and a luminance increment / decrement ΔL as shown in Equation 4 below.

$$(4) \qquad \Downarrow Mc = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

$$\Downarrow Mc = \frac{L_0 + \Delta L - (L_0 - \Delta L)}{L_0 + \Delta L + L_0 - \Delta L}$$

$$Mc = \frac{\Delta L}{L_0}$$

Weber's contrast can be rewritten similarly in a simple fashion as shown in Equation 5.

$$(5) \qquad \Downarrow Wc = \frac{L - L_0}{L_0}$$

$$Wc = \frac{\Delta L}{L_0}$$

The minimum delta luminance, which can be issued by the graphics card is found as the maximum luminance response of the monitor divided by the output resolution of the graphics card as shown in Equation 6.

$$(6) \qquad \Delta L_{abs-\min} = \frac{L_{\max}}{2^{bits}}$$

Inserting Equation 6 into Equations 4 and 5 will thus find the minimum change in Weber's and Michelson's contrast respectively that will result in an actual luminance change on the display. As an example Equation 7 shows the smallest increment in Gabor contrast that can be realized on a display.

(7) $$\Delta Mc_{abs-\min} = \frac{\frac{L_{\max}}{2^{bits}}}{L_0}$$

As Equation 7 implies a better precision can be obtained by a high output resolution graphics card, lowering the max luminance response of the monitor (by reducing brightness on the monitor) or chose a higher background luminance.

Gamma correction of displays

Cathode ray tube, or CRT, displays were the first broadly distributed platform for showing media content to the greater audience. The general principle behind CRTs is that a cathode fires electrons on a phosphor surface across the display in a similar fashion as a typewrite traverses through a page of paper – only slightly faster. The voltage feed to a cathode determines the luminance intensity at any given point on the display. However, the transfer function of the cathode emitting light on the phosphor surface is non-linear, thus the intensity of luminance on a CRT display does not vary linearly with the voltage input.

Equation 8 shows the transfer function for a CRT display where L is the luminance measured on the CRT with a photometer, V is the voltage on the display input (which the digital values in a linear colour space, e.g. RGB are converted to), ß (beta) the offset of the function, which typically is in the range 80-120 depending on the maximum luminance a display can deliver, and γ (gamma) the exponent describing the non-linearity of the response, which is typically 2.2 but may vary from 1.8-2.4 between displays.

(8) $$L = \beta \cdot V^{\gamma}$$

Practically this means that to get a linear response in colour space to luminance on a CRT display the colour space needs to be corrected according to the non-linearity of the display. This can be done fairly straightforward, by adjusting the colour space with the reciprocal gamma value, thus yielding a linear response in luminance on the display, see Figure 3.4.

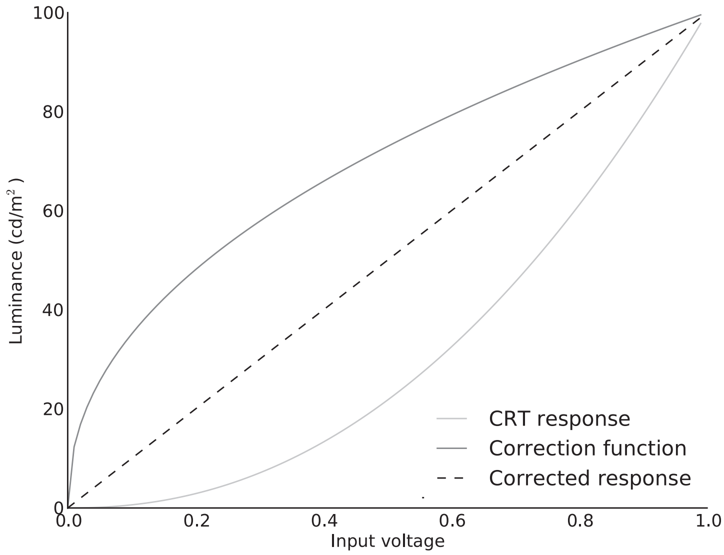

Figure 3.4 Illustration of the principle behind gamma correction. The light gray plot is the inherent non-linear CRT response described in Equation 8, the middle gray the correction function using the reciprocal gamma function, and the dashed black plot, the resulting gamma corrected linear response on the CRT.

Some types of stimuli assumes a linear response in luminance space - for instance additive noise drawn from a Gaussian distribution, which requires the colour space to be gamma corrected according to the principle shown in Figure 3.4. To achieve this, the transfer function needs to be estimated.

A straightforward approach to estimate the transfer function for a CRT is to obtain luminance measures for a continuum of colour space values and model the measures according to Equation 8. Figure 3.5 shows the non-linear response for a CRT monitor and the corresponding modelled gamma function, where the parameters were estimated to, beta = 117 and gamma = 2.13 based on 15 measurement points. As Figure 3.5 illustrates the methods is robust and the error between the estimate and measurements are very small and can be ignored for most purposes.

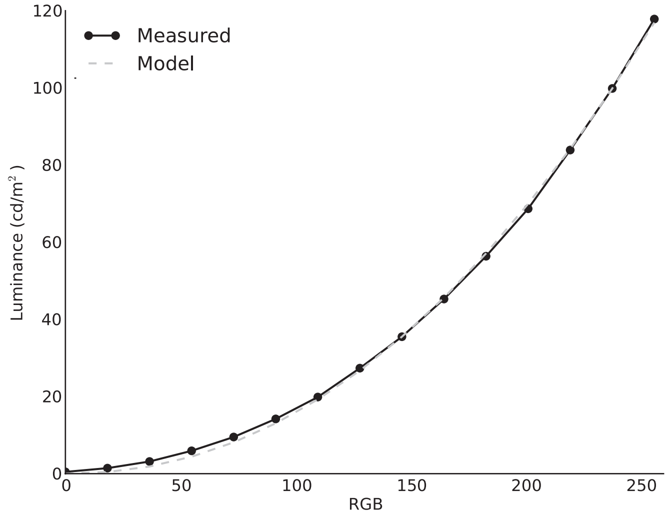

Figure 3.5. Luminance response as a function of RGB colour space (arbitrary scale) measured (solid black line) on a 21" ViewSonic G220f CRT display 42 min after it was turned on. The dashed light gray line show the modelled estimate of the response based on Equation 8 using the parameters ß = 117 and γ = 2.13.

Luminance response variations in displays

The luminance response of a CRT varies as the display warms up, which is a potential source of noise in data. Figure 3.6 shows how the beta and gamma parameters (see Equation 8) changes for a CRT display over the first 42 minutes since it was turned on.

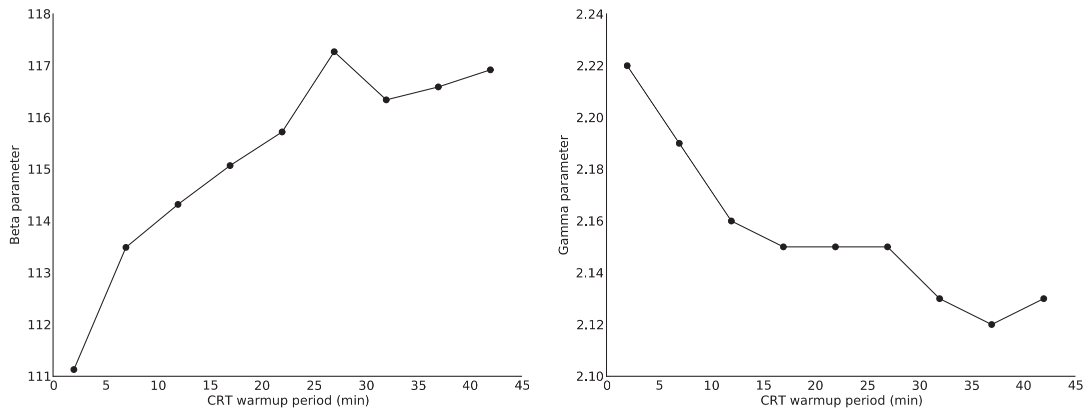

Figure 3.6. Illustration of beta and gamma parameters as a function of the time since a 21" ViewSonic G220f CRT display was turned on. The estimates are based on Equation 8.

As Figure 3.6 illustrates, the beta parameter increases while gamma decreases over time. As a consequence the RGB to luminance response varies accordingly while the CRT warms up, such that the luminance response to a given RGB value increases over time. Figure 3.7 shows the RGB to luminance response functions for a CRT after warming up for 2 minutes and 42 minutes (left subfigure) and the corresponding error function, which is the difference in absolute luminance response of the display after having warmed up for 42 minutes compared to 2 minutes (right subfigure).

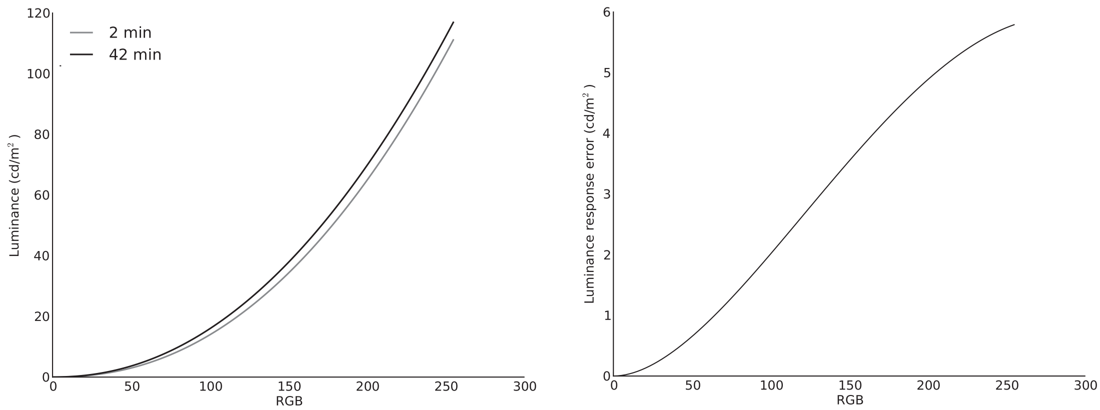

Figure 3.7. Luminance response error function for a 21" ViewSonic G220f CRT display. The graph shows the difference in RGB colour space to luminance response for measures taken when the display had warmed up for 2 minutes, compared to when it had warmed up for 42 minutes.

The practical implication of Figure 3.7 is that the luminance of a stimulus shown on a display, which is warming up varies over time. This may affect how easy the stimulus is to perceive over time, which is a potential source of noise in experiments. It is important to note that the results presented here are not universal to all displays. For instance, here the luminance response increased over time, whereas it may decrease for other displays.

3.4 Contrast sensitivity

The ability to perceive the richness of our environment relies on how well we can distinguish differences in light conditions between immediate points in space, that is, how sensitive we are to contrast. The *contrast sensitivity function* (CSF) is a useful method to assess sensitivity to contrast in individuals. The CSF is the inverse Michelson's contrast threshold for detecting a sinusoidal grating as a function of the grating's spatial frequency (Watson, Barlow, & Robson, 1983). It has been demonstrated that the CSF varies across adulthood with poorer perception of high frequency gratings in elderly (Owsley, Sekuler, & Simens, 1983), meaning that perception of highly detailed information is reduced with age. Also, the CSF varies between individuals (Peterzell, 1996) and recently it was found that action videogame playing can improve the CSF in individuals (Li, Polat, Makous, & Bavelier, 2009).

Individual differences in a matched normal population

In a study, which is not included as a formal part of this thesis, colleagues and I investigated how the CSF was affected in patients with pure alexia compared to a matched control group (Starrfelt, Nielsen, Habekost & Andersen, in prep). The control data from this study allows for an examination of how contrast sensitivity varies in a very comparable[3] normal population.

Ten observers conducted a two-interval forced choice detection task[4] where they had to detect in which of two intervals a Gabor patch occurred. Observer's contrast thresholds were estimated for six different Gabor frequencies[5], and the CSF was estimated for each observers based on these thresholds.

The results are illustrated in Figure 3.8 showing the mean CSF for all ten observers (solid black line) and the individual CSFs for each of the ten observers (dashed light gray lines). Visual inspection of the graph suggests that the CSF varies substantially across observers, which is confirmed when analysing the data using a two-way ANOVA (Observer x Gabor frequency) that reveals a significant difference in CSF across observers [$F(9,45) = 18.13$, $p = 0.02$].

Conclusively these data show that even in a very comparable (matched) normal population contrast sensitivity differs, which emphasizes the importance of correcting for individual differences in contrast sensitivity when manipulating contrast, which is the topic of the next section.

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[3] It is assumed that the control group have similar cognitive abilities due to the homogeneity of the factors, which they were matched on.

[4] As part of the study other experiments were included, however since these are irrelevant for the argument they have been left out for sake of simplicity.

[5] Gabor frequency refers to the spatial frequency of the sinusoidal grating, which are measured in cycles per degrees of visual angel.

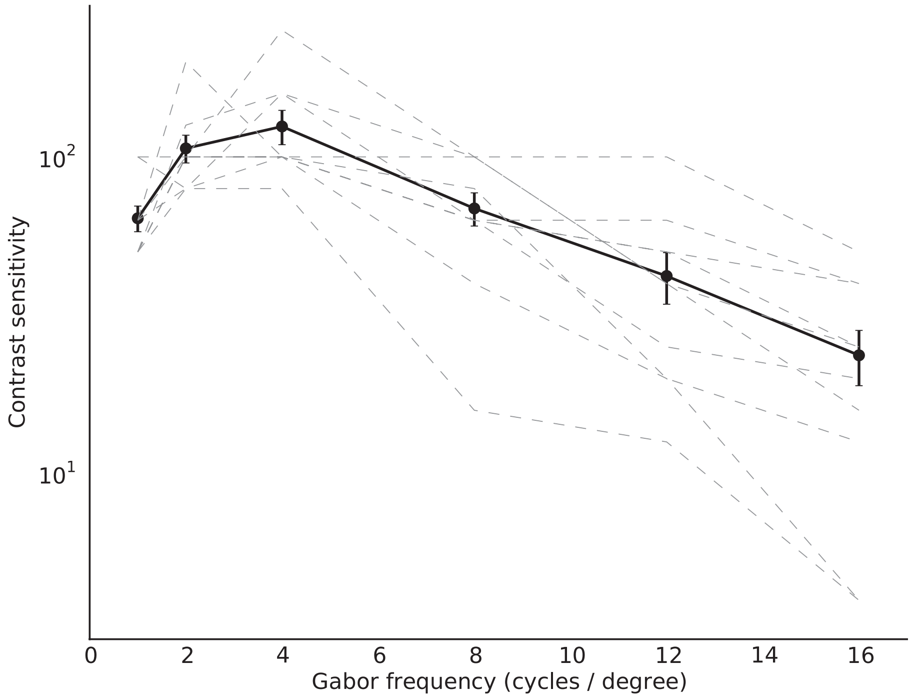


Figure 3.8. Contrast sensitivity function (CSF) for ten matched observers. The contrast sensitivity is calculated as the reciprocal contrast thresholds and is here plotted as function of the spatial frequency of the Gabor patches. The black graph represents the mean of the ten observers, with error bars signifying the standard error of the mean. The dashes light gray graphs illustrates each individual observer's CSF. Note that despite relatively small standard errors on the mean values, the variation in contrast sensitivity from observer to observer is relatively large. The typical pattern for the CSF is as showed here, that contrast sensitivity is greatest in the 2-4 Hz range with a gradual decline towards higher frequencies.

Correcting for individual differences

Given the variation in contrast sensitivity between individuals, this thesis has emphasized to correct for individual differences. To this end adaptive staircase procedures were used to estimate observers individual contrast thresholds corresponding to a desired report accuracy level.

Approximation methods

Two methods have examined in the thesis for determining individual contrast thresholds for observers. *Stochastic approximation* (Robbins & Monro, 1951) is an adaptive procedure, which approximates an intensity level, such as contrast, corresponding to a response accuracy level – see Treutwein (1995) for a review on approximation methods. In Equation 9 the stochastic approximation methods is formulated: n denotes the current trial number, thus X_{n+1} is the contrast level for the next trial, X_n the contrast level for the current trial and c an initial step size. Z_n

is the response, thus in report accuracy paradigms this is either 1 or 0 for hit and miss, and ϕ the desired report accuracy ranging from 0 to 1.

$$(9) \qquad X_{n+1} = X_n - \frac{c}{n}(Z_n - \phi)$$

Thus when progression through trials, the next contrast level is updated such that a correct response will result in an decrement in contrast level and an incorrect response an increment in contrast level, where the step size decreases with the number of trials traversed.

The critical aspect of using adaptive procedures is the number of trials it takes to approximate a level – and the integrity of the threshold of course. Kesten (1958) suggested an improvement of the stochastic approximation method, *Accelerated stochastic approximation* (Equation 10), which converges in fewer trials, due to the size of the step being updated based on the number of reversals, $m_{shift,}$ that is, how many times the response has flipped between correct and incorrect vice versa.

$$(10) \qquad X_{n+1} = X_n - \frac{c}{2 + m_{shift}}(Z_n - \phi), n > 2$$

For $n < 2$, the method follows that of Equation 9, however for $n > 2$, the step size scales with the number of reversals. The logic behind this formulation is that the number of reversals is a more efficient indicator of when a threshold is reached than the number of trials progressed. Thus, letting the step size be equal to the initial step size until a reversal in response occurs, traverses the contrast range towards the threshold faster than when the step size is scaled on every trial.

An example: estimating thresholds using accelerated stochastic approximation

In Publication 2, Experiment 2A, we wanted to obtain identical report accuracy levels for two different stimuli conditions. One conditions had noise added to it and as consequence was more difficulty to perceive thus requiring a greater contrast level to obtain the same report accuracy level as a condition without noise.

Observers were tested in the RSVP paradigm and individual adjustment sessions were devised, using the accelerated stochastic approximation method to estimate the contrast thresholds. The accuracy level was set to 0.8, the initial step size to 0.3 Weber's contrast, and the routine terminated after 15 reversals in both conditions.

Figure 3.9 shows the results from the two adjustment sessions for a single observer. The T1 High graph corresponds to the condition with noise and the T1 Low is the condition without noise. The estimation of the thresholds develops across trials and gradually converges as the step size decreases. After 15 reversals the routines terminated. As expected the T1 High condition with noise required a greater contrast level -0.36 compare to the T1 Low condition without noise, -0.19. Across the 13 participants in the experiment the average accuracy level in the T1 High condition was 0.80 (std 0.03) and 0.83 (std 0.04) in the T1 Low condition, which reflects the robustness of the approach.

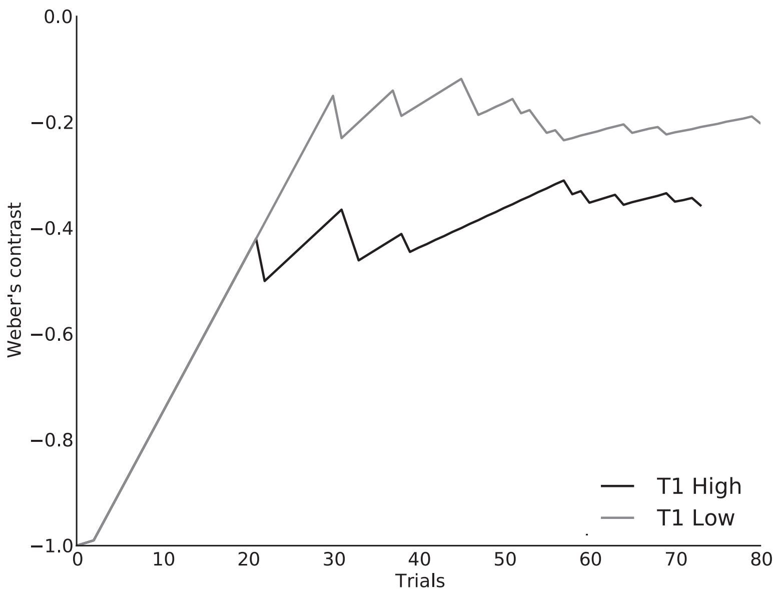


Figure 3.9. Illustration of adaptive staircase procedure using the accelerated stochastic approximation method for a single observer in Publication 2, Experiment 2A. The graphs show the gradual approximation of contrast levels across trials required for the observer to reach an 80% report accuracy threshold in a condition with noise requiring a relative high contrast (T1 High) and a condition without noise requiring a relative low contrast (T1 Low). The procedure is initiated with maximum contrast (-1; dark stimuli on gray background) at trial 1. The first incorrect reports are made near trial 20 and 30 for the T1 High and the T1 Low conditions respectively, after which the procedure begins to converge towards the threshold.

Efficiency of methods

As implied in the theory, on average the accelerated version approximates the thresholds using fewer trials than the non-accelerated version. However, due to the step size only being updated on trials where a reversal occurs the trajectory of the staircase is not very smooth, which visual inspection of Figure 3.9 confirms. This makes the accelerated version prone to converge at non-optimal values, since step sizes are relatively large even when the procedure terminates. Also, if misses that are not related to observers' perceptual ability (often due to inattention, habitation to the paradigm etc.), occurs while the step size is large, the trajectory may deviate from the observers optimal path to such extend than the threshold cannot be estimated properly. Most of these errors tend to happen in the beginning though, thus an initial buffer in the procedure where no correction are made in the first 10 trials, is an efficient means to overcome this problem.

The issues discussed above can be resolved at the cost of spending more trials using the non-accelerated method, which due to the gradual decrease in step size have a smoother trajectory and consequently have a finer estimate of the threshold, and is less sensitive to errors made by the observer. The apparent benefit of a finer threshold estimate, however, must be contrasted with the limited resolution in luminance imposed by the 8 bits graphic cards. For instance, in the example shown in Figure 3.9, the thresholds at which the procedures converged, compared to the previous contrast issued by the staircase, corresponds to a step in Weber's contrast of approximately 0.015 in both conditions. Using Equations 5 and 6, based on a max luminance response of 100 cd/m^2 and background of 50 cd/m^2, the minimum step-size in Weber's contrast that corresponds to a physical change in luminance on the display is 0.008. Thus, in the example shown in Figure 3.9 the staircase actually converged at a physical relevant threshold. However, had the non-accelerated version been used, assuming the same number of trials in the procedure, the step-size in Weber's contrast would be approximately 0.004, thus yielding a fictive value, that would only cause a physical change on the display at every second trial - a prognosis that would only worsen as the number of trials increases. Conclusively the accelerated version supersedes the non-accelerated version as it is more efficient in terms of trials used, and because the benefits in precision offered by the non-accelerated version cannot be realised on typical graphics cards with 8 bits output resolution.

3.5 Using visual noise

Visual noise added to stimuli can be used to vary the visibility of stimuli like exposure duration and contrast can. Often white noise is used since it simulates photon noise of the early visual system and that it is theoretically well defined (Pelli, 1981). White noise can be approximated using Gaussian noise, which has the nice feature that the standard deviation of the distribution determines the amplitude of the noise, which is (disregarding the frequency relation between noise and stimuli) what determines the visibility of stimuli. Signal-to-noise ratio is defined as the squared amplitude, or power, of the signal to the power of the noise. Thus the signal-to-noise ratio of stimuli with Gaussian noise can be estimated as the squared contrast of the stimuli, C^2 to the variance of the noise, σ^2 (see first part of Equation 11).

$$(11)\qquad \begin{aligned} &SNR = \frac{C^2}{\sigma^2} \\ &\Downarrow C = \sqrt{SNR \cdot \sigma^2} \end{aligned}$$

Using additive Gaussian noise has the nice property that the stimuli contrast can be varied independently of the visibility of stimuli. Sampling noise from two Gaussians with different standard deviations and adding them to stimuli will require a greater contrast in the condition with more noise (indexed by the standard deviation) compared to the condition with less noise, which is also illustrated in Figure 3.9.

4 Target contrast and attention capture in the attentional blink

This thesis examines how attention capture influences the AB. Recent studies suggests that pre-T2 items, such as T1 and distractors / masks, captures attention and thus prevents efficient reallocation of attention to T2 (Folk & Leber, 2008; Maki & Mebane, 2006; Visser et al., 2004). Specifically the current work focuses on attention capture in response to target contrast, while controlling for bottleneck effects acting to improve the AB (Chun & Potter, 1995; Christmann & Leuthold, 2004), which have been disregarded in previous studies (Chua, 2005). To this end target contrast is manipulated in the two-target and RSVP paradigms while individual differences in contrast sensitivity are taken into account.

4.1 The effect of first target contrast with targets in different locations

The outset of this thesis is an examination of the effect of T1 contrast in the two-target paradigm, which is presented in Publication 1. Here we address the effect of T1 contrast isolated from other potential effects imposed by experimental paradigms, and to this end the two-target paradigm is a promising candidate due to its inherent simplicity: there are no distractors, which may influence the AB according to input filter theories e.g. (Di Lollo et al., 2004), and targets are presented in spatially distinct locations thus preventing forward masking effects from distractors occurring before a target (Spencer & Shuntich, 1970), and lag-1 sparring effects (Chun & Potter, 1995). To control for across-observer difference in contrast sensitivity we adjusted observers individually using adaptive staircase procedures (accelerated stochastic approximation; Kesten, 1958). In separate sessions, observer's contrast thresholds were estimated based on predefined report accuracy levels. Thus bottleneck effects are maintained constant across observers, assuming that report accuracy is an indicator for processing difficulty.

No effect of first target contrast when the first target is masked

In Experiment 1A, we presented observers with two targets in different locations, and masked targets using pattern masks following a 100 ms. delay thus acting as interruption masks. Two conditions of T1 contrast were devised such that T1 accuracy was approximately 65% in a low contrast condition and 85% in a high condition. Contrast thresholds were determined individually for observers. What The results from Experiment 1A shows that T1 contrast does not significantly affect T2 accuracy across T1 conditions under these conditions. However, Visser and Ohan (2007) previously reported that effects of T1 manipulations were only evident when a backward patterns mask was omitted from T1. Thus it is likely that Experiment 1A were also confounded by the presence of a backwards pattern mask following T1, which we examined in the next experiment.

Unmasking the first target reveals attention capture effects of first target contrast

Experiment 1B test if the presence of T1's mask had influenced the results presented in Experiment 1A, such that an effect of T1 contrast was concealed by the presence of T1's mask, similarly to what was reported in Visser and Ohan (2007). Thus Experiment 1B is a replication of Experiment 1A, with the exception that T1's mask was omitted. The results from Experiment 1B shows that the magnitude of the AB increases with T1 contrast, such that T2 accuracy was lower in the high T1 condition compared to the low T1 condition, which is according to the attention capture hypothesis and to what Chua (2005) found. That the effect of manipulating T1 was only evident in Experiment 1B, when T1 was unmasked is consistent with what Visser and Ohan (2007) found. The influence of T1's masks may be attributed to, that interruption masks interrupt target processing at a central stage, which effectively equates processing difficulties across conditions (Visser, 2007; Jolicœur et al., 1998). Another explanation is that T1's mask it self attracts attention, and that this attention capture effect cancels or 'masks' the effect of T1 contrast. The mask was more salient than T1 since it was presented in a much higher contrast. Thus it is likely that the saliency of the mask determined the capture effect, which the relative small difference in contrast between T1 conditions had little influence on.

Attention capture effects of first target contrast when bottleneck effects are eliminated

The effect of T1 contrast found in Experiment 1B was confined to a single point. However, it is likely that Experiment 1B was influenced by bottleneck effects acting to suppress the capture effect of T1 contrast, since T1 was also easier to perceive in the high contrast condition. Thus Experiment 2 examines the attention capture effect to T1 contrast when bottleneck effects are eliminated. To this end T1 contrast was varied while T1 accuracy was maintained constant across T1 conditions, which was achieved using Gaussian noise. Two T1 conditions were devised with noise sampled from Gaussians with different standard deviations, such that to achieve the same report accuracy level across conditions it required a higher T1 contrast in the condition with more noise (T1 high condition) compared to the condition with less noise (T1 low condition). Observers contrast thresholds corresponding to 80% report accuracy were determined individually for the low T1 condition. The contrast for the high T1 condition was estimated based on the signal-to-noise ratio obtained in the adjustment session for the low T1 condition using Equation 11. The T2 condition was identical to the T1 low condition. Consistent with Experiment 1B, the results from Experiment 2 shows that AB magnitude increases with T1 contrast, such that T2 accuracy was lower in the high T1 condition compared to the low T1 condition, which is according to the attention capture hypothesis. The approach used to maintain T1 accuracy constant across T1 conditions was not optimal. The results show a significant 4% increase in accuracy in the high T1 condition compared to the low one, which however, due to the relatively small improvement in report accuracy is assumed to have little influence on the main findings. Thus maybe the signal-to-noise measure (Equation 11) does not perfectly describe the visibility of stimuli. However, an alternative explanations is that the increased attention to the high T1 condition, which consequently led T2 accuracy to suffer, may have improved T1 processing and thereby report accuracy – matters that cannot be resolved based on the data.

4.2 The effect of first target contrast with targets presented in the same location

Publication 1 shows that the AB increases with T1 contrast, which lends support to an attention capture hypothesis. However, the effects reported in Publication 1 may be purely spatial since targets were presented in different locations. Thus Publication 2 extends the studies from Publication 1 to the strictly temporal domain. To this end we varied target contrast in the RSVP paradigm, which also allowed us to more specifically compare our results to those reported in Chua (2005), in which the RSVP paradigm was used.

Attention capture effects of first target contrast are not just spatial

Experiment 1 test if the findings reported in Publications 1 and those reported by Chua (2005) can be replicated. We devised three conditions of T1 contrast and adjusted observers individually, such that T1 accuracies where approximately 50% in a low T1 condition and 85% in a medium T1 condition. A high T1 condition was determined based on twice the contrast obtained in the medium T1 adjustment session. This condition was inspired by Chua (2005), which reported an effect of T1 contrast only when T1 accuracy was in ceiling. The T2 condition was identical to the medium T1 condition. Consistent with our previous findings and with those in Chua (2005), the results from Experiment 1 shows that the AB increases with T1 contrast, such that T2 accuracy was lower in the medium and high condition, compared to the low T1 condition, which is according to an attention capture hypothesis. In addition we found that T2 accuracy was lower at lag 1 in the high T1 condition compared to the medium and low T1 condition, which is surprising since T2 accuracy is typically sparred at lag 1 (Chun & Potter, 1995). The effect was most likely caused by forward masking of the relatively low contrast T2 by the relatively high contrast T1, which is consistent with studies showing that forward masking increases with the contrast of the masking object (Spencer & Shuntics, 1970).

Attention capture effects of first target contrast when bottleneck effects are eliminated

Experiment 1 may have been influenced by bottleneck effects since T1 was also easier to perceive in the high contrast T1 conditions, in which capture effects was reported. Thus Experiment 2A test the effect of T1 contrast when bottleneck effects are eliminated, which was achieved by teasing apart the effect of T1 contrast from the effect of T1 difficulty similarly to what we did in Publication 1, Experiment 2. We devised two T1 contrast conditions with different contrast levels, high and low, but similar report accuracies across conditions. Since Publication 1, Experiment 2 showed that that the signal-to-noise ratio measure in Equation 11 does not precisely reflect the identifiability of the noise targets we adjusted observers individually in both T1 conditions and found their contrast thresholds corresponding to a report accuracy of 80%. The T2 condition was set to be equal to the T1 low condition. Consistent with our previous findings and the attention capture hypothesis the results from Experiment 2B shows that the AB magnitude increases with T1 contrast. Again, we found an effect of T1 contrast at lag 1, which most likely is due to forward masking from the high contrast T1.

Second target contrast cancels the effect of first target contrast

In Experiment 2A, and Experiment 2 in Publication 1, the T2 condition was identical to the low T1 condition. However, there may be an effect of T1-T2 contrast, which these experiments thus not reveals since they merely test one of the conditions, that is, when T1 is high and T2 is low. Therefore, Experiment 2B test what the effect of a high T1 contrast is when T2 contrast is also high. To this end Experiment 2A was replicated in Experiment 2B, with the exception that the T2 condition was equal to the high T1 condition. The results from Experiment 2B shows that a high T1 contrast does not affect the AB when T2 contrast is also high, such that no difference was observed on the AB between T1 conditions. These findings may reflect that T2 it self had captured attention, and thereby cancelled the effect of T1 attention capture, which is consistent with studies showing that T2 saliency modulates the AB irrespectively of T1 saliency (Shih & Reves, 2007). There are however other possible explanations. In Experiment 2A, only the high T1 condition was presented with noise, whereas the low T1 and the T2 conditions were presented with negligible little noise. Thus it is likely that the high contrast T1 have acted as a singleton object, and captured attention by means of being a singleton (Chua, 2005; Wee & Chua, 2004) more than due to T1's contrast to the background. However, this explanation is unlikely since both stimuli in Publication 1, Experiment 2, had noise added to them, and here we observed the same effect. Another possibility is that in Experiment 2A, the high contrast condition masked the (low contrast) T2 condition. However, it is unlikely that sensory masking effects extend beyond 150 ms. (Spencer & Shuntich, 1970), which corresponds to the T1-T2 delay at which effects of T1 contrast was observed in both Publication 1 and 2. The absence of an effect of T1 contrast at lag 1, further emphasizes that forward masking have caused these previously reported effects in Experiment 1 and 2A. Forward masking effects are expected to be reduced here when T1 is presented in a lower or similar contrast than T2, compared to Experiment 1 and 2A, where it was presented in a higher contrast in the conditions where the effect was observed.

4.3 General discussions

Bottleneck and attention capture effects of first target contrast

The effect of target contrast reported here is consistent with an attention capture hypothesis, and with what Chua (2005) found. However, despite T1 accuracy was controlled across observers, the results from Publication 2, Experiment 1, is inconsistent with predictions from bottleneck models suggesting that making T1 easier to perceive should improve the AB e.g. (Chun & Potter, 1995). Since observers perceived T1 approximately equally efficiently in Publication 2, Experiment 1, based on their report accuracy, we would expect the AB to improve in the medium T1 condition compared to the low T1 condition, similarly to what was reported in Christmann and Leuthold (2004), which we did not. This may be attributed to the blocked design used in Christmann and Leuthold (2004), which have been shown to promote bottleneck effects (Shore et al., 2001).

However, it emphasizes a more interesting point that the effect of attention capture and bottleneck effects may co-exist in the AB paradigm.

Here we examined attention capture effects of T1 contrast, future studies should address the relation between attention capture and bottleneck models. On a more speculative account attention capture and a perceptual bottleneck may to a large extend explain the AB, such that the mechanism with which resources are allocated are best described by attention capture, while the effect of T1 and distractors may limit perception of T2 in two ways. T1's that are more difficult to process may occupy resources longer according to bottleneck models. However, a T1 likely to capture attention may cause an inefficient allocation of resources, such that more resources are allocated / locked for a longer period, that what is required to process the target. Similarly, distractors prone to attention capture due to targets resemblance may be allocated additional resources. In effect the consequence is less resources available for T2 processing. Thus the functional implication of attention capture may be that less resources are available to process subsequent targets, which is consistent with bottleneck models and may also describe the results presented here. This interpretation is also consistent with what recent studies have suggested (Dux, Asplund, & Marois, 2008), and it would be worth while to pursue studies in which the bottleneck effects are examined in isolation of capture effects, in a similar fashion as attention capture effects was examined here.

Effects of target-distractor contrast

The effect of T1 contrast reported in Publication 2, Experiment 1, may pertain to the target-distractor contrast more than the contrast between T1 and the background. The distactors were always presented in the highest contrast. Thus the medium and high contrast T1 conditions in which we reported attention capture effects were also the conditions where targets resembled distractors the most, which have been found to increase the AB (Raymond et al., 1992: Chun & Potter, 1995; Di Lollo et al., 2004). However, this explanation is unlikely to account for the effect reported in Publication 2, Experiment 1, since we observed the same effect in Publication 1, Experiment 1B, when no distractors were present. Also, the same effect was reported in Chua (2005), when distractors were presented in a lower contrast than the targets. Thus in Chua (2005) the high contrast condition in which capture was reported was also the condition where targets resembled distractors the least.

5 Conclusion

The purpose of this thesis was to determine the effect of target contrast on the attentional blink (AB; Raymond et al., 1992), with emphasis on examining the relationship to attention capture. To this end, target contrast manipulations were devised in two paradigms. Publication 1 details on the study of first target contrast effects when the AB is examined in the two-target paradigm (Duncan et al., 1994; Ward et al., 1996) where two masked targets (T1 & T2) are presented in different locations. The effects of target contrast was also examined in the RSVP paradigm (Potter & Levy, 1969), in which T1 and T2 are in the same location in a stream of distractors. These results are presented in Publication 2.

Publication 1, Experiment 1 shows that increasing T1 contrast in the two-target paradigm causes an increase in the AB, when T1 is not masked. The effect of T1 contrast reported in Publication 1 may have been purely spatial since the identification of targets required shifts of attention to new locations. Publication 2, Experiment 1, however, replicated the findings from the two-target paradigm using the RSVP paradigm in which targets are presented in the same location thus eliminating the spatial shift. The findings comply with an attention capture hypothesis, and suggests that the effect does not pertain to spatial shifts of attention but may be more central to the functioning of attention.

In Experiment 1 in Publication 1 and 2, T1 contrast varied, which consequently affected the identifiability of the target such that T1 was reported with higher accuracy when T1 contrast was high compared to when it was low. According to bottleneck models (Chun & Potter, 1995) this may improve target processing in a critical second stage, which could reduce the AB. Thus to eliminate potential bottleneck effects, in Experiment 2 of Publication 1 and 2, the effect of T1 contrast was disentangled from how easy the target was to identify (using Gaussian noise). Here the effects of T1 contrast reported previously in Publication 1, Experiment 1A and Publication 2, Experiment 1, were replicated in both the two-target paradigm (Publication 1, Experiment 2) and the RSVP paradigm (Publication 2, Experiment 2A).

The effects of T1 contrast described above were cancelled by the opposing effect of T2 contrast, such that no difference in T2 accuracy was observed across T1 contrast conditions when T2 was shown in the same contrast as the high T1 condition (Publication 2, Experiment 2B). This effect is most likely due to T2 it self capturing attention, which is consistent with what Shih and Reeves (2007) found, showing that T2 saliency modulates the AB irrespectively of T1 saliency.

Publication 2 showed that a high contrast T1 reduced T2 accuracy at lag 1 when T1 was presented in a higher contrast than T2 (Experiments 1 and 2A) - an effect, which disappeared when T1 was presented in a similar or lower contrast as T2 (Experiment 2B). This effect is most likely due to forward masking such that the reduction in T2 accuracy observed at lag 1 was due to T1 forward masking of T2 - an effect that is known to increase with the contrast of the masking object (Spencer & Shuntich, 1970).

In Publication 1, Experiment 1, the effect of T1 contrast was significant only when no mask followed T1, thus suggesting that the mask interfered with the effect of T1 contrast. One explanation is that T1's mask it self captured attention, and that this effect cancelled the capture effect of T1 contrast – a notion that is supported by studies showing that irrelevant items can capture attention in the AB paradigm (Chua, 2005; Wee & Chua, 2004). Another explanation is that, since T1's mask was presented as an interruption masks it is likely that target processing was interrupted at a central stage, which effectively equated processing difficulties across conditions (Visser, 2007; Jolicœur et al., 1998) – matters that cannot be resolved based on the data.

Conclusively the results reported here, suggest that T1 attention capture can trigger an AB, and that the AB increases with T1 contrast unless T2 it self is highly salient. The results are consistent with an attention capture hypothesis e.g. (Folk & Leber, 2008) and does not lend support to bottleneck models suggesting that increasing T1 contrast may improve second stage processing and reduce the AB (Christmann & Leuthold, 2004; Chun & Potter, 1995). However, bottleneck models and the attention capture hypothesis are not properly differentiated to contrast the two theories based on these results, and it may very well be that the effect of attention capture and that of T1 processing in fact is complementary in describing the dynamics and functioning of the AB – topics for further studies.

6 References

Berthet, V. V., & Kouider, S. S. (2012). The role of spatial switching in the attentional blink. *Spanish journal of psychology*, *15*(1), 3–9.

Brehaut, J. C. J., Enns, J. T., & Di Lollo, V. (1999). Visual masking plays two roles in the attentional blink. *Perception & Psychophysics*, *7*, 1436–1448.

Breitmeyer, B. G. (1984). *Visual Masking: An Integrative Approach.* Oxford University Press, USA.

Breitmeyer, B. G., Ehrenstein, A., Pritchard, K., Hiscock, M., & Crisan, J. (1999). The roles of location specificity and masking mechanisms in the attentional blink. *Perception & Psychophysics*, *61*(5), 798–809.

Burnham, B. R. B. (2007). Displaywide visual features associated with a search display's appearance can mediate attentional capture. *Psychonomic Bulletin & Review*, *14*(3), 392–422.

Christmann, C., & Leuthold, H. (2004). The attentional blink is susceptible to concurrent perceptual processing demands. *The Quarterly Journal of Experimental Psychology Section A*, *57*(2), 357–381. doi:10.1080/02724980343000350

Chua, F. K. (2005). The effect of target contrast on the attentional blink. *Attention, Perception & Psychophysics*, *67*(5), 770–788.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 109–127.

Coltheart, M. (1980). Iconic Memory and Visible Persistence. *Perception & Psychophysics*, *27*(3), 183–228.

Di Lollo, V., Kawahara, J.-I., Ghorashi, S. M., & Enns, J. T. (2004). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research Psychologische Forschung*, *69*(3), 191–200. doi:10.1007/s00426-004-0173-x

Duncan, J. C., Ward, R., & Shapiro, K. L. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, *369*(6478), 313–315. doi:10.1038/369313a0

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception & Psychophysics*, *71*(8), 1683–1700. doi:10.3758/APP.71.8.1683

Dux, P. E., Asplund, C. L., & Marois, R. (2008). An attentional blink for sequentially presented targets: Evidence in favor of resource depletion accounts. *Psychonomic Bulletin & Review*, *15*(4), 809–813. doi:10.3758/PBR.15.4.809

Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, *4*(9), 345–352. doi:10.1109/ICMTCE.2011.5915514

Folk, C. L., & Leber, A. (2008). Top-down control settings and the attentional blink: Evidence for nonspatial contingent capture. *Visual Cognition*.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(4), 1030–1044.

Giesbrecht, B., & Di Lollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of experimental psychology*.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*(2), 138–202. doi:10.1006/cogp.1998.0684

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, *18*(4), 560–578. doi:10.1080/09541440500423210

Kesten, H. (1958). Accelerated Stochastic Approximation. *The Annals of Mathematical Statistics*, *29*(1), 41–59. doi:10.1214/aoms/1177706705
Keysers, C., & Perrett, D. I. (2002). Visual masking and RSVP reveal neural competition. *Trends in Cognitive Sciences*, *6*(3), 120–125.
Legge, G., & Foley, J. (1980). Contrast masking in human vision. *JOSA*.
Li, R., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nature neuroscience*, *12*(5), 549–551. doi:10.1038/nn.2296
Maki, W. S., & Mebane, M. W. (2006). Attentional capture triggers an attentional blink. *Psychonomic Bulletin & Review*, *13*(1), 125–131.
Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience & Biobehavioral Reviews*, *34*(6), 947–957. doi:10.1016/j.neubiorev.2009.12.005
Mclaughlin, E. N., Shore, D. I., & Klein, R. M. (2001). The attentional blink is immune to masking-induced data limits. *The Quarterly journal of experimental psychology. A, Human experimental psychology*, *54*(1), 169–196. doi:10.1080/02724980042000075
Moore, C. M., Egeth, H. E., Berglan, L. R., & Luck, S. J. (1996). Are attentional dwell times inconsistent with serial visual search? *Psychonomic Bulletin & Review*, *3*(3), 360–365.
Nielsen, S., & Andersen, T. S. (2011). The attentional blink is modulated by first target contrast: Implications of an attention capture hypothesis. *Proceedings of the Cognitive Sciences Society's Annual meeting 2011*, 1–5.
Nieuwenstein, M. R., Van der Burg, E., Theeuwes, J., Wyble, B., & Potter, M. C. (2009). Temporal constraints on conscious vision: On the ubiquitous nature of the attentional blink. *Journal of Vision*, *9*(9), 18–18. doi:10.1167/9.9.18
Norman, D. A., & Bobrow, D. G. (1975). On Data-limited and Resource-limited Processes.
Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review*, *115*(4), 836–863. doi:10.1037/a0013395
Olivers, C. N. L., Stigchel, S., & Hulleman, J. (2005). Spreading the sparing: against a limited-capacity account of the attentional blink. *Psychological Research Psychologische Forschung*, *71*(2), 126–139. doi:10.1007/s00426-005-0029-z
Owsley, C., Sekuler, R., & Simens, D. (1983). Contrast Sensitivity Throughout Adulthood. *Vision Research*, *23*(7), 689–699.
Pelli, D. G. (1981). Effects of visual noise. *PhD thesis*, 1–281.
Peterzell, D. (1996). Individual differences in contrast sensitivity functions: The lowest spatial frequency channels. *Vision Research*.
Potter, M. C. M., & Levy, E. I. E. (1969). Recognition memory for a rapid sequence of pictures. *Journal of experimental psychology*, *81*(1), 10–15. doi:10.1037/h0027470
Raymond, J. E., Shapiro, K. L., & Arnell, K. M. M. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? . *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860.
Robbins, H., & Monro, S. (1951). A Stochastic Approximation Method. *The Annals of Mathematical Statistics*, *22*(3), 400–407. doi:10.1214/aoms/1177729586
Shapiro, K. L., Raymond, J. E., & Arnell, K. M. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(2), 357–371.
Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(4), 591–600.
Shih, S.-I., & Reeves, A. (2007). Attentional capture in rapid serial visual presentation.

Spatial vision, *20*(4), 301–315. doi:10.1163/156856807780919019
Shore, D. I., Mclaughlin, E. N., & Klein, R. M. (2001). Modulation of the attentional blink by differential resource allocation. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *55*(4), 318–324.
Spalek, T. M., Falcon, L. J., & Di Lollo, V. (2006). Attentional blink and attentional capture: endogenous versus exogenous control over paying attention to two important events in close succession. *Perception & Psychophysics*, *68*(4), 674–684.
Spencer, T. J., & Shuntich, R. (1970). Evidence for an interruption theory of backward masking. *JEP*, 1–3.
Starrfelt, R., Nielsen, S., Habekost, T., & Andersen, T. S. (in prep) How low can you go: Spatial frequency sensitivity in pure alexia.
Stevens, S. S. (1957). On the psychophysical law. *Psychological Review*, *64*(3), 153–181.
Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*(6), 599–606.
Treutwein, B. (1995). Adaptive psychophysical procedures. *Vision Research*, *35*(17), 2503–2522.
Visser, T. A. W., & Bischof, W. F. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin*.
Visser, T. A. W., & Ohan, J. L. (2007). Data-limited manipulations of T1 difficulty modulate the attentional blink. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *61*(2), 102–108. doi:10.1037/cjep2007011
Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (2004). Rapid serial visual distraction: task-irrelevant items can produce an attentional blink. *Perception & Psychophysics*, *66*(8), 1418–1432.
Visser, T. A. W., Zuvic, S. M., Bischof, W. F., & Di Lollo, V. (1999). The attentional blink with targets in different spatial locations. *Psychonomic Bulletin & Review*, *6*(3), 432–436.
Ward, R., Duncan, J. C., & Shapiro, K. L. (1996). The Slow Time-Course of Visual Attention. *Cognitive Psychology*, *30*(1), 79–109. doi:10.1006/cogp.1996.0003
Ward, R., Duncan, J. C., & Shapiro, K. L. (1997). Effects of similarity, difficulty, and nontarget presentation on the time course of visual attention. *Perception & Psychophysics*, *59*(4), 593–600.
Watson, A. B., Barlow, H. B., & Robson, J. G. (1983). What does the eye see best? *Nature*, *302*(5907), 419–422.
Wee, S., & Chua, F. K. (2004). Capturing Attention When Attention "Blinks". *Journal of Experimental Psychology: Human Perception and Performance*, *30*(3), 598–612. doi:10.1037/0096-1523.30.3.598
White, C., & Lorber, C. (1976). Spatial-Frequency Specificity in Visual Masking. *Perception & Psychophysics*, *19*(4), 281–284.
Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture. *JEP*, 1–13.

7 Appendix

A Publication 1. Proceedings of the Cognitive Sciences Society's meeting 2011

B Publication 2. Submitted to Psychological Research

C Poster presented at the Vision Sciences Society's meeting 2009

D Poster presented at the Vision Sciences Society's meeting 2010

E Poster presented at the Cognitive Neurosciences Society's meeting 2011

F Poster presented at the Cognitive Sciences Society's meeting 2011

The Attentional Blink is Modulated by First Target Contrast: Implications of an Attention Capture Hypothesis

Simon Nielsen* **(sini@imm.dtu.dk)**

Tobias S. Andersen (ta@imm.dtu.dk)

Cognitive Systems Section,
Institute for Informatics and Mathematical Modeling
Richard Petersens Plads, Building 321
Technical University of Denmark
2800 Lyngby, Denmark
*Corresponding author

Abstract

When two targets (T1 & T2) are presented in rapid succession, observers often fail to report T2 if they attend to T1. The bottleneck theory proposes that this attentional blink (AB) is due to T1 occupying a slow processing stage when T2 is presented. Accordingly, if increasing T1 difficulty increases T1 processing time, this should cause a greater AB. The attention capture hypothesis suggests that T1 captures attention, which cannot be reallocated to T2 in time. Accordingly, if increasing T1 difficulty decreases T1 saliency, this should cause a smaller AB. In two experiments we find support for an attention capture hypothesis. In Experiment 1 we find that AB magnitude increases with T1 contrast – but only when T1 is unmasked. In Experiment 2 we add Gaussian noise to targets and vary T1 contrast but keep T1 's SNR constant. Again we find that AB magnitude increases with T1 contrast.

Keywords: Attentional Blink; Attention Capture; First Target Interference; Temporal Attention; Spatial Attention; Human Vision.

Introduction

The attentional blink (AB) is widely used to study temporal attention and refers to the finding that observers often fail to report the second of two targets (T1 & T2) presented in rapid succession. Raymond, Shapiro and Arnell (1992) reported that accuracy of T2 report is a u-shaped function of the lag between T1 and T2 onset. They systematically varied the time between a white letter target (T1) and a black probe (T2, an 'X') embedded in a rapid serial visual presentation (RSVP) stream of black letter distractors. When T2 was presented within 500 ms of T1 observers rarely detected the probe. The AB has predominantly been examined in the RSVP paradigm where stimuli are presented central at fixation. However, Duncan and colleagues (Duncan, Ward & Shapiro, 1994; Ward, Duncan & Shapiro, 1996) used the *two-target* paradigm where two masked targets are presented consecutively in different locations. They observed a phenomenon similar to the AB, which they referred to as the attentional dwell time. Later Ward, Duncan and Shapiro (1997) argued that the dwell time effect may be the consequence of the location switch and not comparable to the AB. To examine this they introduced the *skeletal* paradigm where two consecutive masked targets are presented in the same location. The authors found a dwell time similar to what they observed with the two-target paradigm, and suggested that all three paradigms (RSVP, two-target, skeletal) tap a common attentional limitation - an assumption that is adopted in this study.

One theory offered to explain the AB is the bottleneck theory (Chun & Potter, 1995; Jolicoeur, 1998). This theory assumes two processing stages and suggests that the AB occurs due to slow second stage processing causing a perceptual bottleneck. The first processing stage is rapid, analyzing target features such as color and form. However, the first stage representation is volatile and susceptible to both decay and interference from other objects. In the second stage objects are consolidated and transferred to more durable memories necessary for conscious report. This stage is slow and capacity limited. According to the bottleneck theory the AB occurs when T2 requires second stage processing while T1 occupies the second stage.

The bottleneck theory predicts that making T1 identification more difficult prolongs second stage processing and consequently increases the AB (Chun & Potter, 1995). This prediction has led to several studies examining how T1 difficulty influences the AB. Target difficulty can be approached in either a data limited or resource limited fashion (Norman & Bobrow, 1975). Data limited methods vary T1 difficulty by varying stimulus attributes whereas resource limited methods do it by varying the task or introducing distractors to occupy attentional resources. Here we limit analysis to studies using a data limited approach. McLaughlin, Shore and Klein (2001) varied T1 exposure duration in three conditions mixed within blocks in the skeletal paradigm and observed no effect on the AB between conditions. Shore, McLaughlin and Klein (2001) replicated this study only this time they varied T1 exposure between blocks and found that increasing T1 exposure decreased AB magnitude in accordance with the bottleneck theory. A study by Christmann and Leuthold (2004) reported similar results. They varied T1 contrast in three conditions between blocks in an RSVP stream and found that increasing T1 contrast decreases AB magnitude. That the effect of T1 difficulty should depend so strongly on whether it is varied within or between blocks may seem surprising, but Shore et al. (2001) suggested that observers voluntarily allocate more resources to T1 when they expect it to be difficult to see, which is the case in a block of trials when T1 is difficult to see. This leads to fewer resources being allocated to T2 and hence to a larger AB. When T1 difficulty varies between trials, observers have no expectation of whether the next T1 will be difficult or not and hence do not change their allocation of attentional resources between the targets, which is why there is no effect of T1 difficulty on the AB. Contrary to the predictions of the bottleneck theory, Chua (2005) found that AB magnitude increased with T1 contrast in three conditions in a RSVP paradigm. Chua (2005) concluded that a high contrast T1 captures attention, and that this T1 attention capture prevents reallocation of resources to T2 in time for its appearance.

Test of Attention Capture Hypothesis

In summary it appears that there are two competing effects influencing the AB when varying T1 difficulty in a data limited fashion. Making T1 easier to perceive either by T1 exposure duration (Shore et al., 2001) or T1 contrast (Christmann & Leuthold, 2004) may decrease AB magnitude. This may be due to a bottleneck effect or to reallocation of attentional resources as the effect depends strongly on T1 difficulty being varied between blocks. However, making T1 easier to perceive by increasing T1 contrast, may increase AB magnitude by virtue of T1 attention capture, which increases with T1 saliency (Chua, 2005).

Here we test the attention capture hypothesis in a new set of experiments using the two-target paradigm (see Figure 1). We vary T1 contrast, which may vary T1 capture and thereby AB magnitude. We use an adaptive staircase procedure to control T1 difficulty in individual adjustments sessions allowing us to systematically examine how T1 difficulty affects the AB. In Experiment 1 we vary T1 difficulty by T1 contrast in two conditions, such that T1 accuracy in an easy condition is approximately 20% higher than in a hard condition. According to the bottleneck theory a smaller AB should be observed in the easy T1 condition, whereas the attention capture hypothesis carries the opposite prediction. Experiment 1 is subdivided into Experiment 1A and 1B, which differs by the presence or absence of T1's mask respectively. T1's mask is omitted in Experiment 1B because we are uncertain of how it affects the AB under these conditions. In Experiment 2 we aim to keep T1 difficulty constant between two conditions but vary T1 contrast. If this varies T1 saliency we may tease apart the effect of T1 capture from the effect of T1 difficulty. According to the bottleneck theory, no difference in AB effect should be observed between T1 conditions since difficulty is kept constant. The attention capture hypothesis however suggests that if T1 contrast increases T1 saliency this causes an increase in AB magnitude.

Experiment 1

We varied T1 difficulty by T1 contrast in two conditions such that T1 accuracy was 20% higher in an easy condition than in a hard condition. T1's mask was present in Experiment 1A and absent in Experiment 1B.

Methods

Observers

We tested 19 naïve observers, 8 females and 11 males between 18 and 28 years of age with a median age of 22 all with normal or corrected to normal vision. Observers were students at the Technical University of Denmark participating for an hourly fee, except for 2 who participated out of collegial interest.

Design

We varied three factors in this experiment, T1 mask [Present, Absent], SOA [100, 200, 300, 400, 600], and T1 difficulty [Easy, Hard]. T1's mask varied between Experiment 1A (Present) and 1B (Absent). SOA and T1 difficulty conditions were combined in a full factorial design. The sequential order of conducting Experiment 1A and 1B was counterbalanced across observers. Each letter in the target set appeared as T1 and T2 with identical frequency. We used an adaptive staircase procedure (accelerated stochastic approximation; Treutwein, 1995) and adjusted proportions correct for each observer to 0.5 in the T1 Hard condition, 0.8 in the T1 Easy condition, and 0.5 in the T2 condition i.e. to the same level as the T1 Low condition. Experiment 1 was structured in two (Experiment 1A) or three (Experiment 1B) individual-adjustment sessions of approximately 40 trials, one training session of 20 trials and four experimental blocks each of 120 trials. For each experiment the four experimental blocks yields 480 trials and thus 48 repetitions in each SOA x T1 difficulty condition.

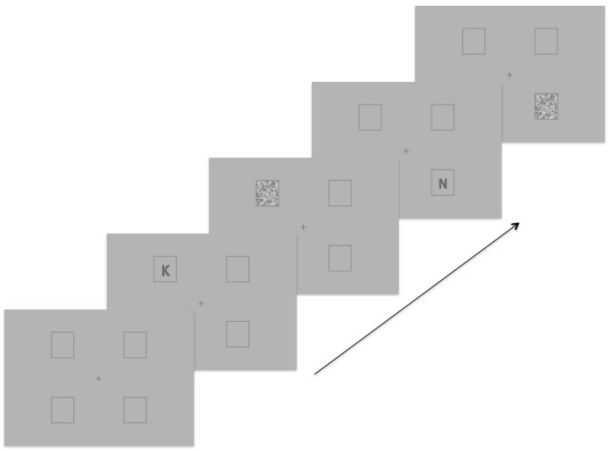


Figure 1: Two-target paradigm. T1 and T2 onsets are separated by a varying *stimuli onset asynchrony* (SOA). Targets appear in different boxes and have different identities. Masks are presented after a inter stimulus interval (ISI) of 100 ms. The task for the observer is to report the identity of both targets.

Stimuli

Target stimuli were 20 capital letters from the English alphabet chosen to emphasize a homogenous yet still varied target set. For this reason [C, I, Q, U, W, Y] were excluded either because they diverge substantially (e.g. L vs. W) or resemble other letters (e.g. O vs. Q). Stimuli were presented as dark on a 25.6 cd/m^2 grey background with 8.2 cd/m^2 fixation cross and boxes. Table 1 shows target luminance and contrast statistics obtained in the individual adjustment sessions. Standard deviations are thus the standard error of mean across observers. Pattern masks were moderate-density black dots with luminance levels of 0.0 cd/m^2. On each frame a dot patterns was randomly generated and displayed. This creates a masking effect perceived as if targets dissolved.

Table 1: Luminance, contrast and SNR levels for Experiment 1 and 2. Weber's contrast measures are used. Negative contrasts imply towards dark visa versa.

		Luminance		Contrast		SNR	
		Mean	Std	Mean	Std	Mean	Std
Experiment 1A							
T1	Easy	2.11	2.70	-0.96	0.05		
	Hard	10.29	4.01	-0.82	0.07		
T2		10.29	4.01	-0.82	0.07		
Experiment 1B							
T1	Easy	3.19	3.64	-0.95	0.06		
	Hard	11.29	4.27	-0.81	0.07		
T2		8.87	5.18	-0.85	0.09		
Experiment 2							
T1	Low	54.20	0.54	-0.07	0.01	0.51	0.13
	High	45.94	1.61	-0.21	0.03	0.51	0.13
T2		51.99	0.94	-0.11	0.02	1.47	0.42

Apparatus

A computer running the PsychoPy psychophysics software (Peirce, 2007) controlled stimulus presentation on a 15-inch View Sonic CRT monitor with a vertical refresh rate of 100 Hz. Observers conducted the experiment with a distance of approximately 75 cm from the monitor, yielding a stimulus angle of 1.37 degrees for targets and 1.76 degrees for masks.

Procedure

The AB was examined in the two-target paradigm with four boxes arranged on an imaginary rectangle and a fixation cross in the centre. Two targets were presented such that they had different identities and appeared in different locations. In Experiment 1A both targets were masked whereas in Experiment 1B T1's mask was omitted. Observers initiated a trial by pressing space after which a blank interval of 100 ms followed. T1 was then presented for 10 ms. After 100 ms T1 was followed by a pattern mask of 250 ms duration in Experiment 1A. In Experiment 1B a blank interval took the place of the pattern mask. T2 was presented for 10 ms after a variable SOA interval from T1 onset. An ISI of 100 ms then followed before T2's mask was presented for 250 ms. Observers were required to input the identity of T1 and T2 on the keyboard in an unspeeded, forced choice fashion with no regard to the presentation order of targets. The experiments were conducted in a dimly lit room. Prior to a session, observers adapted to the dim lighting for 5 minutes. Experiment 1A and 1B were conducted on different days, with approximately two weeks in between.

Results

Experiment 1A

One observer showed no difference in T1 accuracy between T1 conditions and was for this reason excluded from the experiment. Thus 18 observers were used in the analysis. The average of proportions corrects for T1 across SOA was 0.83 (std 0.02) for the T1 Easy condition and 0.64 (std 0.03) for the T1 Hard condition, showing that T1 difficulty was significantly varied [$F(1,17) = 48.14$, $p < 0.001$]. T2 results are plotted in Figure 1. An AB is evident from a significant main effect of SOA [$F(4,68) = 13.61$, $p < 0.001$]. However there is neither a main effect of T1 difficulty [$F(1,17) = 0.73$, $p = 0.41$] nor a T1 difficulty x SOA interaction effect [$F(4,68) = 1.24$, $p = 0.30$] indicating that T1 difficulty has little effect on the AB.

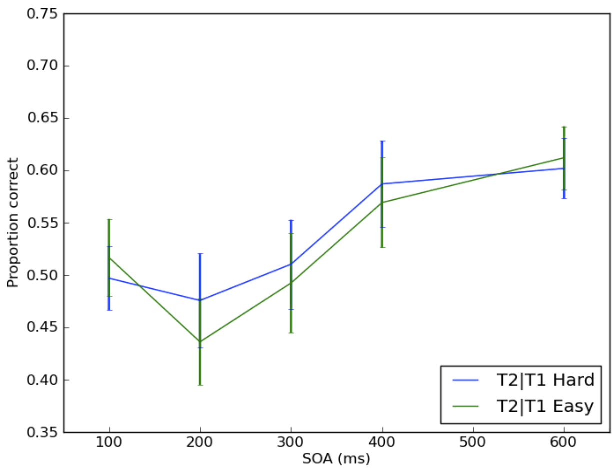


Figure 3: T2 Results in Experiment 1A (T1 masked). T2 accuracy conditioned by correct T1 report (T2|T1) is plotted for the T1 Hard and the T1 Easy condition.

Experiment 1B

The average of proportions corrects for T1 across SOA was 0.84 (standard error 0.02) for the T1 Easy condition and 0.62 (standard error 0.02) for the T1 Hard condition showing that T1 difficulty was significantly varied [$F(1,17) = 72.78$, $p < 0.001$]. T2 results are plotted in Figure 2. An AB is evident from a main effect of SOA [$F(4,68) = 18.70$, $p < 0.001$]. There is no main effect of T1 difficulty [$F(1,17) = 0.60$, $p = 0.45$] however a T1 difficulty x SOA interaction effect was found [$F(4,68) = 8.03$, $p < 0.001$]. This justified a post-hoc analysis revealing a main effect of T1 difficulty at SOA 200 ms [$F(1,17) = 25.89$, $p < 0.001$].

Summary

When T1 was masked (Experiment 1A) we found no effect of T1 difficulty on the AB. However, when T1 was unmasked (Experiment 1B) AB magnitude increased with T1 contrast at SOA 200 ms.

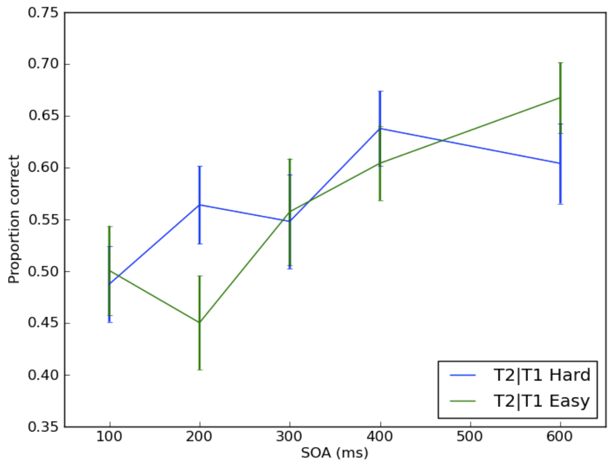


Figure 4: T2 Results in Experiment 1B (T1 unmasked). T2 accuracy conditioned by correct T1 report (T2|T1) is plotted for the T1 Hard and the T1 Easy condition.

Experiment 2

In Experiment 1 we varied T1 difficulty by T1 contrast and found that an easy T1 increased AB magnitude when T1 was unmasked. This is the opposite of what the bottleneck theory predicts. However, increasing T1 contrast also increases T1 saliency - and an increase in T1 saliency is likely to increase T1 attention capture, which may explain the increase in AB magnitude. In Experiment 2, we aim to tease apart the T1 capture effect from the effect of T1 difficulty. We do so by keeping T1 difficulty constant while varying the signal-to-noise ratio. Between two T1 conditions we add Gaussian noise with different standard deviation and keep T1 difficulty constant across conditions measured by T1's signal to noise ratio (SNR). Targets with noise, where the noise have a large standard deviation, requires a high contrast to achieve a given accuracy level relative to targets with noise sampled with a small standard deviation. This allows us to increase T1 contrast independently of T1 difficulty. If this causes an increase in T1 saliency, we may be able to isolate the effect of T1 capture from the effect of T1 difficulty. Since we found no AB effect of T1 difficulty in Experiment 1 when a pattern mask followed T1 we let T1 be unmasked in Experiment 2.

Methods

The experimental configurations in Experiment 2, was similar to those in Experiment 1 with the following exceptions: We tested 22 naïve observers, 8 females and 14 males between 20 and 35 years of age with a median age of 24 all with normal or corrected to normal vision. Observers were students at the Technical University of Denmark participating as part of the introductory cognitive psychology course at the department. We varied two factors: Six SOA conditions [100, 200, 300, 450, 600, 900] and two T1 contrast conditions [High, Low]. In the adjustment sessions proportion correct for T1 was set to 0.6 in both the T1 High and the T1 Low condition. T2 was set to 0.8. Gaussian noise was added to targets. The noise was sampled from a contrast distribution with its mean corresponding to the display background luminance, which was 58.33 cd/m^2. The noise standard deviation was 0.3 in the T1 High condition and 0.1 in the T1 Low condition. Thus in order to achieve the same level of T1 accuracy in both T1 conditions, observers required a high T1 contrast in the T1 High condition compared to the T1 Low condition. We measured T1 difficulty by T1's SNR, and to ensure that T1 difficulty was equal between T1 conditions, we used the average of the SNR levels obtained in the T1 High and T1 Low adjustment sessions. Figure 3 shows sample stimuli for the two T1 conditions with identical SNR and different T1 contrast levels. Targets plus noise were displayed at a visual angle of 1.76 degrees. Fixation cross and boxes was presented at 46.66 cd/m^2. Luminance, contrast and SNR statistics are shown in Table 1.

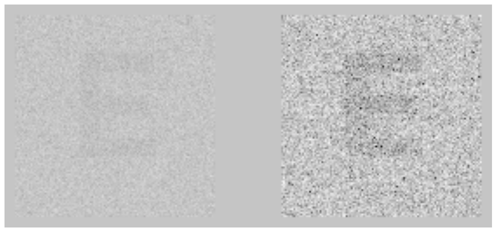


Figure 5: Sample stimuli from Experiment 2 showing the T1 Low (left) and T1 High (Right) contrast conditions. The stimuli have the same signal-to-noise ratio, but different contrasts. Rendering in print may affect the signal-to-noise ratio. Left. SNR: 0.49, standard deviation for noise: 0.3, target contrast: -0.21, target contrast energy 1544. Right. SNR: 0.49, standard deviation for noise: 0.1, target contrast: -0.07, target contrast energy: 173.

Results

Three observers were excluded from the study because they showed a difference in T1 accuracy between T1 conditions of more than 18% averaged across SOA. Thus 19 observers were used in the analysis. The average of proportions corrects for T1 across SOA was 0.76 (standard error 0.04) for the T1 Low condition but 0.80 (standard error 0.03) for the T1 Low condition. Despite the increase in T1 accuracy was marginal, it was consistent across observers thus leading to a T1 effect of difficulty [$F(1,18) = 12.89$, $p = 0.002$]. This indicates that T1's SNR may not optimally determine T1 difficulty under these conditions.

T2 results are plotted in Figure 4. An AB was evident from a main effect of SOA [$F(5,90) = 2.56$, $p = 0.03$]. T1 contrast x SOA produced no interaction effect [$F(5,90) = 0.49$, $p = 0.79$], however a main effect of T1 contrast [$F(1,18) = 5.54$, $p = 0.03$] was observed. This justified a post-hoc analysis showing a main effect of T1 contrast at SOA 300 ms [$F(1,18) = 6.87$, $p = 0.02$]. In summary, we varied T1 contrast with little influence of T1 difficulty and found that AB magnitude increased with T1 contrast at SOA 300 ms.

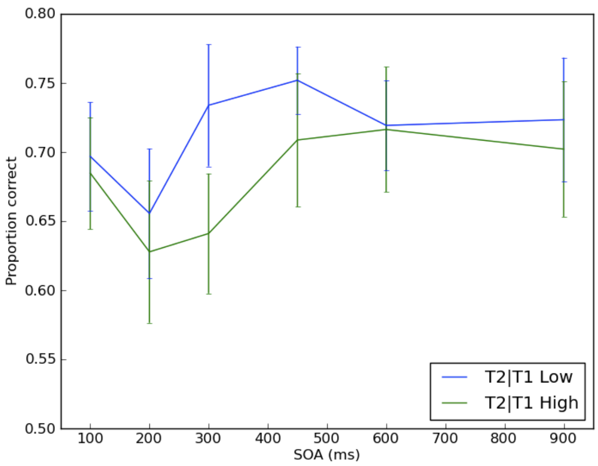


Figure 6: T2 Results in Experiment 2. T2 accuracy conditioned by correct T1 report (T2|T1) is plotted for the T1 High and the T1 Low condition.

Discussion

This study indicates that attention capture to T1 modulates the AB. In Experiment 1B we varied T1 difficulty by T1 contrast and found that an easy T1 increased AB magnitude compared to a hard T1. This is the opposite of bottleneck predictions, and of what Christmann and Leuthold (2004) and Shore et al. (2001) found. However, the finding is in line with Chua (2005) and supports the attention capture hypothesis suggesting that a salient T1 engages attention such that it cannot be reallocated to T2 in time. We did not observe an AB effect of T1 contrast when T1 was masked (Experiment 1A). This finding may explain why other studies using pattern masks did not report AB effects of T1 difficulty (McLaughlin et al., 2001; Nielsen, Petersen and Andersen, 2009; Ward et al., 1997). But how should we understand the effect of T1's mask? Pattern masks are typically jumbled feature constructs shown in high contrast to interrupt target processing after offset. It is likely that they engage attention in a similar fashion as targets and thereby interferes with the effect of T1 difficulty. A study by Chua (2005) lends support to this suggestion. Chua (2005) found that a to be ignored 5-dot singleton construct, appearing before a single target in an RSVP stream produced an AB, and that AB magnitude increased with singleton contrast. Thus it is likely that T1's mask captured attention in a similar fashion as the singleton in Chua (2005), and that this capture effect interfered with the capture effect of T1 contrast in Experiment 1A.

To test the effect of attention capture further, in Experiment 2 we varied T1 contrast in two conditions but kept T1's SNR constant between conditions. Again we found an effect on AB magnitude that increased with T1 contrast. The purpose with this paradigm was to keep T1 difficulty constant by keeping its signal-to-noise ratio constant. In this, we did not succeed as the high contrast T1 was marginally easier to perceive as measured by the proportion of correct T1 identifications. Hence one might suggest that bottleneck effects could have influenced this result. However, as in Experiment 1, our results were opposite of what the bottleneck theory would predict as we found a stronger AB when T1 contrast was high, which happened to also be the condition where it was marginally easier as seen in a higher proportion correct. Hence, our findings unanimously support a strong effect of T1 saliency on the AB.

References

*Christmann, C. and H. Leuthold (2004). "The attentional blink is susceptible to concurrent perceptual processing demands." Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology **57**(2): 357-377.*

*Chua, F. K. (2005). "The effect of target contrast on the attentional blink." Percept Psychophys **67**(5): 770-88.*

*Chun, M. M. and M. C. Potter (1995). "A 2-Stage Model for Multiple-Target Detection in Rapid Serial Visual Presentation." Journal of Experimental Psychology-Human Perception and Performance **21**(1): 109-127.*

*Duncan, J., R. Ward, et al. (1994). "Direct Measurement of Attentional Dwell Time in Human Vision." Nature **369**(6478): 313-315.*

*Jolicoeur, P. (1998). "Modulation of the attentional blink by on-line response selection: evidence from speeded and unspeeded task1 decisions." Mem Cognit **26**(5): 1014-32.*

*McLaughlin, E. N., D. I. Shore, et al. (2001). "The attentional blink is immune to masking-induced data limits." Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology **54**(1): 169-196.*

*Nielsen, S., A. Petersen, et al. (2009). "Under which conditions does T1 difficulty affect T2 performance in the attentional blink?" Journal of Vision **9**(8): 156.*

Norman, D. A. and D. G. Bobrow (1975). "On Data-limited and resource-limited Processes." Cognitive Psychology 7: 44-64.

*Peirce, J. W. (2007). "PsychoPy--Psychophysics software in Python." J Neurosci Methods **162**(1-2): 8-13.*

*Raymond, J. E., K. L. Shapiro, et al. (1992). "Temporary Suppression of Visual Processing in an Rsvp Task - an Attentional Blink." Journal of Experimental Psychology-Human Perception and Performance **18**(3): 849-860.*

*Shore, D. I., E. N. McLaughlin, et al. (2001). "Modulation of the attentional blink by differential resource allocation." Canadian Journal of Experimental Psychology-Revue Canadienne De Psychologie Experimentale **55**(4): 318-324.*

*Treutwein, B. (1995). "Adaptive psychophysical procedures." Vision Res **35**(17): 2503-22.*

*Ward, R., J. Duncan, et al. (1996). "The slow time-course of visual attention." Cognitive Psychology **30**(1): 79-109.*

*Ward, R., J. Duncan, et al. (1997). "Effects of similarity, difficulty, and nontarget presentation on the time course of visual attention." Perception & Psychophysics **59**(4): 593-600.*

Target saliency and attention capture in the attentional blink

Authors

Simon Nielsen[*1], Tobias S. Andersen[1]

[1] Cognitive Systems Section,
Institute for Informatics and Mathematical Modeling
Technical University of Denmark, Building 321
2800 Lyngby, Denmark

[*]corresponding author email: sini@imm.dtu.dk phone: +45 26233577

Abstract

Observers often fail to report the second of two visual targets (T1 & T2) presented within 200-500 ms. Recent studies suggest that this attentional blink (AB; Raymond Shapiro & Arnell, 1992) is influenced by T1 attention capture (Folk, Leber & Egeth, 2008), which is supported by findings showing that the AB increases with T1 saliency (Chua, 2005). Here we examine attention capture effects by varying T1 contrast while controlling for bottleneck effects, which may reduce the AB when T1 identifiability increases (Chun & Potter, 1995). In Experiment 1 we vary T1 contrast and find that the AB increases with contrast according to the attention capture hypothesis. In Experiment 2A and 2B we use Gaussian noise and vary T1 contrast while keeping T1 accuracy constant. Again, we find that the AB increases with T1 contrast (2A), and that this capture effect can be cancelled by the effect of T2 contrast (2B).

Keywords

Attentional blink, attention capture, visual attention, temporal attention.

Introduction

When studying constraints in temporal attention, the attentional blink (AB) paradigm is often used. The AB is a perceptual deficit occurring when observers are required to pay attention to two visual targets (T1 & T2) presented in rapid succession. When T2 is shown within 200-500 ms of T1, report accuracy of T2 is impaired (Raymond, Shapiro, & Arnell, 1992). Several theoretical and computational models have been proposed to explain the AB, see (Dux & Marois, 2009; Martens & Wyble, 2010) for comprehensive reviews.

A recent hypothesis, suggests that T1 induces attention capture and a sluggish reallocation of attention to T2, which causes a decrease in T2 accuracy (Folk & Leber, 2008). According to the attention capture hypothesis increasing T1 saliency decreases T2 accuracy at critical lags for the AB (Chua, 2005). However, increasing T1 contrast may also reduce the AB according bottleneck models (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicoeur & Dell'Acqua, 1998), which suggests that the AB occurs because T1 occupies a slow second stage of processing when T2 is presented, and that making T1 easier to perceive should clear the second stage processing faster and consequently increase T2 accuracy. Thus, varying T1 contrast may have two opposing effects on the AB, one that increases T2 accuracy when processing of T1 becomes easier (according to the bottleneck theory), and another which decreases T2 accuracy when T1 saliency increases (according to the attention capture hypothesis).

The present study examines the attention capture hypothesis in the AB, by manipulating T1 luminance contrast (henceforth T1 contrast), while controlling for bottleneck effects. We constrain our review of the literature to studies in which T1 saliency and T1 difficulty[1] may have been varied. This type of manipulation falls into the category of data-limited manipulations in which the perceptual quality of stimuli is varied, for instance by manipulating stimuli attributes or by masking, as opposed to resource-limited manipulations varying the task or introducing distractors to occupy attentional resources (Norman & Bobrow, 1975).

Mclaughlin, Shore and Klein (2001) varied T1 difficulty by exposure duration in the skeletal paradigm where two, masked targets are presented centrally. They found no effect on T2 accuracy when T1 conditions were mixed within blocks. The authors argued that this could have been due to the fact that they varied T1 difficulty between trials. This prevents a strategy of expectation, which could allow observers to allocate fewer resources to an easy T1 compared to a difficult T1. When T1 difficulty varies between trials observers have no expectation of whether or not the next T1 will be difficult and hence do not change their allocation of attentional resources accordingly, which is why there was no effect on the AB. To test this hypothesis Shore, Mclaughlin, and Klein (2001) replicated the study by Mclaughlin et al. (2001) with the exception that T1 difficulty was varied between blocks and found that the AB increased with T1 difficulty. They interpreted their finding as being in support of the bottleneck theory. Christmann and Leuthold (2004) varied T1 contrast in three

[1] We use “difficulty” in terms of how well a target is identified based on accuracy data and make no assumptions about how difficulty the target is to process.

conditions between blocks in a rapid serial visual presentation (RSVP) stream. In agreement with the bottleneck theory they also found that AB magnitude increased with T1 difficulty. Seiffert and DiLollo (1997) presented observers with an RSVP stream and manipulated T1 difficulty between blocks by varying the time between T1 and its subsequent distractor, thereby degrading the perceptual quality of T1. In further support of the bottleneck theory, Seiffert and DiLollo (1997) found that the AB increased when perceptual quality of T1 was reduced. Thus these studies suggest that bottleneck effects thrive when difficulty conditions are blocked.

Another stimulus design factor that influences bottleneck effects is the presence of a pattern mask following T1. Visser and Ohan (2007) conducted a study in which the perceptual quality of T1 was degraded by inserting a forward mask prior to T1 in a skeletal paradigm. T1 difficulty was varied between trials by the time between the mask and T1. This had a subsequent effect on T2 accuracy in agreement with the bottleneck theory, however only when there was no pattern mask following T1. Visser and Ohan (2007) argued that the pattern mask following T1 not only reduces perceptual quality of T1, but also disrupts processing in the bottleneck, which effectively equates the processing times across T1 difficulty conditions. Previously we (Nielsen & Andersen, 2011) found similar effects of backwards pattern masking in the two-target paradigm where targets are presented in difference locations (Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996), such that an effect of T1 contrast was only evident when no mask followed T1. In contrast to Visser and Ohan (2007), we interpreted the effect in terms of the saliency hypothesis: If the mask is more salient than T1 it will determine the saliency of the T1-mask complex. Therefore the saliency of the T1-mask complex will be influenced little by variations in the saliency of T1.

Very few studies have found support for the capture hypothesis. Chua (2005) varied T1 contrast in three conditions in an RSVP stream. He found that T2 accuracy decreased with T1 contrast and concluded that a high contrast T1 captures attention, and that this T1 attention capture prevents reallocation of resources to T2 in time for its appearance. However, Chua’s (2005) findings may have been influenced by bottleneck effects acting to suppress the capture effect of T1 contrast, since both T1 difficulty, indexed by T1 accuracy, and T1 contrast varied. In fact, the capture effect from a high contrast T1 was only observed at ceiling levels for T1 accuracy (99% correct report) when the contrast was very high, compared to near ceiling level (97%) and to a level of approximately 90% correct report. Thus, it is likely that in the low and medium T1 contrast conditions the capture effect and the bottleneck effect have cancelled each other out, which however cannot be determined by the data.

Previous studies manipulating T1 contrast have not taken individual differences in contrast sensitivity into account (Christmann & Leuthold, 2004; Chua, 2005). In fact previous studies varying T1 difficulty in general have not taken individual differences in perceptual ability into account (Chun & Potter, 1995; Seiffert & DiLollo, 1997; Mclaughlin et al., 2001; Visser, 2007). Consequently T1 accuracy levels vary between studies according to procedural differences, not to mention between individuals. We suggest that it is critical to control T1 accuracy across observers, especially when attempting to examine capture effects isolated from bottleneck effects to avoid contributions from both. The study by Chua (2005) showed a capture effect of T1 contrast only when T1 contrast was very high. Contrast is perceived according to individual's contrast sensitivity, thus differences in contrast sensitivity may caused some observes to benefit from bottleneck effects at a given T1 contrast level, while the same level would inflict attention capture in others.

The question remains how manipulating T1 contrast, influence the AB when T1 accuracy is controlled (to efficiently control for bottleneck effects by accounting for across observer differences), T1 conditions are mixed within blocks (to prevent high level strategies of differential resource allocation), and avoiding backwards pattern masking (to prevent capture or disruption of target processing), which is what we set out to answer in this study.

Experiment 1

In the first experiment three conditions of T1 contrast (low, medium and high) were devised to replicate the findings by Chua (2005), while controlling T1 accuracy levels for observers to control for bottleneck effects. To this end a low and a medium T1 condition were configured such that T1 accuracy was approximately 50% in the low condition and 80% in the medium condition. The high condition was inspired by Chua (2005), in which capture effects were reported only when T1 had a very high contrast. Thus, according to the capture hypothesis, the high T1 condition should cause a decrease in T2 accuracy compared to the medium T1 condition, while it is uncertain if the low and medium condition will be influenced by both bottleneck and capture effects. To account for individual differences in contrast sensitivity we controlled T1 accuracy across observers, and adjusted T1 contrast individually using adaptive staircase procedures.

Methods

Observers

Twenty-five observers were recruited. Two observers were excluded from the experiment because they were non-blinkers (Martens, Munneke, Smid, & Johnson, 2006). The remaining 23 observers were a mix of undergraduate and graduate students, all participating for an hourly fee of approximately DKK 120. There were 12 females and 11 males between 20-30 years of age, with median age of 24. All observers had normal or corrected to normal vision. The experiments in this study were conducted with consent from the observers.

Apparatus

Stimuli presentation was controlled using the PsychoPy psychophysics software (Peirce, 2007) running on a PC. The display was a 21" ViewSonic G220f monitor with a vertical refresh rate of 100 Hz and observers viewed stimuli at a distance of approximately 75 cm. The experiment was conducted in a facility with 7 test booths.

Design and procedure

The experiment was conducted in a dimly lit room, and observers were adapted to the light conditions in the room for 5 min. prior to commencing the experiment. An experimental trial consisted of an RSVP stream containing 20 items with presentation durations of 50 ms and an SOA of 100 ms. A trial was initiated by pressing space. There was a 250 ms delay before the RSVP stream started. T1 occurred at lag 4-6. T2 occurred with a lag of 1-4, 6 or 8 with respect to T1 (see Figure 1). At the end of a trial the observers were required to report the identity of T1 and T2 with an unspeeded forced choice with no regards to the presentation order of targets, which was achieved by observers entering their guess on the keyboard. If in doubt about the identity of targets, observers were required to guess, and the guessing rate constituted by the 20 letter target set was thus 5%. The experiment began with two single target adjustment sessions where the 50% (low) and 80% (medium) contrast thresholds were determined by an adaptive staircase procedure (Accelerated stochastic approximation; Treutwein, 1995). In the adjustment sessions only T2 was presented with lags that varied randomly between 5-14. The test phase began immediately after the adjustment sessions. Two factors were varied in the test phase, T1-T2 lag and T1 contrast. T1 contrast was varied in three conditions [low, medium, high]. The contrast in the high condition was twice the contrast in the medium condition. The T2 contrast was always equal to the medium T1 contrast. T1-T2 lags and T1 difficulty were combined in a full factorial design. The test phase was divided into 6 blocks, each containing 72 trials corresponding to 24 repetitions of each T1 contrast x T2 lag combinations per observer. The order of trials was randomized within blocks.

Stimuli

The target stimuli were pseudo randomly selected from [A, D, E, H, J, K, N, R, T, V, X, Z] such that T1 and T2 were never identical within a trial, and such that all letters appeared with the same frequency between blocks. The distractors were digits randomly selected from [2, 3, 4, 5, 6, 8, 9] with the constraint that two consecutive digits were never identical. Stimuli were displayed in Helvetica Bold font covering a visual angel of 0.76 by 1.15 degrees (horizontal, vertical). Stimuli were displayed in dark on a bright gray background with mean luminance 57.17 cd/m^2 std. 2.67 across the 7 test booths. Distractor contrast (Weber) was -0.5. The mean and standard deviation of target contrast and luminance across observers are presented in Table 1

	T1 low	T1 medium	T1 high	T2
Mean contrast	-0.09	-0.15	-0.30	-0.15
Std. mean contrast	0.05	0.07	0.13	0.07
Mean luminance	51	48	39	48
Std. mean luminance	3.7	3.9	7.5	3.9

Table 1 Contrast and luminance statistics for Experiment 1: Weber's contrast measures are displayed. Negative contrasts mean that the object was darker than the background. Note that variations in luminance statistics are influenced by variations in background luminance across test stations, see Apparatus section

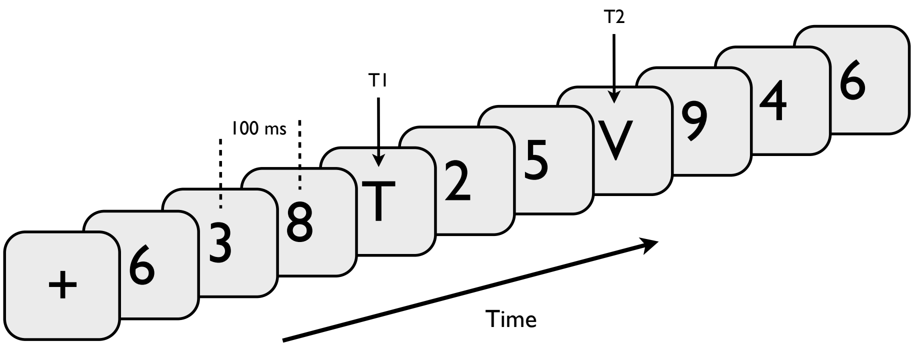


Fig. 1 RSVP paradigm: Observers view streams of digits with two target letters embedded and are required to report the identity of the two target letters at the end of a trial

Results

T2 results are shown in Figure 2. Target accuracies were arcsine transformed and analyzed with repeated measures ANOVAs. F-statistics were tested for sphericity and Greenhouse Geisser correction was applied when sphericity was violated. Original non-corrected degrees of freedom are reported. The T2 analysis showed a significant main effect of lag, $F(5,110) = 21.5$, $p <= 0.0001$, indicating an AB. There was an interaction between lag and T1 contrast, $F(10,220) = 3.2$, $p = 0.004$, and a main effect of T1 contrast, $F(2,44) = 4.9$, $p = 0.02$. Simple effects analyses showed a main effect of T1 contrast at lag 1, $F(2,44) = 11.3$, $p = 0.001$, and lag 2, $F(2,44) = 8.3$, $p <= 0.003$. The effect at lag 1 reflects that T2 accuracy was 11% lower in the T1 high condition compared to the T1 low and medium conditions. The effect at lag 2 reflects that T2 accuracy was 14% lower in the high and medium condition compared to the low condition. This is better illustrated in Figure 3, which shows the paired T2 differences between the low-medium and medium-high conditions (which is what is used in the ANOVA). Figure 3, also clarifies the absence of a simple effect at lag 3 (by overlap in standard errors), which inspection of Figure 2 would suggest.

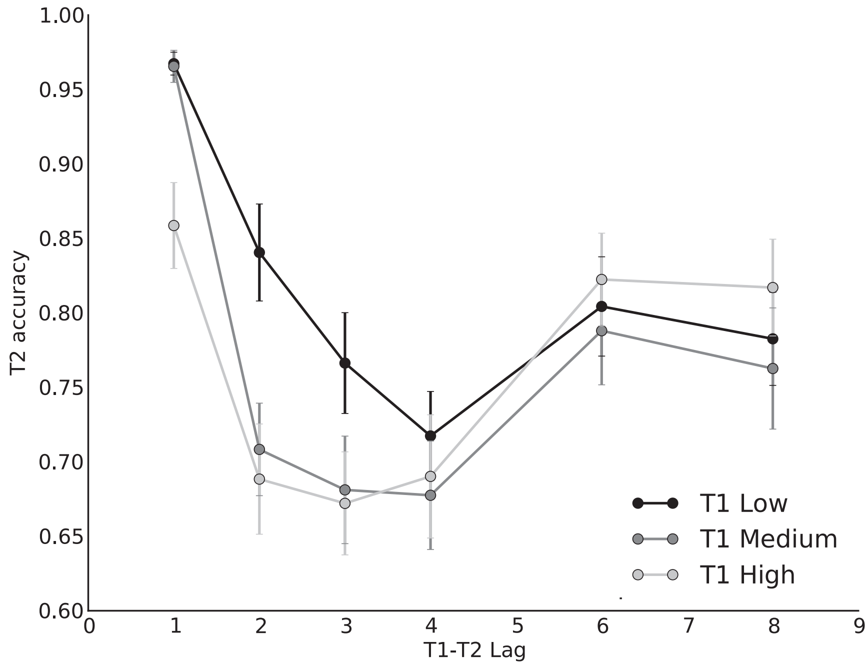


Fig. 2 Results from Experiment 1: T2 accuracies are plotted across T1-T2 lags. The graphs illustrate T2 for each of the T1 conditions. Error bars show standard errors of the mean

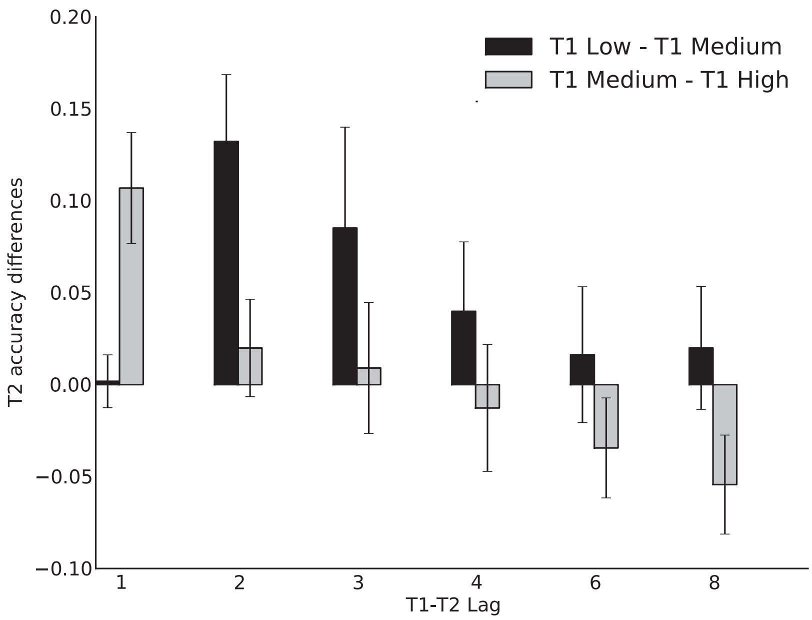


Fig. 3 Results from Experiment 1: Paired differences in T2 accuracy between T1 conditions are plotted across T1-T2 lags. The 'T1 Low – T1 Medium' bars signify the differences in T2 accuracy between the T1 low and T1 medium conditions, whereas the 'T1 Medium – T1 High' bars are the differences in T2 accuracy between the medium and high T1 conditions. Error bars show standard errors of the mean

T1 results are illustrated in Figure 4. T1 accuracy was efficiently varied using T1 contrast reflected in the significant main effect of T1 contrast, $F(2,44) = 90.2$, $p <= 0.0001$. Mean (std) T1 accuracy across lags was 0.51 (0.05), 0.88 (0.02) and 0.98 (0.01) for the low, medium and high T1 conditions respectively. There was a T1 main effect of lags, $F(5,110) = 9.7$, $p <= 0.0001$. This effect was not intended but has been reported previously (e.g. Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009). We suspect that it is related to backward masking and that it has little effect on our primary results.

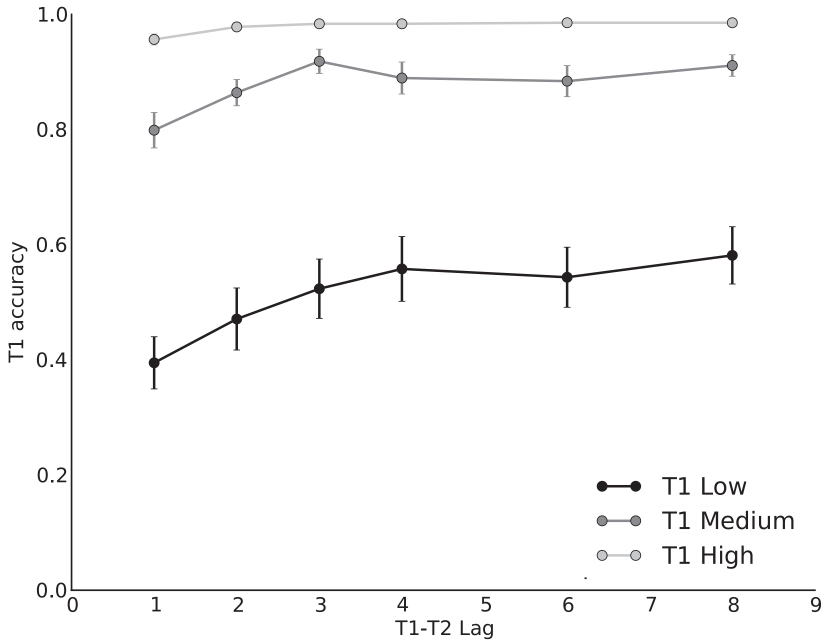


Fig. 4 Results from Experiment 1: T1 accuracies are plotted across T1-T2 lags. The graphs illustrate each of the T1 conditions. Error bars show standard errors of the mean

Discussion

The general main effect, and the main effect of T1 contrast at lag 2 imply that the high and medium T1 conditions increased the AB, compared to the low T1 condition. Thus the effect at lag 2 found here are according to the Chua (2005) study that reported a similar effect at lag 2, which are according to the attention capture hypothesis. Similarly to Chua (2005) we found an effect of T1 contrast at lag 1, which most likely are caused by forward masking from the preceding high contrast T1, which is according to what Spencer and Shuntics (1970) reported.

Experiment 2A

In Experiment 1 we varied T1 contrast and found that higher T1 contrast leads to a greater AB, which suggests that a high contrast T1 captures attention, thus preventing reallocation of attention to T2 in time. This capture effect may be tied solely to T1 contrast or it could be tied to the perceptibility of T1, which cannot be determined from Experiment 1 where T1 accuracy was also varied. Since the effects of attention capture and bottleneck effects are contradictory in terms of how they affect T2 processing, it is likely that both these effects have coexisted in Experiment 1 and that the bottleneck effect of an easy T1 masked the capture effect caused by the easy T1 being highly salient vice versa. Therefore in Experiment 2 we tease apart the effect of T1 capture from the potential bottleneck effect that may arise when T1 accuracy is varied. To this end we use additive Gaussian noise in one of two T1 conditions and vary T1 contrast while keeping T1 accuracy constant. Since it requires a greater T1 contrast to perceive a target with noise, than one without noise, T1 contrast can be manipulated independently T1 accuracy.

Method

The methods used in Experiment 2 are identical to those in Experiment 1 with the following exceptions:

Observers

Thirteen observers were recruited for the experiment, four females and nine males between 20-37 years of age, with median age of 23.

Design

Two factors were varied in the experiment, T1-T2 lag and T1 contrast. T1-T2 lags were the same as in Experiment 1 and T1 contrast was varied to two levels [low, high]. T1 contrast levels were again determined individually for observers, such that T2 accuracy was 80% in both conditions. T2 contrast was always equal to the T1 low condition where no noise was added. As in Experiment 1, observers conducted two adjustment sessions in which the T1 contrast levels were determined and six test blocks. Each test block consisted of 48 trials in total yielding 24 repetitions of each T1 contrast x T1-T2 lag combination per observer. There were 18 items in the RSVP stream.

	T1 low	T1 high	T2
Mean contrast	-0.31	-0.40	-0.31
Std. mean contrast	0.19	0.08	0.19
Mean luminance	39	34	39
Std. mean luminance	11.4	4.8	11.4

Table 2 Contrast and luminance statistics for Experiment 2A: Weber's contrast measures are displayed. Negative contrasts mean that the object was darker than the background. Note that variations in luminance statistics are influenced by variations in background luminance across test stations

Stimuli

In the T1 high condition, noise was added to T1. The noise was sampled from a Gaussian distribution with mean luminance corresponding to the background luminance and a standard deviation of 0.25 Weber's contrast truncated at 2 standard deviations. A Gaussian envelope was applied to the noise stimuli to smooth transient effects between the noise patch and the background (see Figure 5 for example stimuli). Stimuli were displayed in Helvetica Bold font and the stimuli with noise covered a visual angel of 1.53 by 1.53 degrees (horizontal, vertical), whereas the stimuli without noise subtended an angle of 0.76 by 1.15 degrees. Contrast and luminance statistics for targets are presented in Table 2.

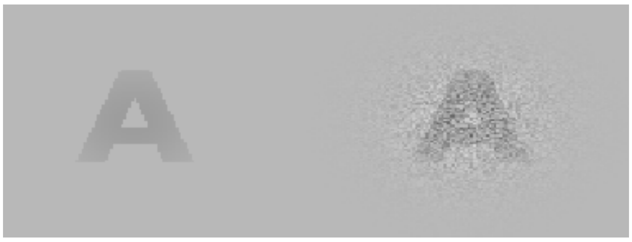


Fig. 5 Stimuli used in Experiments 2A and 2B showing the T1 low (left) and T1 high condition (right). Contrast settings are according to mean contrasts for the two conditions. The left stimulus has contrast -0.29 with no noise, and corresponds to the T1 low, and the T2 condition. The right stimulus corresponds to the T1 high condition, and has contrast -0.40 and added noise with std. of 0.25. The contrast in the figure may depend on rendering specifics

Results

The T2 results are illustrated in Figures 6 and 7. An AB was evident from a main effect of lags, $F(5,60) = 19.9$, $p <= 0.0001$. T2 accuracy was significantly affected by T1 contrast, as is evident from a T2 main effect of T1 contrast, $F(1,12) = 5.7$, $p = 0.04$. Simple effects analyses showed a main effect of T1 contrast at lag 1, $F(1,12) = 12.2$, $p = 0.004$. The large effect at lag 1 relatively to other lags is particularly evident in Figure 7, which is similar to Figure 3 in that it illustrates the differences in T2 accuracy between conditions.

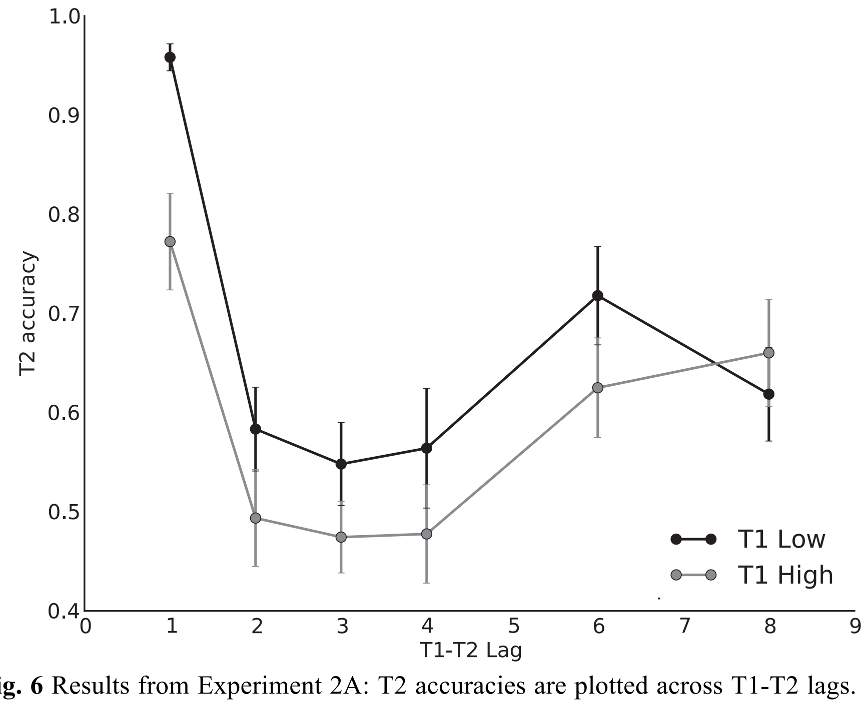


Fig. 6 Results from Experiment 2A: T2 accuracies are plotted across T1-T2 lags. The graphs illustrate T2 conditioned by each of the T1 conditions. Error bars show standard errors of the mean

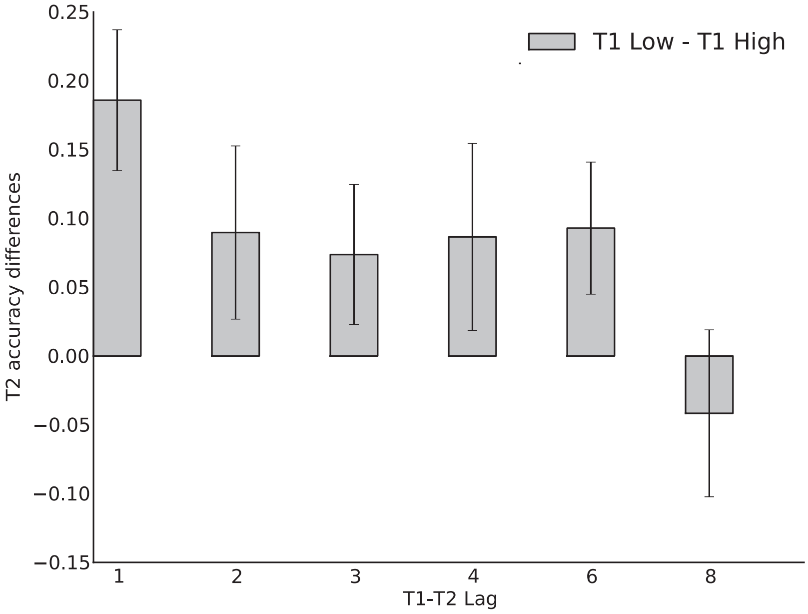


Fig. 7 Results from Experiment 2A: Differences in T2 accuracy between T1 conditions are plotted across T1-T2 lags. 'T1 Low – T1 High' signifies the differences in T2 accuracy between the low and high T1 conditions. Error bars show standard errors of the mean

T1 results are illustrated in Figure 8. T1 accuracy was successfully controlled between T1 conditions. Mean (std) T1 accuracy across lags was 0.83 (0.03) and 0.80 (0.04) for low and high contrast respectively. ANOVA statistics verified that there was no main effect of T1 difficulty, $F(1,12) = 0.5$, $p = 0.50$. As in Experiment 1 there was a main effect of lags on T1 accuracy, $F(5,60) = 8.2$, $p <= 0.0001$.

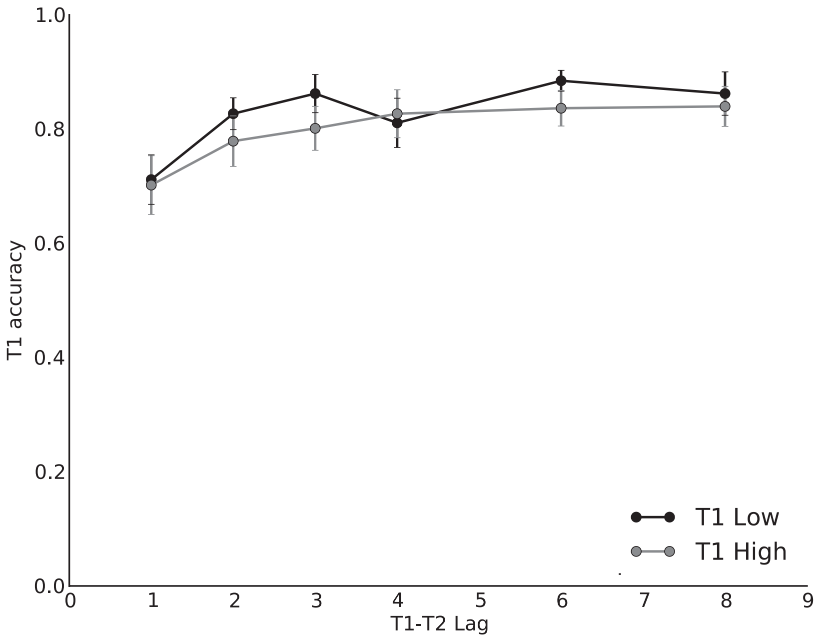


Fig. 8 Results from Experiment 2A: T1 accuracies are plotted across T1-T2 lags. The graphs illustrate each of the T1 conditions. Error bars show standard errors of the mean

Discussion

We found a main effect of T1 contrast on T2 accuracy, implying that T1 contrast decreases T2 accuracy, which is in accordance with an attention capture hypothesis (Chua, 2005; Folk & Leber, 2008). The T2 effect of T1 contrast was pronounced at lag 1, which resembles what was observed in Experiment 1 for the T1 high condition. Thus it is likely that here too the high contrast T1 acted to forward mask the lower contrast T2 similarly to what was found by Spencer and Shuntich (1970).

T1 contrast was successfully varied while T1 accuracy was kept constant between conditions, such that any bottleneck effects that may have influenced findings in Experiment 1 should have been eliminated. The main effect of T1 contrast seem more pronounced at later lags here (Figure 6), compared to the effects found in Experiment 1 (Figure 2), which may suggest that bottleneck effect influenced Experiment 1 and acted to suppress the effect of T1 capture.

That the high contrast T1 was the only target in the stream with noise may have caused it to pop out, such that the effect reported here in fact was due to singleton capture, more than due to T1's contrast. However, this is unlikely since we (Nielsen & Andersen, 2011) previously observed the same effect when all targets had noise added to them.

Experiment 2B

Experiment 2A indicated that a high contrast T1 captures attention and impairs T2 accuracy, compared to when T1 is presented in a low contrast. This capture effect may depend on the contrast of T2, which in Experiment 2A was low. If T2 is presented in high contrast, it is likely to capture attention and diminish the capture effect from the high contrast T1 - a notion, which is supported by Shih and Reeves (2007) demonstrating that the AB is modulated by T2 saliency, irrespective of T1 saliency. Thus in Experiment 2B we let T2 contrast be high, and expect that this would reduce the T1 capture effect. Also, in both Experiments 1 and 2A we found indications of forward masking effects at lag 1, when T1 is shown in a higher contrast than T2. In Experiment 2B we examine these forward masking effects when T1 is presented in a similar or lower contrast than T2. If forward masking caused the effects found at lag 1 in Experiments 1 and 2A, we expect the effects to be reduced here since forward masking effects decreases with the contrast of the masking object (Spencer & Shuntich, 1970).

Method

The methods are identical to those used in Experiment 2A, with the following exceptions: T2 was always identical to the T1 high condition. Seventeen observers were recruited. Two observers were excluded from the experiment. One because the individual adjustment session was unsuccessful, such that the observer showed a 20% increase in T1 accuracy in the T1 low condition compared to the T1 high condition and the other because there was no AB effect. The remaining 15 observers were seven females and eight males between 19-36 years of age with median age of 25. Contrast and luminance statistics are shown in Table 3.

	T1 low	T1 high	T2
Mean contrast	-0.29	-0.39	-0.39
Std. mean contrast	0.18	0.08	0.18
Mean Luminance	41	35	41
Std. mean luminance	10.1	5.2	5.2

Table 3 Contrast and luminance statistics for Experiment 2B: Weber's contrast measures are displayed. Negative contrasts mean that the object was darker than the background. Note that variations in luminance statistics are influenced by variations in background luminance across test stations

Results

The T2 results are illustrated in Figures 9 and 10. An AB was evident from a main effect of lags, $F(5,70) = 17.2$, $p <= 0.0001$. There was neither an interaction effect between T1 contrast and lags, $F(5,70) = 0.8$, $p = 0.52$, nor a main effect of T1 contrast, $F(1,14) = 1.2$, $p = 0.30$. Figure 10 is similar to Figures 3 and 7 and illustrates the paired differences in T2 accuracy between T1 conditions.

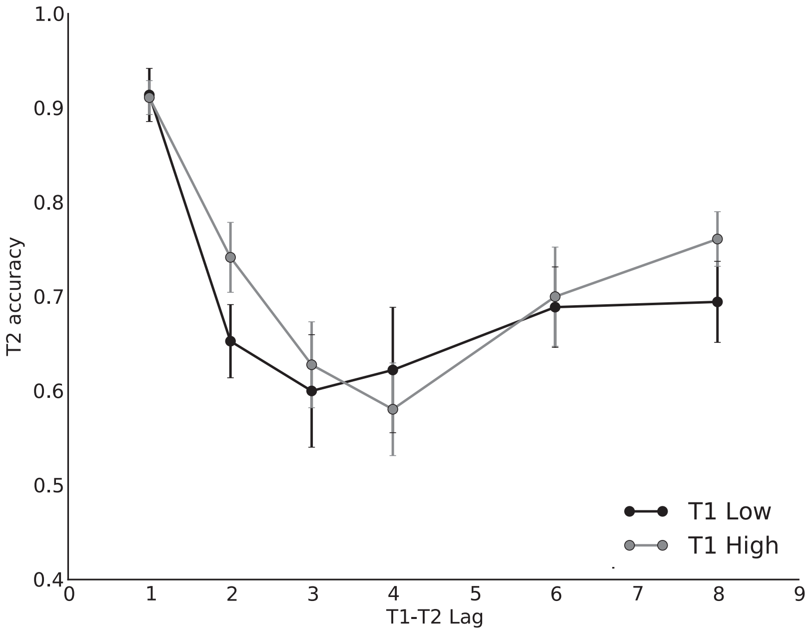


Fig. 9 Results from Experiment 2B: T2 accuracies are plotted across T1-T2 lags. The graphs illustrate T2 conditioned by each of the T1 conditions. Error bars show standard errors of the mean

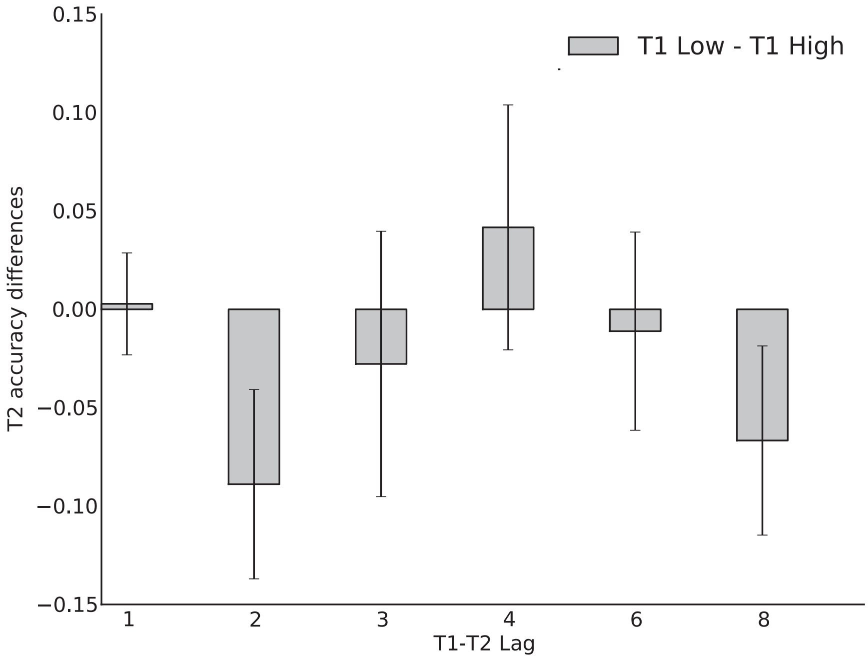


Fig. 10 Results from Experiment 2B: Differences in T2 accuracy between T1 conditions are plotted across T1-T2 lags. 'T1 Low – T1 High' signifies the differences in T2 accuracy between the low and high T1 conditions. Error bars show standard errors of the mean

The T1 results are illustrated in Figure 11. T1 accuracy was successfully controlled between T1 conditions. Mean (std) T1 accuracy across lags was 0.83 (0.03) and 0.81 (0.03) for low and high contrast respectively. ANOVA statistics verified that there was no effect of T1 difficulty, $F(1,14) = 0.7$, $p = 0.42$. There was a main effect of lags $F(5,70) = 17.8$, $p <= 0.0001$.

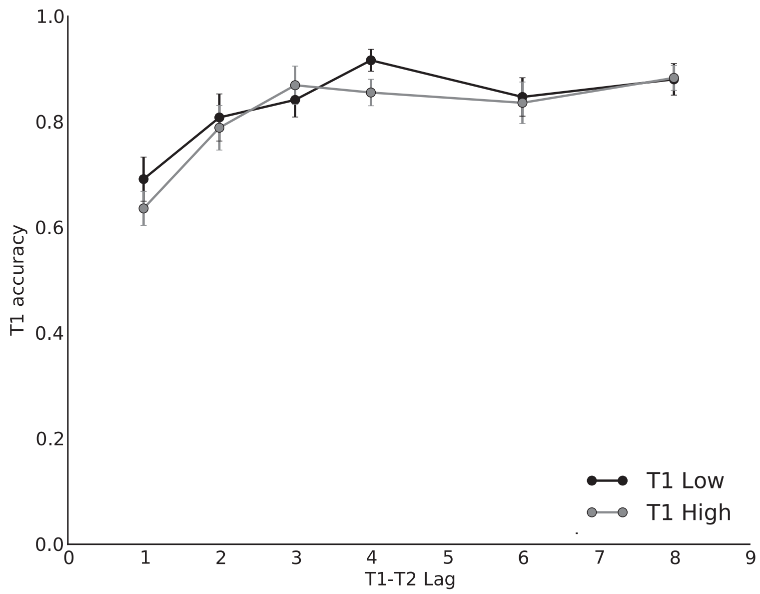


Fig 11 Results from Experiment 2B: T1 accuracies are plotted across T1-T2 lags. The graphs illustrate each of the T1 conditions. Error bars show standard errors of the mean

Discussion

We did not observe the capture effect from a high contrast T1 as in Experiment 2A. This is not surprising, though, since the high contrast T2 is likely to have captured attention and thus counteracted the capture effect from the high contrast T1, which is in agreement with what Shih and Reeves (2007) found. The lag 1 effects of T1 contrast found in Experiments 1 and 2A are absent here, suggesting that forward masking caused them. Forward masking is strongest when the contrast of the mask is (much) higher than the target (Spencer & Shuntich, 1970), which it was in Experiment 1 and 2A where these effects was observed, and which it was not here where not effect was observed. As in Experiment 2A, T1 contrast was successfully varied while controlling T1 difficulty between T1 conditions.

General discussion

The goal of the present study was to examine attention capture effects (Chua, 2005) in the AB paradigm while controlling for bottleneck effects (Chun & Potter, 1995). To this end, we varied T1 contrast and adjusted observers individually to account for differences in contrast sensitivity. We devised a design where conditions were mixed within blocks to avoid contributions from high level strategies that has been found to promote bottleneck effects (Shore et al., 2001). Further, we did not use backwards pattern masks to avoid interference with the effect of T1 contrast, either by disruption of processing in the bottleneck (Visser & Ohan, 2007) or by attention capture (Nielsen & Andersen, 2011).

Across three experiments we found that T1 contrast influences the AB in different ways, depending on design configurations. In Experiment 1 we varied T1 contrast in three conditions. Experiment 1 showed that T1 contrast reduces T2 accuracy at lags 1 and 2. The effect at lag 2 replicates what was reported in Chua (2005) and can be explained by an attention capture hypothesis suggesting that a salient T1 captures attention such that it cannot be reallocated to T2 in time (Chua, 2005; Folk & Leber, 2008). The effect at lag 1, is most likely caused by forward masking of T2 by a high contrast T1 (see next section for a discussion of this). Experiment 1 may have been influenced by bottleneck effects since T1 accuracy varied between conditions, which may have caused a high contrast T1 to be processed faster than a low contrast T1 consequently leading to a reduction in the AB. In Experiment 2A we aimed to further examine the capture effect of T1 contrast found in Experiment 1. Particularly we were interested in eliminating the influence of bottleneck effects that may have confounded findings in Experiment 1. Using additive Gaussian noise, in Experiment 2A we devised two T1 contrast conditions such that T1 contrast varied between conditions while T1 difficulty was kept constant. Experiment 2A showed the same pattern of results as Experiment 1; that a high contrast T1 causes a capture effect, which impairs report accuracy of a subsequent T2. The T1 capture effect was eliminated in Experiment 2B when T2 contrast was either greater than or equal to that of T1 (compared to less than or equal in Experiment 2A), such that T2 itself captured attention and thereby equated the effect of T1 capture (Shih & Reeves, 2007).

In Experiments 1 and 2A we observed forward masking effects at lag 1 from a high contrast T1, similarly to what was reported in Spencer and Shuntich (1970). However, forward masking cannot explain the effects reported here at lags 2 and beyond, since Spencer and Shuntich (1970) showed that 150 ms. (which corresponds to lag 2 in the current study) is the effective range for a very high mask to have any effect on report accuracy of a subsequent target. Thus the current study shows that an effect of T1 contrast exists, which cannot be explained by forward masking but most likely are caused by T1 attention capture.

It can be argued that the effect of T1 contrast found here is in fact an effect of the contrast between targets and distractors and not the contrast between target and the background. The distractors always had a higher contrast than the targets, thus the high contrast conditions in which a capture effect was observed, may have been due to that the similarity between targets and distractors increased, which have been found to increase the AB (Chun & Potter, 1995). However, this is unlikely since Chua (2005) reported the same effect even when distractors were always presented in a lower contrast than the targets. Also, previously we (Nielsen & Andersen, 2011) have demonstrated the same effect in the two-target paradigm with two targets presented in different locations. Here, the only items in the display was the two targets and a backwards pattern mask following T2. Thus, the effect is unlikely to have been caused by target distractor similarity since it also has been showed to occur when no distractors are present.

In this study we reported T2 irrespective of whether or not T1 was correctly identified. We did this for two reasons. First, in Experiment 1, T1 accuracy in the Hard condition was only 51%. Reporting T2 conditioned by correct identification of T1 (T2|T1) would nearly halve the number of trials in the analysis in this condition. Second, the effects examined here are likely influenced by attention capture, which do not depend on the processing of the targets more than the allocation of attention to the target. This is supported by recent studies showing that an AB occurs, even though T1 is attempted ignored, as long as T1 shares T2 features (Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006; Nieuwenstein et al., 2009) especially when varying T1 contrast (Christmann & Leuthold, 2004; Chua, 2005). In addition, it has been showed than the AB is not contingent on correct identification of T1, but merely requires the registration of T1 (Nieuwenstein et al., 2009). Also, the analysis of T2|T1 produced significant results for the same variables as the T2 analysis, except for the main effect of T1 contrast in Experiment 1, which was (marginally) significant only in the T2 analysis (an interaction effect was evident from both analyses), and an interaction effect between T1 contrast and T2 lag in Experiment 2A, which was significant only in the T2|T1 analysis. Further, the differences in statistics between the T2 and T2|T1 analyses have no consequences for the qualitative conclusion, that T1 contrast increases the AB.

In conclusion we found that T1 contrast influences the AB such that a high contrast T1 causes a greater AB than a low contrast T1. This effect can be cancelled by the opposing action of T2 contrast. The effect is most likely caused by attention capture, such that a high contrast target is more salient and therefore attracts attention, which impairs reallocation to a subsequent target unless the following target itself is highly salient.

References

Christmann, C., & Leuthold, H. (2004a). The attentional blink is susceptible to concurrent perceptual processing demands. *The Quarterly Journal of Experimental Psychology Section A*, *57*(2), 357–381. doi:10.1080/02724980343000350

Christmann, C., & Leuthold, H. (2004b). The attentional blink is susceptible to concurrent perceptual processing demands. *The Quarterly journal of experimental psychology. A, Human experimental psychology*, *57*(2), 357–377. doi:10.1080/02724980343000350

Chua, F. K. (2005). The effect of target contrast on the attentional blink. *Attention, Perception & Psychophysics*, *67*(5), 770–788.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 109–127.

Duncan, J. C., Ward, R., & Shapiro, K. L. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, *369*(6478), 313–315. doi:10.1038/369313a0

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception & Psychophysics*, *71*(8), 1683–1700. doi:10.3758/APP.71.8.1683

Folk, C. L., & Leber, A. (2008). Top-down control settings and the attentional blink: Evidence for nonspatial contingent capture. *Visual Cognition*.

Giesbrecht, B., & DiLollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of experimental psychology*.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*(2), 138–202. doi:10.1006/cogp.1998.0684

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, *18*(4), 560–578. doi:10.1080/09541440500423210

Martens, S., & Wyble, B. (2010). The attentional blink: Past, present, and future of a blind spot in perceptual awareness. *Neuroscience & Biobehavioral Reviews*, *34*(6), 947–957. doi:10.1016/j.neubiorev.2009.12.005

Martens, S., Munneke, J., Smid, H., & Johnson, A. (2006). Quick minds don't blink: Electrophysiological correlates of individual differences in attentional selection. *Journal of Cognitive Neuroscience*, *18*(9), 1423–1438.

Mclaughlin, E. N., Shore, D. I., & Klein, R. M. (2001). The attentional blink is immune to masking-induced data limits. *The Quarterly journal of experimental psychology. A, Human experimental psychology*, *54*(1), 169–196. doi:10.1080/02724980042000075

Nieuwenstein, M. R., Van der Burg, E., Theeuwes, J., Wyble, B., & Potter, M. C. (2009). Temporal constraints on conscious vision: On the ubiquitous nature of the attentional blink. *Journal of Vision*, *9*(9), 18–18. doi:10.1167/9.9.18

Norman, D. A., & Bobrow, D. G. (1975). On Data-limited and Resource-limited Processes.

Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review*, *115*(4), 836–863. doi:10.1037/a0013395

Peirce, J. W. (2007). PsychoPy--Psychophysics software in Python. *Journal of*

Neuroscience Methods, *162*(1-2), 8–13. doi:10.1016/j.jneumeth.2006.11.017
Raymond, J. E., Shapiro, K. L., & Arnell, K. M. M. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? . *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860.
Seiffert, A. E., & DiLollo, V. (1997). Low-level masking in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(4), 1061–1073.
Shih, S.-I., & Reeves, A. (2007). Attentional capture in rapid serial visual presentation. *Spatial vision*, *20*(4), 301–315. doi:10.1163/156856807780919019
Shore, D. I., Mclaughlin, E. N., & Klein, R. M. (2001). Modulation of the attentional blink by differential resource allocation. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *55*(4), 318–324.
Spencer, T. J., & Shuntich, R. (1970). Evidence for an interruption theory of backward masking. *JEP*, 1–3.
Treutwein, B. (1995). Adaptive psychophysical procedures. *Vision Research*, *35*(17), 2503–2522.
Visser, T. A. W. (2007). T1 difficulty and the attentional blink: Expectancy versus backward masking. *The Quarterly Journal of Experimental Psychology*, *60*(7), 936–951. doi:10.1080/17470210600847727
Visser, T. A. W., & Ohan, J. L. (2007). Data-limited manipulations of T1 difficulty modulate the attentional blink. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *61*(2), 102–108. doi:10.1037/cjep2007011
Ward, R., Duncan, J. C., & Shapiro, K. L. (1996). The Slow Time-Course of Visual Attention. *Cognitive Psychology*, *30*(1), 79–109. doi:10.1006/cogp.1996.0003

DTU Technical University of Denmark

Under which conditions does T1 difficulty affect T2 performance in the attentional blink?

Simon Nielsen[1], Anders Petersen[2], Tobias Andersen[3]

1,3 Cognitive Systems, Informatics and Mathematical Modelling, Technical University of Denmark

2 Center for Visual Cognition, Psychology, Copenhagen University, Denmark

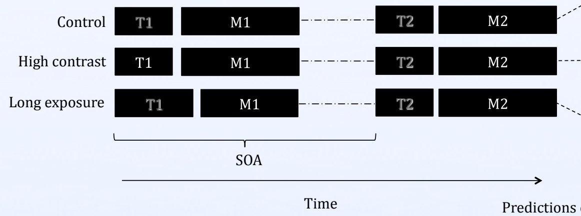
Introduction

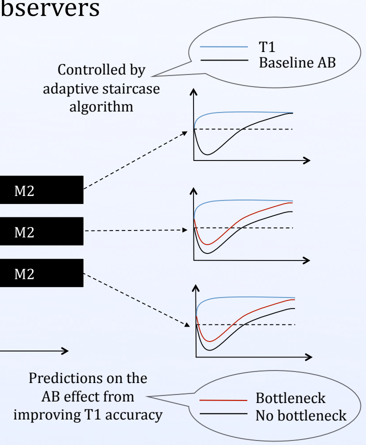
- We examine how the perceptual difficulty of T1 affects the attentional blink (AB) by increasing T1 exposure duration and T1 contrast relative to a control level
- Bottleneck theories suggest that a slow pre VSTM stage accounts for the AB and predicts that T1 difficulty is inversely related to the AB magnitude

Method

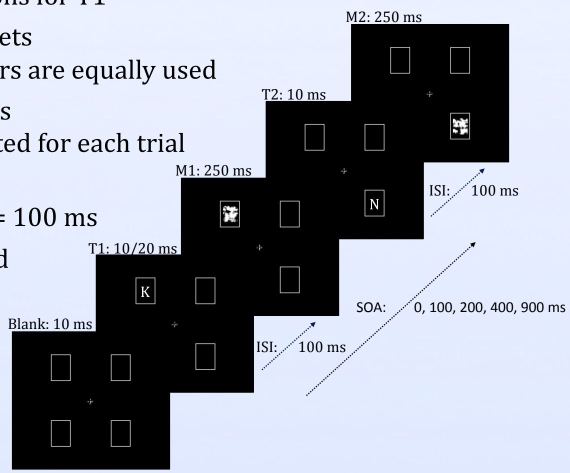
- Three T1 difficulty conditions
- T1 accuracy adjusted individually for observers

Condition	T1 accuracy	Contrast	Duration
Control	50%	Low	Short
High contrast	85%	High	Short
Long exposure	85%	Low	Long



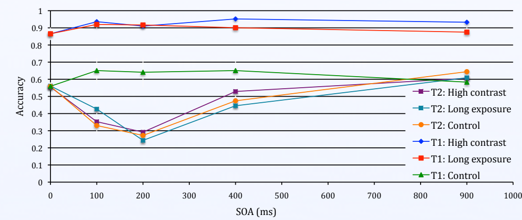


- Two target paradigm
  - 5 SOA conditions
  - 3 difficulty conditions for T1
- Report two letter targets
  - Each of the 26 letters are equally used
- Random feature masks
  - New masks generated for each trial
- Interruption masking
  - Target to mask ISI = 100 ms
- 6 observers conducted trials in each of the 15 conditions



Findings

- T2 main effect of SOA in all conditions indicating an AB
- No T2 main effect of T1 difficulty in the contrast or the exposure condition
- T2 interaction effect ($p = 0.04$) both in the contrast and the exposure condition



Conclusion

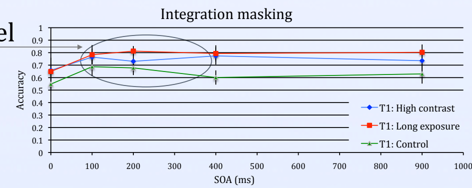
- Varying perceptual difficulty of T1 is not sufficient to modulate the AB magnitude
- Interaction effect may indicate temporal displacement of the AB
- These findings lend little support to the bottleneck theories

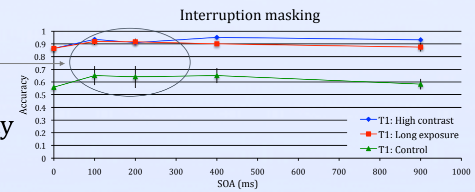
Discussion on visual masking

Integration masking causes large variation in data:

-Observers cannot sustain adjusted T1 accuracy level

- RSVP studies use interruption masking due to masking study by Brehaut et al. (1999)
- Two-target studies does not? (Duncan et al., 1994; Moore et al., 1996; Ward et al., 1996,1997; McLaughlin et al., 2001)
- Consistent with Brehaut and colleagues' study we find that Interruption masking facilitates
- Less variation in data
- Larger AB magnitude (35% increase)





Masking may confound interference from T1 difficulty

- Target processing is interrupted by attentional capture towards the mask
- This may prevent us from observing any effect on T2 performance from improving T1 accuracy

DTU Informatics
Department of Informatics and Mathematical Modelling

DTU Technical University of Denmark

T1 difficulty modulates the attentional blink only when T1 is unmasked: Implications of attentional capture in the attentional blink

Simon Nielsen, Tobias Andersen

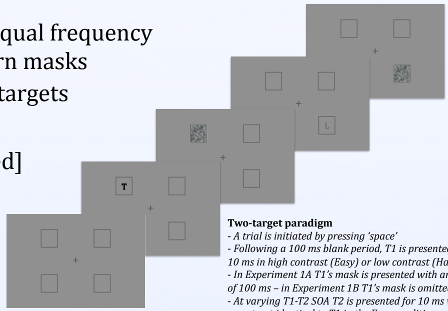
Cognitive Systems, Informatics and Mathematical Modelling, Technical University of Denmark

Introduction

- We use the two-target paradigm and examine bottleneck predictions of how T1 difficulty affects the attentional blink
- Bottleneck theories suggest that making T1 easier to perceive should clear second stage processing faster resulting in a reduced attentional blink
- Previously we found no effect from varying T1 contrast or T1 duration, but proposed that the effect may have been confounded by involuntary attention directed to the mask
- In a new study we vary T1 contrast and examine the effect on the attentional blink when T1 is masked compared to when T1 is unmasked

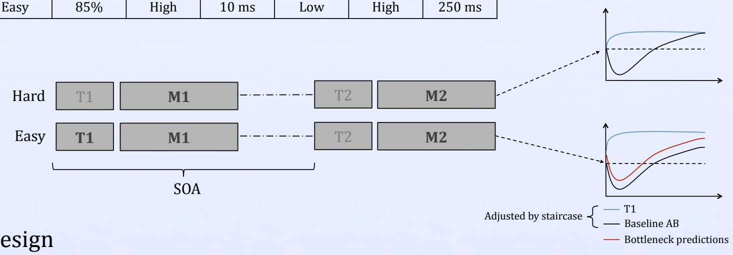
Method

- Stimuli
  - 20 letter targets presented at equal frequency
  - Randomly generated dot pattern masks
  - Masks presented 100 ms after targets
- Main variables
  - T1 masking [Masked, Unmasked]
  - SOA [100, 200, 300, 400, 600]
  - T1 difficulty [Hard, Easy]
- Instructions
  - Report identity of T1 and T2
  - Guess if uncertain



Two-target paradigm
- A trial is initiated by pressing 'space'
- Following a 100 ms blank period, T1 is presented for 10 ms in high contrast (Easy) or low contrast (Hard)
- In Experiment 1A T1's mask is presented with an ISI of 100 ms – in Experiment 1B T1's mask is omitted
- At varying T1-T2 SOA T2 is presented for 10 ms with a contrast identical to T1 in the Easy condition
- T2 is succeeded by a mask with an ISI of 100 ms
- T1 and T2 positions are different within trials and pseudo-randomly selected between trials

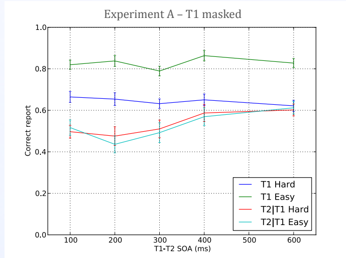
Condition	T1 accuracy	T1 contrast	T1/T2 duration	T2 contrast	Mask contrast	Mask duration
Hard	60%	Low	10 ms	Low	High	250 ms
Easy	85%	High	10 ms	Low	High	250 ms

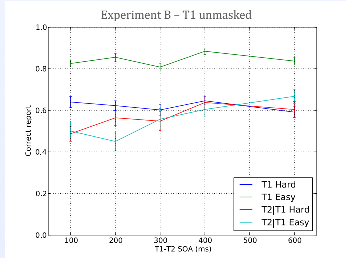


- Design
  - T1 masking varied between Experiment 1A and 1B
  - Factorial ordered SOA and T1 difficulty within experiments
  - 48 trials in each of the 10 factorial combinations
  - 18 observers conducted Experiment 1A and 1B in counterbalanced order

Findings

- Proportions of correct report are plotted as function of SOA
- Proportions were arcsine transformed and analyzed with repeated measures ANOVAs
- T2 main effect of SOA in Experiment A and B indicates an attentional blink
- Experiment A – T1 masked:
  - % Main effect (T1 difficulty) [F(1,17) = 0.73, p = 0.41]
  - % Interaction effect (SOA x T1 difficulty) [F(4,68) = 1.24, p = 0.30]
- Experiment B – T1 unmasked:
  - % Main effect (T1 difficulty) [F(1,17) = 0.60, p = 0.45]
  - ✓ Interaction effect (SOA x T1 difficulty) [F(4,68) = 8.03, p < 0.001]
    - ✓ Main effect (T1 difficulty, SOA = 200 ms) [F(1,17) = 25.90, p < 0.001]





Preliminary conclusion*

- Varying T1 difficulty by target contrast modulates the attentional blink only when T1 is unmasked
- Contrary to bottleneck predictions we observed that making T1 easier to perceive increases the magnitude of the attentional blink
- We suggest that this finding indicates capture of involuntary attention which increases with contrast
- Similarly we suggest that involuntary attention directed towards T1's mask confounded the effect of T1 difficulty in Experiment A

* Inference is based on a single significant data point. In follow up experiments we examine if the effect observed in Experiment B is modulated by properties of T1

DTU Informatics
Department of Informatics and Mathematical Modelling

Technical University of Denmark

Exogenous attention capture modulates the attentional blink

Simon Nielsen, Tobias Andersen
Cognitive Systems Section, Department of Informatics and Mathematical Modelling, Technical University of Denmark

Introduction

- Observers often fail to report the second of two sequential targets (T1 & T2) presented within 500 ms – a phenomenon know as the attentional blink (AB)

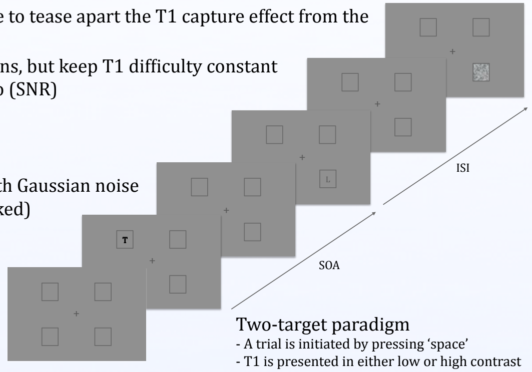
AB hypothesis	Cause of AB	Prediction on how T1 difficulty affects the AB
Bottleneck / Two-stage models	T1 occupies a slow second processing stage when T2 is presented	If increasing T1 difficulty increases T1 processing time this should cause a greater AB
Attention capture	T1 captures attention which cannot be reallocated to T2 in time	If increasing T1 difficulty decreases T1 saliency this should cause a smaller AB

Method

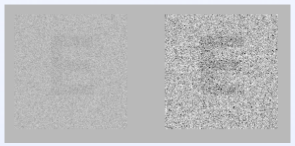
- Here we use additive Gaussian noise to tease apart the T1 capture effect from the effect of T1 difficulty
- We vary T1 contrast in two conditions, but keep T1 difficulty constant measured by T1 signal to noise ratio (SNR)

Experiment 1

- Stimuli
  - Letter targets superimposed with Gaussian noise
  - T2 pattern mask (T1 is not masked)
- Conditions
  - T1-T2 SOA [100, 200, 300, 450, 600, 900]
  - T1 contrast [Low, High] (with identical SNR)
- Design
  - 19 observers
  - SOA and T1 contrast mixed within blocks in a full factorial design
  - 48 repetitions in each of the 12 factorial combinations



Two-target paradigm
- A trial is initiated by pressing 'space'
- T1 is presented in either low or high contrast
- T2 is presented after a T1-T2 SOA interval
- T2 is masked after an ISI of 100 ms
- Report identity of T1 and T2



Sample stimuli
Sample stimuli from Experiment 1 and 2 showing the Low (left) and High (Right) T1 contrast conditions. The stimuli have identical signal-to-noise ratio, but different contrast levels. (Rendering in print may affect the signal-to-noise ratio).

T1 Condition	T1 accuracy	T1 contrast	T1 SNR	T2 contrast	T2 SNR
Low	80%	Low	α_1	Low	α_1
High	80%	High	α_1	Low	α_1

Target attributes
The table shows target attributes for the T1 conditions in Experiment 1 and 2. SNR level α_1 imply that the same SNR level was used across conditions.

Experiment 2

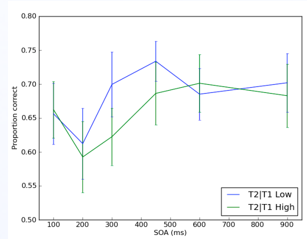
- Identical to Experiment 1 with following exceptions
  - Skeletal version of the two-target paradigm used, with stimuli presented in the same location
  - SOA 900 ms was omitted
  - 15 observers was tested

Results

Experiment 1

- We found that AB magnitude increased with T1 contrast, evident from a T2|T1 main effect of T1 contrast [F (1,18) = 5.54, *p* = 0.03]
  - Further post-hoc analysis showed a main effect at SOA 300 ms [F (1,18) = 6.87, *p* = 0.02]
- T1 accuracy across SOA was 0.76, SE 0.04 for the Low T1 condition and 0.80, SE 0.03 for the High T1 condition
  - Despite the effect was marginal it was consistent leading to a T1 main effect of T1 contrast [F (1,18) = 12.89, *p* < 0.01]

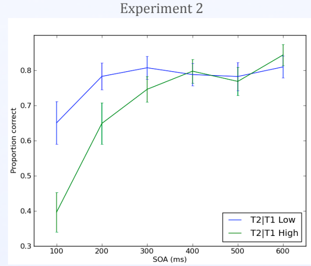
Experiment 1



Experiment 2

- We found that AB magnitude increased with T1 contrast, evident from a T2|T1 main effect of T1 contrast [F (1,14) = 24.05, *p* < 0.01]
  - Further post-hoc analysis showed a main effect at SOA 100 ms [F (1,14) = 48.53, *p* < 0.01] and at SOA 200 ms [F (1,14) = 8.85, *p* = 0.01]
- T1 accuracy across SOA was 0.76, SE 0.03 for the Low T1 condition and 079, SE 0.04 for the High T1 condition
  - Despite the effect was marginal it was consistent leading to a T1 main effect of T1 contrast [F (1,14) = 8.08, *p* = 0.01]

Experiment 2



Proportions correct were arcsine transformed and analyzed with repeated measures ANOVAs

Summary

- Previously we varied T1 difficulty with T1 contrast and found that AB magnitude increased with T1 contrast
- Here we used additive Gaussian noise and varied T1 contrast with little influence on T1 difficulty
- We found that AB magnitude increased with T1 contrast at SOA 300 ms in the two-target paradigm and at SOAs 100 ms and 200 ms in the skeletal paradigm
- Lag-1 sparring was not observed in the skeletal paradigm, suggesting that forward masking confounded the AB effect of T1 contrast at SOA 100 ms
- These findings supports an attention capture hypothesis suggesting that slow reallocation of attention plays an important role in the AB

Corresponding author:
Simon Nielsen
sini@imm.dtu.dk

DTU Informatics
Department of Informatics and Mathematical Modelling

The Attentional Blink is Modulated by First Target Contrast:

Implications of an Attention Capture Hypothesis

Technical University of Denmark

Simon Nielsen, Tobias Andersen

Cognitive Systems Section, Department of Informatics and Mathematical Modelling, Technical University of Denmark

Introduction

- Attentional blink: Difficult to see the second of two sequential targets (T1 & T2) presented within 500 ms

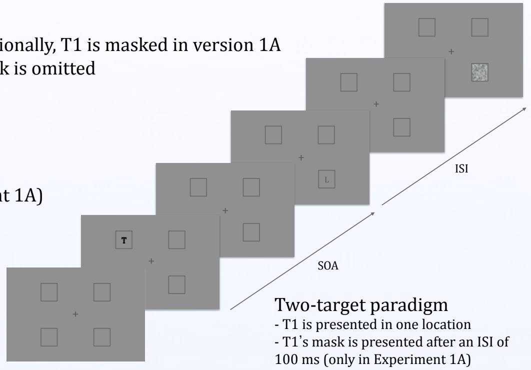
AB hypothesis	Cause of AB	Prediction on how T1 contrast affects the AB
Bottleneck / Two-stage models	T1 occupies a slow second processing stage when T2 is presented	Increase T1 contrast -> decrease T1 difficulty -> decrease T1 processing time -> decrease AB
Attention capture	T1 captures attention which cannot be reallocated to T2 in time	Increase T1 contrast -> Increase T1 saliency / capture -> increase AB

Experiment 1

- We vary T1 contrast in two conditions. Additionally, T1 is masked in version 1A of the experiment and in version 1B T1's mask is omitted

Methods

- Stimuli
  - Letter targets
  - T1,T2 pattern mask (T1 only in Experiment 1A)
- Conditions
  - T1's mask [Present, Absent]
  - T1-T2 SOA [100,200, 300, 400, 600]
  - T1 contrast [Low, High]
- Design
  - 18 observers
  - T1 accuracies adjusted individually for observers
  - SOA and T1 contrast varied within the experiments 1A and 1B and T1's mask between
  - 48 repetitions in each of the factorial combinations

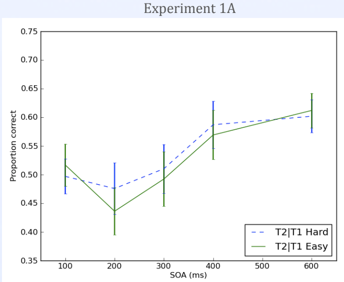


Two-target paradigm
- T1 is presented in one location
- T1's mask is presented after an ISI of 100 ms (only in Experiment 1A)
- T2 is presented after the T1-T2 SOA at a different location
- T2 is masked after an ISI of 100 ms
- Report the identity of T1 and T2

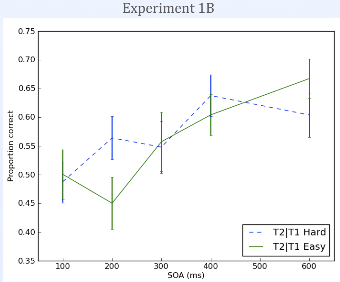
Results – "AB magnitude depends on T1 contrast only when T1 is unmasked"

- We found a T1 difficulty x SOA interaction in Experiment 1B when T1 was unmasked [F (4,68) = 8.03, p < 0.001]
  - A simple effect analysis showed a main effect at SOA 200 ms [F (1,17) = 25.89, p < 0.001]
- When T1 was masked (Experiment 1A) we did not observe any interaction effect [F (4,68) = 1.24, p = 0.30]

Experiment 1A



Experiment 1B



Experiment 2

- Here we use additive Gaussian noise to targets and vary T1 contrast in two conditions, but keep T1 SNR constant to control T1 difficulty

Methods

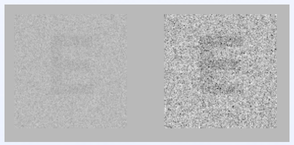
- Identical to Experiment 1 except:
  - 22 observers was used
  - Gaussian noise was added to targets
  - T1 accuracy was matched across T1 contrast conditions
  - SOA 900 ms was added
  - T1 was never masked

Experiment	T1 contrast	T1 accuracy	T1 SNR
1A (T1 masked)	Low/High	50%/80%	-
1B (T1 unmasked)	Low/High	50%/80%	-
2 (Gaussian noise)	Low/High	60%/60%	α_1/α_1

Target attributes
The table shows target attributes for the T1 conditions in Experiment 1 and 2. SNR level α_1 imply that the same SNR level was used across conditions.

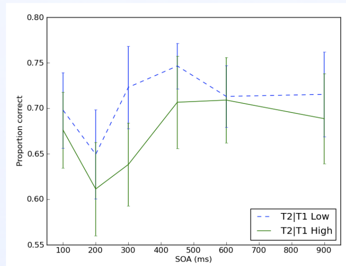
Results – "AB magnitude depends on T1 contrast even when T1 difficulty is constant"

- We found A main effect of T1 contrast [F (1,18) = 5.54, *p* = 0.03]
- T1 accuracy across SOA was 0.76, SE 0.04 for the Low T1 condition and 0.80, SE 0.03 for the High T1 condition
  - Despite the effect was marginal it was consistent leading to a T1 main effect of T1 contrast [F (1,18) = 12.89, *p* < 0.01]



Sample stimuli
Sample stimuli from Experiment 2 showing the Low (left) and High (Right) T1 contrast conditions. The stimuli have identical signal-to-noise ratio, but different contrast levels. (Rendering in print may affect the signal-to-noise ratio).

Experiment 2



Summary

- In Experiment 1 we varied T1 contrast in two conditions. Between Experiment 1A and 1B we always presented T1's mask (1A) or always omitted it (1B)
  - We found that AB magnitude increases with T1 contrast only when T1 is unmasked - implying that T1 masking may confound studies examining AB effects of T1 difficulty
- In Experiment 2 we varied T1 contrast in two conditions with little influence on T1 accuracy
  - We found that AB magnitude increases with T1 contrast - implying a strong effect of T1 saliency on the AB, which is independent of T1 difficulty
- These findings support an attention capture hypothesis of the AB

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